Archives of Environmental Protection
Vol. 46 no. 4 pp. 121–131
PL ISSN 2083-4772
DOI 10.24425/aep.2020.135770

Converting sewage holding tanks to rainwater harvesting tanks in Poland

Sadżide Murat-Błażejewska, Ryszard Błażejewski*

Poznań University of Life Sciences, Poland

*Corresponding author's e-mail: ryszard.blazejewski@up.poznan.pl

Keywords: rainwater harvesting, sewage holding tank, storage, irrigation, cost.

Abstract: The aim of this study was an assessment of feasibility of conversion of sewage holding (SH) tanks to rainwater harvesting (RWH) tanks in Poland. Such a conversion may partly solve the problem of water scarcity for irrigation of plants in individual small gardens and reduce tap water consumption. Seven methods of RWH tanks sizing were applied to an example of a small harvesting system of the roof area equal to the garden irrigation area of 100 m^2 for three different irrigation doses. A new criterion was introduced to optimize the tank capacity. Economic optimization was provided for new RWH tanks and for the tanks adapted from abandoned SH tanks. Results obtained for a system sited in west-central Poland in an average year have shown that design capacity of RWH tanks varied markedly between sizing methods. The conversion of SH tanks to RWH tanks is profitable, especially for irrigation due to scarcity of water in relatively dry west-central regions. Conversion of individual SH tanks in a good technical state to RWH tanks is relatively simple and cheap. The potential increase in storage volume due to the conversion of individual SH tanks to RWH tanks could reach all over Poland 215–350 dam^3 per year, and individually can save up to 18–25% of total annual water use.

Introduction

It seems purposeful to begin with the explanation of the term *sewage holding tank* (SH tank) due to misunderstandings and ambiguity of some basic terms in the literature. For instance, Vorne et al. (2017) define the *holding tanks* as devices that store wastewater but do not provide treatment, and claim that they are known also as *cesspools* or *cesspits*. According to Tilley et al. (2014), a *cesspit* (or *cesspool* or *soak pit* in some contexts), is a term with various meanings – it is used to describe either a *soak pit* (not sealed at the bottom and side walls) or an underground watertight SH tank. The latter meaning and term will be used throughout this paper. SH tanks are sometimes called *septic tanks* (e.g. Burchart-Koroll and Zawartka 2019), but it is not correct, as *septic tanks* provide preliminary treatment and possess both inlet and outlet, whereas SH tanks do not provide any treatment and possess an inlet only.

Article 3(1) of the Council Directive 91/271/EEC (1991) allows the EU Member States to use individual and other appropriate systems where the establishment of a collecting system is not justified either because it would produce no environmental benefit or because it would involve excessive cost, as long as they ensure the same level of environmental protection as a collection and treatment system. Member States must report on how much wastewater is collected by the individual and other appropriate systems, but the directive does not specify any provision that obliges them to ensure monitoring of the resulting effluent or environmental impacts.

In 2018, there were on average 2.34 inhabitants per one household in Polish cities, and 3.23 in rural areas, with an average value of 2.63 for the whole Poland (Statistics Poland 2019). At that time, 86% of the total number of SH tanks was located in rural areas, i.e., approx. 1.9 million installations (Local Data Bank 2020); it results from the fact that 1.9 · 3.23 = 6.1 million inhabitants in the countryside used SH tanks, while in cities 0.3 · 2.34 = 0.7 million inhabitants, in total 6.8 million inhabitants, i.e., 18% of the total population in Poland. It is known that the operation of SH tanks is a last resort solution for sewage management, mainly due to its high operation and maintenance costs (WSDH 2012). Replacing these tanks with household sewage treatment plants or collective systems, assuming unit investment outlays of 1.2–1.7 thousand EUR/cap., would consume approx. EUR 8–11 billion, i.e., approx. half of the expenditure on the implementation of the National Program for Municipal Wastewater Treatment (NPMWWT). This program, embracing agglomerations above 2,000 p.e., was commenced in 2003 (one year before Poland's access to EU) to comply with the EU legal regulations in the field of municipal wastewater discharge and treatment, which were set out in particular by the Council Directive 91/271/EEC (1991), and were introduced into the Polish national legal framework through the Act on Water Law. The implementation of the NPMWWT in Poland is currently assessed positively (EC 2019, Piasecki 2019). However, despite Poland's efforts supported with substantial EU Cohesion Policy funds and the progress achieved, a compliance gap remains serious

(Umweltbundesamt et al. 2017). On January 25, 2018, the European Commission (EC) sent a letter of formal notice to the Polish Minister of Foreign Affairs concerning a failure (infringement decision No. 20172183) to fulfil obligations under the Articles 3, 4 and 5 of the Directive 91/271/EEC (1991) urging Poland to take immediate remedial action. The underlying compliance gap mainly concerned improper management of sewage delivery from SH tanks, faulty technical conditions of "household sewage treatment plants" and their operation (EC 2018). More specifically, one of the reasons for this infringement procedure was a lack of proper records of SH tanks and small sewage treatment plants sited in the agglomerations. Recently, the EC raised the same concern in the reasoned opinion sent to Poland on 14 May 2020 in a follow-up action under the same infringement decision. Should Poland fail to take appropriate action within four months by October 2020 the EC may decide to refer it to the Court of Justice of the European Union (EC, 2020).

An adequate remedial action by Poland requires therefore a significant acceleration in establishing connections with collective sewerage systems in Poland and decreasing the number of SH tanks. The latter had been decreasing from 2440 thousand at the end of 2008 to 2136 thousand at the end of 2015 (Fig. 1), i.e., 304 thousand during 7 years (on average 43.4 thousand per year). The total relative decrease was 12.5%, i.e., 1.8% per year. Keeping up that decreasing rate, a complete liquidation of SH tanks would be expected after 56 years only. However, two voivodships, Opolskie and Podkarpackie, have shown much greater progress than the national average, approximately – 30% (Fig. 2). Anyhow, the access to sewage collective systems in rural areas, which reached 42% of 15 million inhabitants in 2019, is still unsatisfactory.

