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Assessment of the Variability of Rainwater Quality and the Functioning of Retention Reservoirs in the Urban Area

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1. Introduction

The rapid development of urban agglomerations in many countries results in significant environmental changes and the deformation of local hydrological cycles. Compacting technical infrastructure and increasing the share of sealed surfaces in urban space means reducing infiltration of rainwater to the ground, limiting retention, rapid outflow and, as a consequence, a decrease in the quantity and deterioration in the quality of water resources (Congying 2012, Geiger & Dreiseitl 2001). Changes in land use, combined with more and more extreme weather events (global climate change), lead in some urbanised catchments to the accumulation of rainwater, which in turn should be safely collected and directed to the right receivers. The increase in non-uniformity of flows with simultaneous unsatisfactory throughput of sewerage networks results in hydraulic overloads and local flooding (Hlavínek & Zelenakova 2015, Huang et al. 2015). In this context, the unreasonable development of technical infrastructure becomes an indirect threat to… the technical infrastructure (e.g. housing, transport, and communications).

Pollutants in rainwater and snowmelt runoff are another significant problem. Some authors emphasize that rainwater can be a major threat to the environment – including direct water receivers (Barałkiewicz et al. 2014, Yuan et al. 2017, Zubala 2018). The degree of water pollution depends, among other things, on the way of land use and topography, type, method of maintenance and operation of sealed surfaces, traffic intensity, degree of air and drained surface pollution, precipitation characteristics and the quantity and quality of sediments in sewerage systems. Performing an accurate forecast of runoff quality is very difficult due to the presence of so many different factors. There is no typical composition of rainwater. However, due to the possibility of significant negative impacts on the environment (pollution) and technical infrastructure (hydraulic overload), it is necessary to develop and implement effective rainwater management systems in urban agglomerations (precautionary and preventive principles).

A good solution may be storage (delaying outflow) and pre-treating rainwater at the place where it appears. The application of uncomplicated devices which are based on the use and intensification of natural self-purification processes, as well as reducing the intensity of outflow to the receiver, is justified in economic and environmental terms. Permeable surfaces, wells and infiltration basins, grit chambers and settlement tanks can be given as examples (Barszcz 2015, Fuchs et al. 2013, Geiger & Dreiseitl 2001, Langeveld et al. 2012). In the case of the availability of larger areas, detention ponds and wetlands with sedimentation, flotation, sorption and biological decay of pollution are used (Herrmann 2012, Liu et al. 2014, Moore & Hunt 2012). Their operation consists in slowing down the flow of liquid, which allows the sedimentation of solid particles (the use of gravity forces). In infiltration systems, rainwater additionally infiltrates into the ground where purification also takes place. The participation of microorganisms and aquatic vegetation is very important in self-purification processes.

It is necessary to conduct permanent qualitative monitoring in the case of terminal devices from which rainwater goes directly to natural receivers. Data obtained in various conditions and places in the world will allow not only a thorough understanding of the phenomena occurring in these facilities but also enable the preparation of reliable review papers and define project recommendations increasing the reliability of specific technologies. These issues are particularly important in developing countries, where the problem of rainwater management has been often postponed.

The aim of this work is to assess the variability of the quality and to compare the degree of pollution of rainwater collected and pre-treated in two reservoirs in the agglomeration of Lublin, with the simultaneous estimation of possible environmental threats. The functioning of the analysed reservoirs was assessed in the context of a different construction and ways of land use. Changes in weather conditions prevailing during the study period were taken into account. Reservoir 1 (R1) has a permeable bottom and collects runoffs from a section of national road. Reservoir 2 (R2) is a sealed concrete structure in which rainwater is collected from a housing estate. Large variation in some factors may determine the variability of retained water quality. The quality of rainwater and percentage differences in the content of pollutants in various aspects (e.g. between objects, within an object, in different periods) were determined as a part of three-year study. An attempt was also made to assess the basic technical and operating parameters of both systems after several years of functioning and the legitimacy of using specific solutions.

The collected data should be a valuable material for scientists in the field of environmental protection and water management, as well as for designers and users of rainwater management systems.

2. Materials and methods

2.1. Study area

Lublin is located in south-eastern Poland (the Lublin Upland macro-region), where it serves as the central hub of the agglomeration. It is the fastest growing and largest city on the eastern side of the Vistula River, with an area of 147 km^2 and about 340 thousand inhabitants. Important international transport routes intersect here and there are many industrial plants of various industries (including automotive, machinery, construction, and food industry). Residential, commercial and service buildings, recreational areas and road infrastructure have been growing particularly quickly in recent years in Lublin (SO 2017).