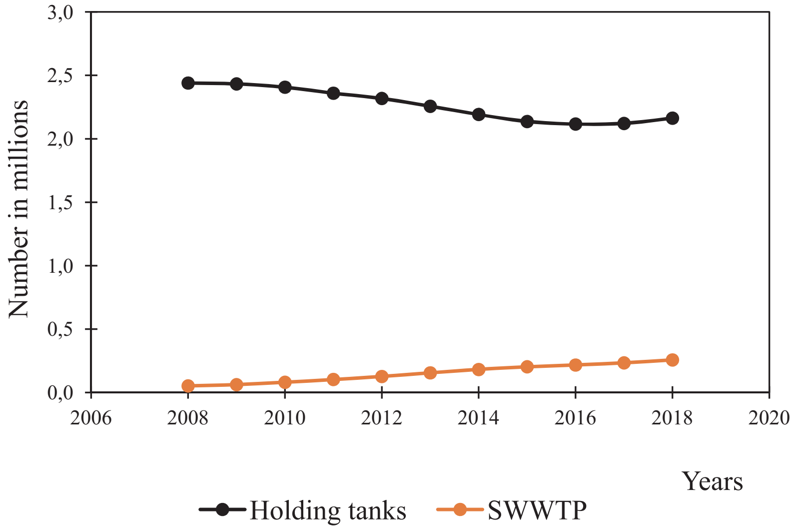

Fig. 1. Course of numbers of SH tanks and small wastewater treatment plants in Poland. Source: Statistics Poland. Local Data Bank (2020)

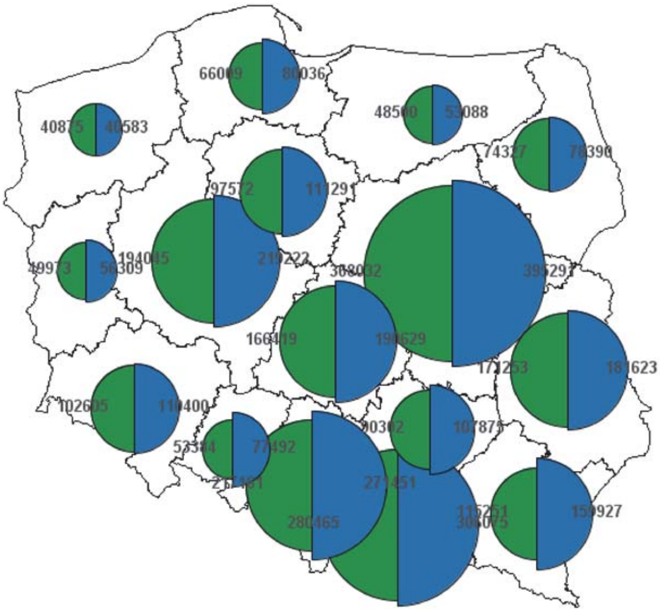

Fig. 2. Changes in numbers of SH tanks for liquid waste in Polish voivodships between the years 2008 (blue semicircles) and 2015 (green semicircles) Source: Statistics Poland. Geostatistics portal (2016)

There is no reliable statistical data, but typical volumes of SH tanks are corresponding to the volumes of cisterns (5–15 m^3) on hauling trucks. Our questionnaire done in 2020 in several communes of the Great Poland (Wielkopolska) region revealed that a typical SH tank volume ranged from 5 m^3 to 8 m^3, however, very rarely, the extremal values 2 m^3 and 20 m^3 occurred. The total loss of storage volume, at the average SH tank volume 5–8 m^3, had been equal to 215–350 dam^3. Relatively high tap water and the hauled sewage prices lead to low water usage (50–100 dm^3/cap.d). As a consequence the SH tanks are emptied once per 2–4 weeks instead of recommended once per week (WSDH, 2012). In many cases SH tanks in rural Poland are emptied once per several months. According to official statistics, people generate less sewage delivered to publicly owned wastewater treatment plants than they use the publicly-supplied water – 15–30 dm^3/cap.d (Statistics Poland, 2019). The main reason explaining this discrepancy is a relatively high price for the hauled sewage (up to EUR 8 per 1 m^3 or even more at distances above 10 km). To reduce costs people try to save water (a positive effect), to dispose the preliminary treated sewage to ground and/or on the soil surface or to pay less without receipt (negative effects). To address the negative effects, a majority of communes have recently introduced stricter scrutiny of the haulers' activities, and in several communes a flat-rate system has been applied. In the latter case a fixed price was established (about EUR 30 per household per month) for the service, regardless of generated sewage volume. The recent amendment to the Act on Maintaining Cleanliness and Order in Communes (PL OJ 2019, pos. 2010) requires local authorities to keep electronic records of SH tanks for liquid waste and records for household sewage treatment plants.

Having connected households to a sewerage network, the abandoned or liquidated SH tanks have been partly converted to rainwater harvesting (RWH) tanks, mainly for irrigation purposes. However, that conversion process has not been monitored nor investigated yet. Unfortunately, the closing of the NPMWWT (formally in 2015) and dynamic development of suburban areas without sewerage network have brought about a stopping of that desirable decreasing trend in the number of SH tanks (Fig. 1) and even a slight increase can be observed.

On a small scale rainwater harvesting in Poland was popular for centuries. Rainwater has been collected in buried barrels and other underground tanks or abandoned wells. In rural areas the harvested water was used for watering gardens and laundering. It has been especially appreciated in west-central Poland where the mean annual precipitation is relatively low, 480 mm/a (Szwed 2019) and even less than 300 mm/a in dry years. Low precipitation and dry periods are common in the central regions, e.g., in the growing seasons of the years 1972–2001 the dry period lasting more than 20 days occurred every second year. The longest period without precipitation lasted for 38 days (Kasperska-Wołowicz et al. 2003). The number of dry days with daily precipitation less than 1 mm has shown an increasing trend, however these changes have been more pronounced in eastern and south-eastern Poland (PNAS, 2013). Moreover, Szwed (2019) found a shift in precipitation from warmer towards colder season and she speculated that this unfavorable trend would continue. A growing season (defined as the period in which the mean daily air temperature is above 5°C) lasts for 190–220 days per year, starting from the end of March. Poland has relatively limited water resources, and especially in the west-central Poland temporary difficulties in maintaining adequate water supply can occur. In summertime there are periods with temporary ban on using tap water for irrigation purposes.

Following the EU policy on natural water retention measures (WFD CIS 2014) the Ministry of Maritime Economy and Inland Navigation is elaborating a Retention Development Program (Program Rozwoju Retencji) for 2021–2027 with a perspective by 2030. The activities indicated in the Program will take into account all types of surface water retention distinguished by their scale – large, small and micro retention and the type of retention – natural and artificial.

Authorities support rain harvesting by lowering prices for RWH tank of volume equal to 10%, 20% or 30% and more of the mean annual outflow volume (Rozp. RM, 2017). Additionally, in some big cities, an action “Catch the rain” has been carried out since 2019. The action is addressed to homeowners who are willing to harvest their own rainwater. In Warsaw, the co-financing of the installation of a RWH tank, infiltration trench or rain garden has reached up to EUR 2,400, in Cracow and Wrocław – up to EUR 1,200. On June 2, 2020, the Ministry of Climate and the National Fund for Environmental Protection and Water Management announced the nationwide subsidy program “Moja Woda” (My Water) for home installations harvesting rainwater or snowmelt. It is possible to obtain a subsidy of up to PLN 5,000, (~ EUR 1,136) but not more than 80% of eligible costs incurred after June 1, 2020 for the purchase, assembly and commissioning of the installation for one project. The budget of the program for 2020–2024 is PLN 100 million. Some communes have organized photography competition aimed to promote rainwater harvesting.

Systematic literature reviews to assess the state-of-art in the field of optimization of domestic RWH systems have been done recently by Pacheco and Campos (2017) and Semaan et al. (2020). From 2695 relevant journal articles found in the four biggest data bases, 45 articles were chosen by authors of the latter paper for further analysis. It has occurred that most works used historical rainfall and average water demands as input to their systems, while the most popular sizing method was the daily water mass balance. In seven articles simulation-based optimization methods to find the global optimum were used, whereas in the prevailing rest the authors were looking for local optima in terms of sizing. The sizing of storage was identified as the most important objective of optimization, however, the most frequently applied outcome of optimization was the cost. The authors suggested that future optimization studies should take into account greater variation in water demands and various climate change scenarios. Usage of smart sensors and Internet of Things were recommended to improve the optimality of sizing RWH systems.

Palla et al. (2012) examined the performance of domestic RWH systems to find their optimal design volume under various precipitation regimes. For this purpose, 46 sites were selected within the European territory; the closest to our study site was Berlin. A behavioral model was implemented and non-dimensional parameters were used to suitably compare the system performance under various hydrologic and operational (storage capacity and daily flushing of toilets) conditions. They concluded that the main hydrologic parameter affecting the system behavior is the length of the antecedent dry weather period, while rainfall event characteristics (including event rainfall depth, intensity and duration) revealed weak correlations with the system performance.

To design and financially analyze RWH tanks, a simple, spreadsheet based, daily water balance model was developed by Imtaez et al. (2011) using rainfall data, contributing roof area, rainfall loss factor, available storage volume, tank overflow and irrigation water demand. The effectiveness of two large tanks under different climatic scenarios was assessed. The analysis showed that both tanks could be quite effective in wet and average years, however less effective in dry years. Payback periods of the tanks have occurred relatively long (15–21 years) depending on tank size, climatic conditions and future water price increase rates. Another finding of the work was that in a wet year to have a zero overflow loss, a roof area of less than 900 m^2 is needed, however to achieve a zero tap water use the roof area should be at least 2000 m^2. Therefore, the authors pointed out another optimizing factor, i.e., if there is larger roof area, tap water use may come down to zero, but there will be significant overflow losses. However, no relevant optimization problem was formulated mathematically.

The aim of this paper is to assess feasibility of conversion of SH tanks to RWH tanks in Poland, especially in relatively dry west-central region, to address water scarcity for irrigation of plants in individual small gardens or to reduce indoor tap water use.

Methods

When considering a new or reused RWH system, it is crucial to determine its optimal size, which is closely linked to its financial feasibility (Liaw and Tsai 2004, Kim et al. 2014). In both cases the most influential factor is the size of the RWH tank. Seven different methods of RWH tank sizing were compared. The first two of them (A and B), popular both in Poland and Germany, are recommended by the German standard DIN 1989-1 (2002). Method A assumes that the tank capacity should cover water demands during 3 weeks (21 days) lasting dry period. In method B the dry period was related to the whole year, giving 21/365 = 0.06, i.e., 6% of the yearly water demand or harvested volume, whichever is lower. Next five methods (C-G) are based on daily water balance. Methods C and D are referred to water accessibility, i.e., reliability of supply (see equation 6) and water self-sufficiency, i.e., a degree of rainwater use comparing with water demand (see equation 9), respectively. One of the oldest and well-proved methods (here, method E) is creating mass curves (Fewkes 2006) and finding the maximum difference between the cumulative demand and harvest, determining the tank size. In methods F and G additionally annual expected costs and payback periods were taken into account.

Assuming that water demand is occurring after rain (e.g., just before midnight – to avoid thermal stress and high evaporation), daily water balance for a tank, as in Fig. 3, has been written in the following form (Dixon et al. 1999, Karim et al. 2014):

$$S_t = Y_t + S_{t-1} - D_t \tag{1}$$

subject to the following restrictions:

$$S_t = 0 for S_t \leq 0 \tag{2a}$$

and

$$S_t = S_{max} for S_t \geq S_{max} \tag{2b}$$

where S_t is the cumulative volume of water stored in the RWH tank (m^3) at the end of *tth* day, $_{St-1}$ is the storage in the tank (m^3) at the beginning of t^{th} day, Y_t is the harvested rainwater (yield) volume (m^3) on the t^{th} day, Dt is the daily rainwater demand (m^3) on the t^{th} day, S_{max} is the capacity of RWH tank (m^3).

D_t is the rainwater demand (m^3) on the t^{th} day, dependent on the preceding (antecedent) rainfall depth P; for a once per week irrigation with the minimum required depth d_{min} it reads:

$$D_t = \left(d_{min} - \sum_{i=t-6}^{i=t} P_i \right) A_w \geq 0 \tag{3}$$

where A_w is irrigated area, (m^2).

Plant irrigation is more effective when the proper water dose is greater and less frequent rather than smaller and more frequent, due to deeper penetration of the water into root zone.

The spilled water volume (demand after spillage, as recommended by EN 16941-1 (2018)) can be expressed as:

$$Z_t S_{t-1} + Y_t - S_{max} for S_t > S_{max} \tag{4}$$

and water needed from other sources (make-up) as:

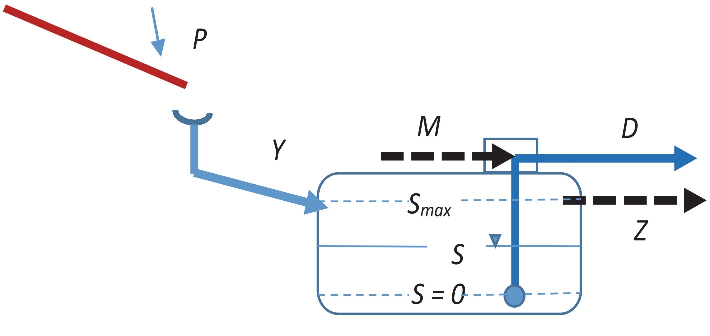

Fig. 3. Elements of the RWH tank balance

$$M_t = D_t – S_t for S_t < D_t \tag{5}$$

We used MS Excel spreadsheet to analyze the water balance with respect to time.

Time based reliability of the RWH system was calculated using the following equation (Imteaz et al. 2011):

$$R_e = \frac{N - U}{N} 100 \tag{6}$$

where U is the total number of days when harvested rainwater was unable to meet the daily water demand alone and N denotes the total number of days (365 or 366) in a calendar year or in the growing season when water is used for outdoor irrigation.

Total water saving efficiency (Dixon et al. 1999) can be assesed using the ratio:

$$E = \frac{\sum_{t=1}^{n} O_t}{\sum_{t=1}^{n} D_t} = \frac{\sum_{t=1}^{n}(M_t + D_t)}{\sum_{t=1}^{n} D_t} = 1 + \frac{\sum_{t=1}^{n} M_t}{\sum_{t=1}^{n} D_t} \to 1 \tag{7}$$

where O_t is the outflow from storage tank to water closet.

Umapathi et al. (2012) assessed diurnal water demand patterns (washing machine, water closet, garden) to determine supply reliability of 20 plumbed RWH tanks in South East Queensland (Australia). They used the following modified volumetric reliability index:

$$R_V = \frac{\sum_{t=1}^{n}(D_t - M_t)}{\sum_{t=1}^{n} W_t + \sum_{t=1}^{n}(D_t - M_t)} \tag{8}$$

where t is minutely time step, D_t is water supplied from the RWH tank, M_t is tap water top-up into the RWH tank, W_t is tap water used in household during the t^{th} minute.

Water balance analysis on the dynamics of the RWH tanks found that the rainwater source alone could offset the peak hour water demand by 28%, with a daily average offset of 10% (Umapathi et al. 2012).

The objective function in our model has been formulated as a hydraulic performance penalty index (*HPPI*), in which both water make-up (tap water uptake) M and total spillage Z are penalized, in the following form:

$$HPPI = \frac{\sum_{i=1}^{k}\left(\sum_{t=1}^{n} M_t + \sum_{t=1}^{m} Z_t\right)}{\sum_{i=1}^{k}\sum_{t=1}^{n} D_t} \to 0 \tag{9}$$

where n is number of days in the growing season, and m is number of days in the i^{th} year.

Equation 9 is the ratio of the cumulative volume of water needed from other sources and the spilled rainwater to the cumulative water demand.

In financial optimization analyses the total expected costs per year are often chosen as the objective function (Brown and Leung 1991, Mortazavi-Naeini et al. 2014):

$$C_e = I \cdot r + C_{O\wedge M} = I\frac{p(1+p)^T}{(1+p)^T - 1} + C_{O\wedge M} \to min \tag{10}$$

where I is investment (capital) cost, (EUR); r is annuity factor, (a^{-1}); T is project (RWH tank) life span, (a); p is discount rate, (–); $C_{O\&M}$ is yearly operation and maintenance cost, (EUR a^{-1}).

Payback period, i.e., the length of time required for analyzed investment to recover its initial outlay I in terms of profits or savings, was calculated by dividing the investment (capital) cost I by the difference between yearly operation and maintenance (O&M) cost without the investment object ($C_{O\&M}$) and the expected yearly O&M cost with it, according to the formula:

$$T_{PB} = \frac{I}{\Delta C_{O\wedge M}} \tag{11}$$

Negative values of $\Delta C_{O\&M}$ and T_{PB} indicate that the investment is unprofitable.

The precipitation data were referred to the Szamotuly-Baborowko meteo-station (16°38’E, 52°35’N) run by the Polish Institute of Meteorology and Water Management. Daily precipitation of depth 0.1 mm and higher were recorded. Due to the measurement error estimated as –13% the real values were by approximately 13% higher (Kowalczyk and Ujda 1987), but in this paper we assumed that the runoff coefficient for the roof is equal to 1/1.13 = 0.88, therefore we have used the raw input rainfall data without any correction.

Summarizing, seven sizing methods have been used, as listed below:

A. DIN1989-1 (tank volume covers water demand during 21-day drought);
B. DIN 1989-1 (tank volume equal to 6% of yearly water demand);
C. Maximum reliability of the RWH system *Re* (see equation 6);
D. Minimum of the hydraulic performance penalty index *HPPI* (see equation 9);
E. Cumulative demand and harvest curves (mass curve – see Fewkes 2006);
F. Economically optimal according to annual expected cost (see equation 10);
G. Economically optimal according to payback period (see equation 11).

The following assumptions have been made in our example:

1. Roof area: A_r = 100 m^2, irrigated garden area: A_w = 100 m^2 – values typical for Polish suburban areas;
2. Prices: tap water C_M = 1.5 EUR/m^3, rain water disposal to drainage network C_Z = 1.0 EUR/m^3, (Aquanet 2020), electric energy C_E = 0.2 EUR/kWh;
3. Three types of investment cost: 1) new RWH tank made of PE + pump: $I_1 = 500 + 0.3\ S_{max}$ [EUR] where S_{max} in dm^3, 2) pump with accessories inserted to an existing, relatively new SH tank: I_2 = 250 EUR and 3) repair of the old SH tank + pump with accessories: $I_3 = 500 + 50\ (S_{max}/3000 - 1)$ [EUR] where S_{max} in dm^3;
4. Project life span: T = 20 years, discount rate: p = 0.05, r = 0.03 (see equation 10);
5. Daily precipitation in the period 2006–2015 (10 years) fallen on a roof closely to the Szamotuly-Baborowko station; a balance sheet year was counted from October 1st to September 30th;
6. Garden irrigation period – April 1st – September 30th, minimum irrigation water needs – 10, 20 and 30 mm/week, therefore the irrigation water volumes (per house) are 1.0, 2.0 and 3.0 m^3/week, respectively;

7. The water remaining in the RWH tank just after the growing season was included in the spilled volume, which is fined as the rain water disposed to drainage network;
8. Alternatively, a whole year's indoor use, equal to 140 dm^3/d, is analyzed.

Analyses were performed for ten sequencing years (2006–2015) to diminish the effect of extremal phenomena. Annual precipitation sums in that period ranged from 371 to 698 mm/a, with the average equal to 530 mm/a. Over the whole 65 years' period of rainwater measurements (1955–2019) the yearly precipitation sums at the chosen site ranged from 324 mm/a to 717 mm/a, on average – 511 mm/a (Fig. 4). The last value is equivalent to 140 dm^3/d of rainwater harvested from the roof of surface area A_r = 100 m^2. In our analysis it has been taken as a whole year's daily indoor use.

Results and discussion

Technically, a conversion of a SH tank to RWH tank seems to be relatively simple and affordable, especially when the tank construction is strong enough. Typically, a small investment is needed to disinfect the SH tank, and equip it with a proper pump and accessories. In the case of indoor use, a dedicated force main could be installed in the abandoned building lateral to diminish construction work and costs.

The optimal capacity of RWH tanks depends mainly on costs, which are related to the local market conditions, but also on the harvested water yield and demand. The mean multi-year precipitation sum in non-growing seasons (October-March) at the study site (Szamotuly-Baborowko) was equal to 193 mm/season. From Fig. 4 it can be seen that with 95% reliability one may expect 120 mm to 340 mm of precipitation in the non-growing period. For the roof surface area A_r = 100 m^2 it provides as minimum as 12 m^3 of rainwater or melted snow. Only once per twenty years the rainwater harvest in the non-growing season has been less, but not less than 10 m^3.

The results of water balance and cost calculations are presented in Tables 1 and 2.

Operation and maintenance costs, *CO&M*, of rainwater disposal to urban drainage and the same irrigation system without any RWH tank are reaching on average 66, 96 and 133 EUR/a for irrigation water demands 1.0, 2.0 and 3.0 m^3/week, respectively.

Operation and maintenance costs, *CO&M*, of the home plumbing system without any RH tank are reaching 128 EUR/a. The assumption about duration of design dry period, applied in the German standard DIN 1989-1 (2002), (method A), has occurred correct also in Polish conditions as the long-term (1972 –2001) mean duration of the yearly longest dry periods in central Poland lasted for 21 – 22 days (Kasperska-Wołowicz et al. 2003). Three weekly irrigations of area Aw = 100 m^2 with intensity $dmin$ = 10, 20 or 30 mm/week during drought require the RWH tank volumes of $Smax$ = 3.0, 6.0 or 9.0 m^3, respectively. Method B gave the lowest tank sizes; it works better when the whole year (not seasonal only) water demand is taken into account, giving the same result as obtained by method A (Table 3).

The greater the size of the RWH tank, the higher its reliability (Fig. 5 and 7) and better its hydraulic performance measured by the *HPPI* index (Fig. 6 and 7).

Figure 8 shows an example given to elucidate the principle of method E. One has to find the minimum volume required to keep the tank non-empty during the given time period, here (Fig. 8), the growing season 2013. Considering 10 analyzed years (2006–2015), the average optimal tank sizes have occurred highly differentiated (Table 1), 1.9±0.6 m^3 (coefficient of variation Cv = 100%), 9.0±1.9 m^3 (Cv = 67%), and 27.3±2.7 m^3 (Cv = 31%) for irrigation water demands 1.0, 2.0 and 3.0 m^3/week, respectively. It is indicative of inaccuracy of the term "average year" related to one chosen year with annual average precipitation close to the multi-year mean value, as used in some manuals (e.g., MDPA 2017). The optimal size of RWH tank for whole year's use 140 dm^3/d (~ 1.0 m^3/week)

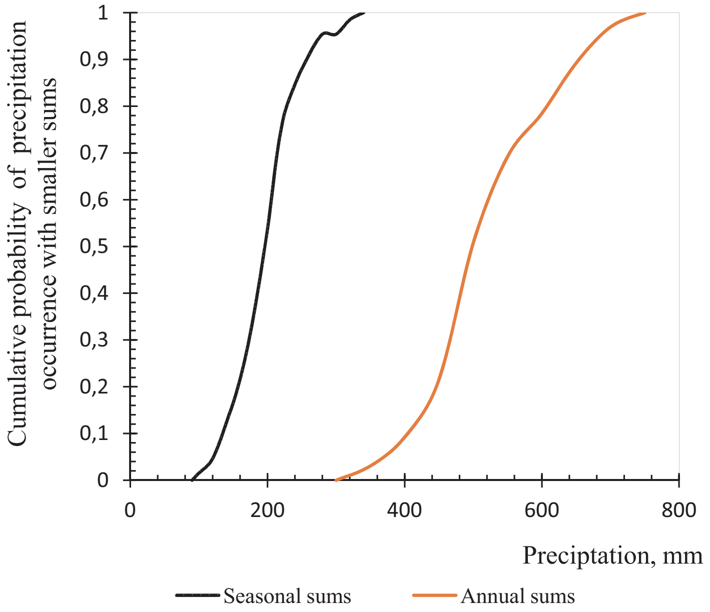

Fig. 4. Cumulative probability of occurrence of seasonal (in non-growing seasons: October–March) and annual precipitation for Szamotuly-Baborowko station

Table 1. Results of water balance and cost calculations for tanks of different capacity at three levels of irrigation intensity. Note: the minimum annual expected costs and payback periods are depicted in **bold**, u.p. means "unprofitable"

Item	Water needs mm/week	Tank size, m^3					
		3.0	6.0	9.0	12.0	15.0	18.0
Tap water make-up, M, m^3/a	10 20 30	0.8 9.5 28.2	0.1 5.1 22.6	0.0 2.8 18.7	0.0 1.8 15.7	0.0 0.9 13.8	0.0 0.2 9.7
Cost of make-up tap water, EUR/a	10 20 30	1.2 14.3 42.3	0.2 7.7 33.9	0.0 4.2 28.1	0.0 2.7 23.6	0.0 1.4 20.5	0.0 0.0 14.0
Spilled rainwater, Z, m^3/a	10 20 30	41.4 30.1 23.2	40.7 25.7 17.6	40.6 23.4 13.7	40.6 22.4 10.6	40.6 21.5 7.5	40.6 20.8 4.7
Fee for spilled water disposal, EUR/a	10 20 30	41.4 30.1 23.2	40.7 25.7 17.6	40.6 23.4 13.7	40.6 22.4 10.6	40.6 21.5 7.5	40.6 20.8 4.7
Operation & maintenance costs, $C_{O\&M}$, EUR/a	10 20 30	42.6 44.4 65.5	40.9 33.4 51.5	40.6 27.6 41.8	40.6 25.1 34.2	40.6 22.9 28.0	40.6 20.8 18.7
Investment cost, I_1 EUR	new tank + pump	1400	2300	3200	4100	5000	5900
Investment cost, I_2 EUR	pump only	250	250	250	250	250	250
Investment cost, I_3 EUR	tank repair + pump	500	550	600	650	700	750
Annual expected cost, C_{e1} EUR/a	10 20 30	**84.6** **86.4** **107.5**	109.9 102.4 120.5	136.6 123.6 137.8	163.6 148.1 157.2	190.6 172.9 178.2	217.6 197.8 195.7
Annual expected cost, C_{e2} EUR/a	10 20 30	50.1 51.9 73.0	48.4 40.9 59.0	**48.1** 35.1 49.3	**48.1** 32.6 41.7	**48.1** 30.4 35.7	**48.1** **28.3** **26.2**
Annual expected cost, C_{e3} EUR/a	10 20 30	57.6 59.4 80.5	**57.4** 49.9 68.0	58.6 45.6 59.8	60.1 44.6 53.7	61.6 43.9 49.0	63.1 **43.3** **41.2**
Payback period, T_{PB1} years	10 20 30	u.p. > 20 > 20	u.p. u.p. > 20	u.p. u.p. u.p.	u.p. u.p. u.p.	u.p. u.p. u.p.	u.p. u.p. u.p.
Payback period, T_{PB2} years	10 20 30	16 6 4	**14** 5 3	**14** **4** 3	**14** **4** 3	**14** **4** 3	**14** **4** **2**
Payback period, T_{PB3} years	10 20 30	> 20 14 10	> 20 12 **8**	> 20 12 **8**	> 20 **10** **8**	> 20 13 **8**	> 20 14 **8**

is 10.5±1.1 m^3, therefore it is much greater than for seasonal irrigation purposes due to lower precipitation in the non-growing season.

Annual expected costs are prohibitively high in the case of investment in a new RWH tank due to their relatively high price, but reasonable and relatively low for the converted SH tanks, even if they need a repair (Table 1 and 2).

Payback periods for new RWH tanks are very long (> 20 years), but they are relatively short (2 and 4 years for irrigation water needs 30 and 20 mm/week, respectively) in the case of converted SH tanks in a good technical state. The former would be even longer due to demolishing an old concrete tank and debris disposal. However, for low irrigation water needs (10 mm/week) even the smallest investment in a RWH tank (I = 250 EUR) is financially doubtful. The repair of a SH tank in a poor technical state can be costly, but still profitable.

Table 3 summarizes the results of the RWH tank sizing. The large variation in design sizes results from differentiated capital costs, rainwater demand and various adopted criteria, both the hydraulic (A, C-E) and economic criteria (B, F and G), related to new tanks, have pointed out relatively small tank sizes, whereas the conversion of SH tanks of typical sizes, even those that needed repair, is more or less profitable. The final choice depends on the decision-maker preferences.

Table 2. Results of water balance and cost calculations for tanks of different size at constant daily rainwater demand equal to 140 dm³/d. Note: the minimum annual expected costs and payback periods are depicted in **bold**, u.p. means “unprofitable”

Item	Unit	Tank size, m³					
		3.0	6.0	9.0	12.0	15.0	18.0
Tap water make-up, *M*	m³/a	8.1	3.6	2.0	1.2	0.8	0.5
Cost of make-up tap water	EUR/a	12.2	5.4	3.0	1.8	1.2	0.8
Spilled rainwater, *Z*	m³/a	11.4	6.7	4.5	4.0	3.9	3.9
Fee for spilled water disposal	EUR/a	11.4	6.7	4.5	4.0	3.9	3.9
Operation & maintenance costs, $C_{O\&M}$	EUR/a	23.6	12.1	7.5	5.8	5.1	4.7
Investment cost, EUR, I_1	EUR	1400	2300	3200	4100	5000	5900
Investment cost, EUR, I_2	EUR	250	250	250	250	250	250
Investment cost, EUR, I_3	EUR	500	550	600	650	700	750
Annual expected cost, C_{e1}	EUR/a	**65.6**	81.1	103.5	128.8	155.1	181.7
Annual expected cost, C_{e2}	EUR/a	31.1	19.6	15.0	13.3	12.6	**12.2**
Annual expected cost, C_{e3}	EUR/a	38.6	28.6	25.5	**25.3**	26.1	27.2
Payback period, T_{PB1}	years	> 20	> 20	**>** 20	u.p.	u.p.	u.p.
Payback period, T_{PB2}	years	2.6	2.3	**2.2**	**2.2**	**2.2**	**2.2**
Payback period, T_{PB3}	years	5.6	**5.5**	5.9	6.3	6.9	7.4

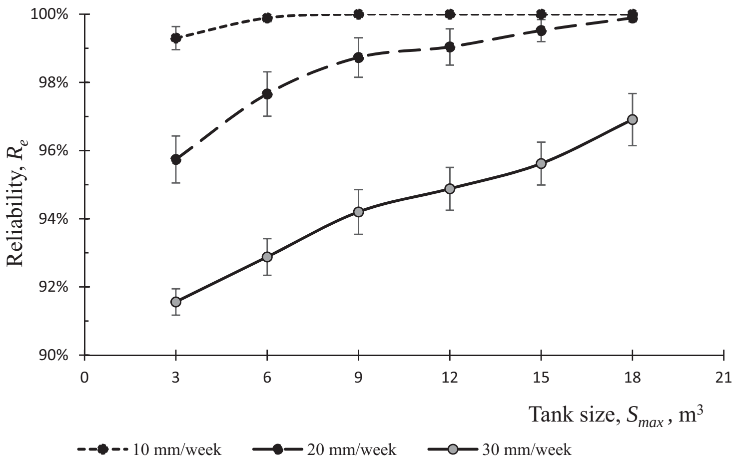

Fig. 5. Reliability R_e vs. RWH tank size S_{max} for $A_r = A_w = 100$ m², in ten irrigation seasons (April 1st – September 30th 2005–2016)

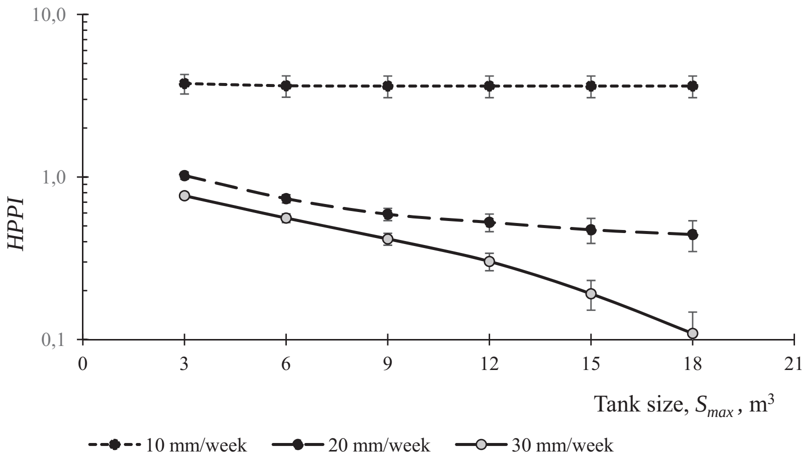

Fig. 6. Hydraulic performance penalty index *HPPI* vs. RWH tank size S_{max} for $A_r = A_w = 100$ m², in ten irrigation seasons (April 1st – September 30th 2005–2016)

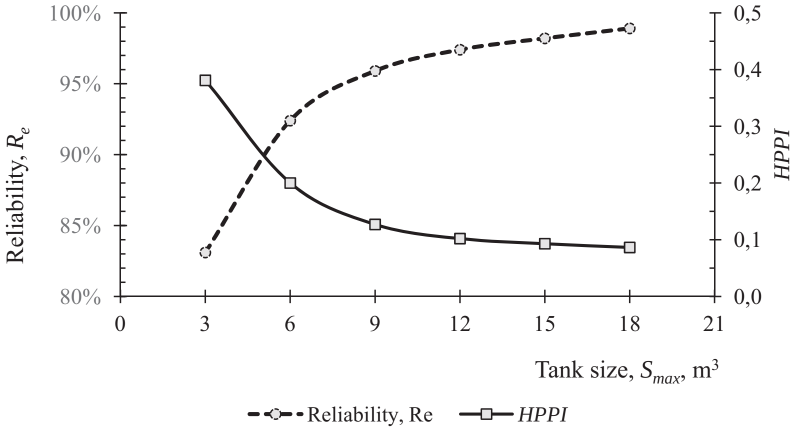

Fig. 7. Reliability and hydraulic performance penalty index *HPPI* vs. RWH tank size S_{max} for $A_r = A_w = 100$ m^2, constant daily rainwater demand (140 dm^3/d) in ten years (January 1st – December 31st 2005–2016)

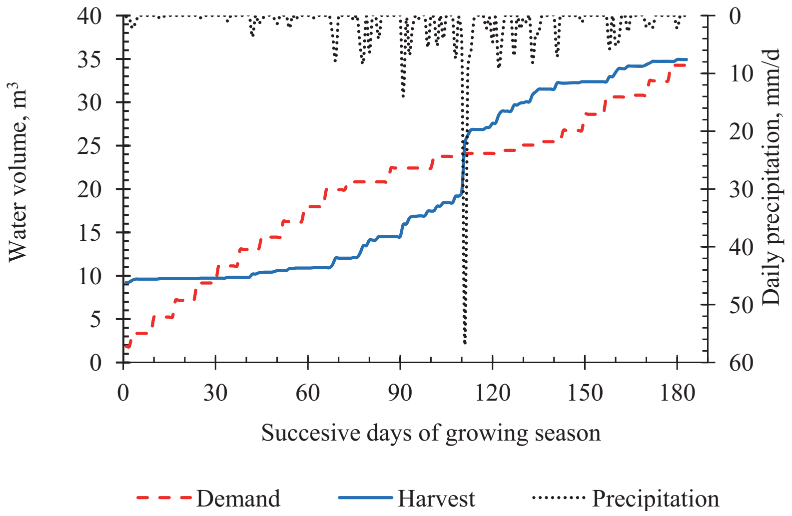

Fig. 8. Cumulative water demand and harvested volumes vs. daily precipitation in a chosen irrigation season (April 1st – September 30th 2013) for $A_r = A_w = 100$ m^2, $S_0 = 9.0$ m^3, $S_{max} = 10.0$ m^3, $d_{min} = 20$ mm/week

Table 3. Comparison of RWH tank sizes determined by different methods (A-G)

Minimum water needs m^3/week	Tank size [m^3] calculated and optimized by the method:										
	A	B	C*	D**	E	F acc. to			G acc. to		
						C_{e1}	C_{e2}	C_{e3}	T_{PB1}	T_{PB2}	T_{PB3}
1.0 (ir)	3.0	0.6±0.1	< 3	6	1.9±0.6	3	9–18	6	< 3	6–18	3
2.0 (ir)	6.0	1.8±0.1	3	12	9.0±1.9	3	18	18	< 3	9–18	12
3.0 (ir)	9.0	3.3±0.1	16	18	27.3±2.7	3	18	>18	< 3	18	6–18
0.98	3.0	3.0	8	12	10.5±1,1	3	18	12	< 3	9–18	6

Note: (ir) denotes irrigation, * for reliability R_e = 95%, ** for *HPPI* = 0.1, the minimum or the value which is not more than 10% greater than that for the tank volume greater by 3.0 m^3.

One more added value of RWH tank is its fire protection role. Typically, underground fire suppression tanks of volume 2.3–190.0 m^3, made of fiberglass, are offered on the market. Therefore, the lowest range of volumes is approximately overlapping with volumes of the abandoned SH tanks. Fire sprinkler systems for domestic and residential occupancies typically use 60–200 dm^3/min (Seaber and Marshall 2013), thus a half of medium volume, e.g., 10 m^3, is sufficient for fire suppression lasting 25–83 min.

When constructing or retrofitting larger systems it is reasonable to apply a real option (multi-stage expansion strategy), which takes into account uncertainty due to climate change, price fluctuations etc. (Kim et al. 2014).

Conclusions

Conversion of individual SH tanks to RWH tanks is relatively simple and affordable – their typical sizes (5–8 m^3) lie in the range close to the optimal ones under conditions of west-central Poland and their payback periods were assessed as 2 nd 4 years for the irrigation water depth equal to 30 and 20 mm/week, respectively.

To make rainwater harvesting economically feasible, a fee for the water disposed to the collective drainage network is indispensable.

Rainwater harvested from roof area of 100 m^2 in west-central Poland can save 18–25% of total annual water use when irrigating a small garden of the same area, or even over 40% when 140 dm^3 of rainwater is used daily by a typical homestead over the whole year.

The maximum potential increase in storage volume due to the conversion of individual SH tanks to RWH tanks could reach all over Poland 215–350 dam^3 per year. That way of storage increase should be included in the Retention Development Program.

Acknowledgments

Authors are grateful to the Polish Institute of Meteorology and Water Management for allowing access to precipitation data.

References

Aquanet (2020). Tariffs for collective water supply. https://www.aquanet.pl/taryfa-dla-zbiorowego-zaopatrzenia-w-wode-od-6062018-do-5062021,747 (10.07.2020).

Brown, J.W. & Leung, P. (1991). Optimal cistern size for hydroponic greenhouse operation. Proc. of the 5th Int. Conf. on Rain Water Cistern Sizing. NTOU, Keelung, Taiwan, pp. 292–304.

Burchart-Koroll, D. & Zawartka, P. (2019). Environmental life cycle assessment of septic tanks in urban wastewater system – a case study for Poland. *Archives of Environmental Protection.* 45, 4, pp. 68–77, DOI: 10.24425/aep.2019.130243.

Council Directive 91/271/EEC (1991), concerning urban waste water treatment. 21 May 1991 (EU OJ L 135 of 30.5.1991).

DIN 1989-1, (2002). Regenwassernutzungsanlagen Teil 1: Planung, Ausfhrung, Betrieb und Wartung.

Dixon, A., Butler, D. & Fewkes, A. (1999). Computer simulation of domestic water reuse system: investigating greywater and rainwater in combination. *Water Science & Technology* 38, 4, pp. 25–32.

EC (2019). Evaluation of the Council Directive 91/271/EEC of 21 May 1991, concerning urban waste-water treatment. Brussels, 13.12.2019 SWD(2019) 700

EC (2020) Reasoned opinion of 14.05.2020 INF/20/859 https://ec.europa.eu/atwork/applying-eu-law/infringements-proceedings/infringement_decisions/ (6. 08. 2020)

EN 16941-1. (2018). On-site non-potable water systems. Systems for the use of rainwater.

Fewkes, A. (2006). The technology, design and utility of rainwater catchment systems: a literature review. In: D. Butler and F.A. Memon, (Eds.) *Water Demand Management.* London, IWA Publishing.

Imteaz, M.A., Shanableh, A., Rahman, A. & Ahsan, A. (2011). Optimisation of RWH tank design from large roofs: A case study in Melbourne, Australia. *Resources, Conservation and Recycling.* 55 (11), pp. 1022–1029.

Kasperska-Wołowicz, W., Łabędzki, L. & Bąk, B. (2003). Dry periods in the Bydgoszcz region. *Water-Environment-Rural Areas*. 3(9), pp. 39–56.

Karim, R.M., Rimi, R.A. & Billah, M.D. (2014). Analysis of storage volume and reliability of the rainwater harvesting tanks in the coastal area of Bangladesh. *Desalination and Water Treatment*, June, DOI:10.1080/19443994.2014.923201.

Kowalczyk, S. & *Ujda,* K. (1987). Comparative measurement of atmospheric precipitation. *Mat. Bad. Ser. Meteorologia*, *IMGW*, 14, Warszawa. (in Polish)

Kim, B., Anderson, K., Lee, S. & Kim, H. (2014). A real option perspective to value the multi-stage construction of rainwater harvesting systems reusing septic tank. *Water Resources Management*. 28, 8, pp. 2279–2291, DOI: 10.1007/s11269-014-0613-3.

Local Data Bank (2020). Statistics Poland. Environmental Protection. Liquid waste. https://bdl.stat.gov.pl/BDL/dane/podgrup/temat (10. 07. 2020).

Mortazavi-Naeini, M., Kuczera, G., Kiem, A.S., Cui, L., Henley, B., Berghout, B. & Turner, E. (2014). Robust optimisation of urban drought security for an uncertain climate. In: Palutikof, J.P. et al (Eds.) *Applied Studies in Climate Adaptation*, DOI: 10.1002/9781118845028.

MPCA, (2017). Minnesota Stormwater Manual. https://stormwater.pca.state.mn.us/index.php/Cost-benefit_considerations_for_stormwater_and_rainwater_harvest_and_use/reuse (10.04.2020).

Pacheco, G.C. & Campos, M.A. (2017). Economic feasibility of rainwater harvesting systems: a systematic literature review. *J. of Water Supply: Research and Technology – AQUA*, 13, 66, pp. 1–4.

Palla, A., Gnecco, I., Lanza, L. G. & La Barbera, P. (2012). Performance analysis of domestic rainwater harvesting systems under various European climate zones. *Resources, Conservation & Recycling.* 62, pp.71–80, DOI: 10.1016/j.resconrec.2012.02.006.

Piasecki, A. (2019). Water and sewage management issues in rural Poland. *Water, 11,* 3, 625; DOI: 10.3390/w11030625.

PNAS (2013). Polish National Strategy for Adaptation to Climate Change with the perspective by 2030, Ministry of the Environment Republic of Poland, Warsaw, https://klimada.mos.gov.pl/wp-ontent/uploads/2014/12/ENG_SPA2020_final.pdf (10.04.2020).

Rozp. RM (2017). Regulation of the Council of Ministers of December 22, 2017 regarding unit rates of fees for water services. (in Polish: rozporządzenie Rady Ministrów z dnia 22 grudnia 2017 r. w sprawie jednostkowych stawek opłat za usługi wodne). *Dziennik Ustaw* pos. 2502. (in Polish)

Semaan, M., Day, S.D., Garvin, M., Ramakrishnan, N. & Pearce, A. (2020). Optimal sizing of rainwater harvesting systems for domestic water usages: A systematic literature review. *Resources, Conservation & Recycling: X,* 6, 100033, DOI: 10.1016/j.rcrx.2020.100033.

Seaber, S. & Marshall, J. (2013). *Guidelines for the supply of water to automatic fire sprinkler systems*, Water UK.

Statistics Poland (2019). Environment. GUS, Warszawa. (in Polish)

Szwed, M. (2019). Variability of precipitation in Poland under climate change. *Theoretical & Applied Climatol*ogy, 135, pp. 1003–1015, DOI: 10.1007/s00704-018-2408-6.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. & Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies* (2nd revised ed.). Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Duebendorf, Switzerland.

Umapathi, S., Chong, M. N. & Sharma, A. K. (2012). Assessment of diurnal water demand patterns to determine supply reliability of plumbed RWH tanks in South East Queensland. 7th Int. Conf. on Water Sensitive Urban Design. Melbourne, Australia.

Umweltbundesamt GmbH (2017). 9th Technical assessment on Urban Wastewater Treatment Directive implementation. With support of Office International de l'Eau, Vito & IzVRS, https://ec.europa.eu/environment/water/water-urbanwaste/implementation/pdf/.

Vorne, V., Silvenius, F., Česonienė, L., Eymontt, A., Pachel, K., Räsänen, K., Sinkko, T., Urtāne, L., Vieraankivi, M.-L. & Virtanen, Y. (2017). *A survey of available wastewater treatment technologies for sparsely populated areas: User's manual* – Version 1.0. LUKE, Helsinki.

WFD CIS (2014). EU policy document on Natural Water Retention Measures Working Group Programme of Measures (WG PoM) TR 082.

WSDH (2012). *Holding Tank Sewage System*. Recommended Standards and Guidance for Performance, Application, Design, and Operation & Maintenance. Washington State Dept. of Health.

Przekształcanie zbiorników bezodpływowych w zbiorniki na wodę opadową w Polsce

Streszczenie. Celem pracy była ocena możliwości przekształcenia zbiorników bezodpływowych do ścieków (ZB) w zbiorniki do gromadzenia wody deszczowej (WD) w Polsce. Taka konwersja może częściowo rozwiązać problem niedoboru wody do nawadniania roślin w małych ogrodach przydomowych i zmniejszyć zużycie wody wodociągowej.

Zastosowano 7 metod określania wielkości zbiornika WD na przykładzie małego systemu zbierającego opady z dachu o powierzchni równej powierzchni nawadnianego ogrodu (100 m^2) oraz do alimentacji domowej instalacji wodociągowej w ilości 140 dm^3/d. Wprowadzono nowe kryterium optymalizacji pojemności zbiornika, bazujące na efektywności hydraulicznej. Optymalizację ekonomiczną wykonano dla nowych zbiorników WD oraz dla zaadaptowanych z wyłączonych z eksploatacji ZB. Wyniki uzyskane dla systemu zlokalizowanego w środkowo-zachodniej Polsce i symulacji wykazały, że pojemność projektowa zbiorników WD różniła się znacznie między metodami wymiarowania. Konwersja ZB na zbiorniki WD jest opłacalna, szczególnie w przypadku nawadniania roślin w okresach niedoboru wody, a konwersja do instalacji wspomagającej wodociąg sieciowy jest jeszcze bardziej opłacalna, gdyż okres jej zwrotu wynosi od 2 do 6 lat. Przekształcanie indywidualnych ZB w zbiorniki WD i POŚ jest stosunkowo proste i tanie. Potencjalny wzrost pojemności retencyjnej w wyniku konwersji indywidualnych ZB na zbiorniki WD może osiągnąć w całej Polsce 215–350 tys. m^3 rocznie, a indywidualnie może zaoszczędzić do 40% całkowitego rocznego zużycia wody.