The studied rainwater reservoirs were built in 2006 (R1) and 2005 (R2). They are situated in the bottoms of dry loess valleys. The first one connects with the Bystrzyca valley – the main river of the Lublin City (R1), and the second with the Czechówka River valley – the Bystrzyca tributary (R2). This part of the city belongs to the highly sculptured mesoregion of the Nałęczów Plateau with soils that are very susceptible to water erosion (surface washes, numerous valleys and ravines, escarpments). Height differences reach several dozen metres (Harasimiuk et al. 2008). In both valleys, there is an increasing urbanization process leading to partial devastation of the area.

Observations have shown that trees and shrubs occur in small quantities on drained surfaces, which relates specifically to the national road. This results from the functions and progressive changes in land use (including the expansion of a new housing estate). Synanthropic plant communities, adapted to living in a strongly transformed environment, are predominant here. In the catchment basin of reservoir 2 there are also small home gardens with decorative vegetation.

R1 is located in the immediate vicinity of the drained section of national road no. 19 (Fig. 1). The road cuts across the dry valley. The size of the drainage area is approximately 10 ha (slight changes in recent years due to modernization), with the impermeable part constituting nearly 80% of the total (roadways, pavements). The rest falls on narrow, sodded stripes. In the vicinity of R1 there are also local roads, crop fields and wasteland. The housing estate from which water flows to R2 is mostly located on the southern slope. Its area is about 14 ha – a large part is occupied by roofs, tight roads and parking spaces (Fig. 1). The biologically active surface constitutes about 50% of the analysed area. The size of the tight surfaces of both catchments is similar. There are construction projects being carried out within the housing estate. Water erosion and the outflow of loess material to the rainwater drainage system may be facilitated by the lack of proper protection of exposed soil and by the steep slope. In the vicinity of R2 there is also a crop field, allotments and wasteland.

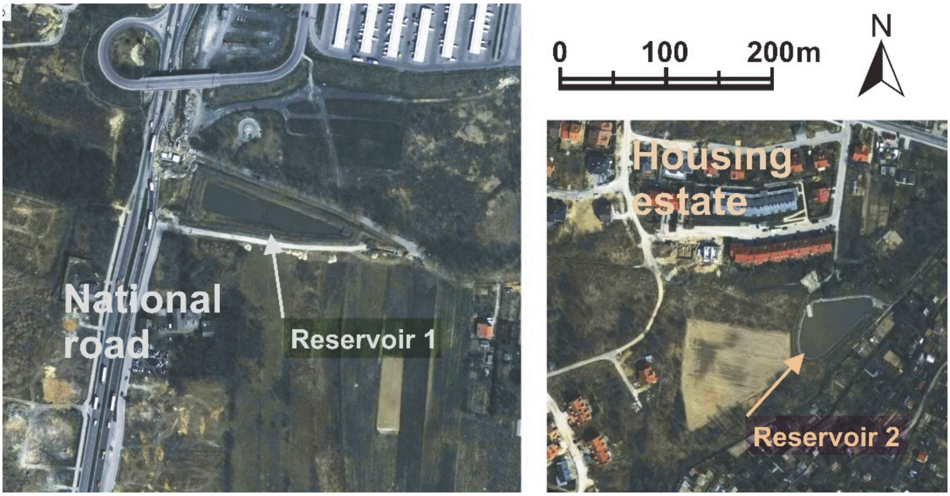


Fig. 1. Location of the analysed rainwater reservoirs with fragments of drained areas (www.geoportal.gov.pl)

2.2. Climatic conditions

Table 1 presents the most important data on climatic conditions in the study area. In the analysed period, the annual sums of precipitation were varied and they ranged from 533 to 792 mm. The years 2013 and 2014 were more abundant in precipitation than the average year in the period 1971-2010. The differences were 53 and 194 mm respectively. The last year of study was exceptionally dry – compared to the average for many years, the sum of precipitation was by 65 mm lower. Exceptionally high temperatures of atmospheric air were also recorded that year. The average annual temperature was 9.4°C and was higher than the average for many years by 1.7°C. In 2013-2014, higher sums of atmospheric precipitation were noted down in the first half of the year (I-VI) and they exceeded 60% of the annual rainfall. In the last year of study, total rainfall in both half-years was almost identical. Analysis of data from many years (1971-2010) showed the prevalence of precipitation in the second half-year (VII-XII). During the research period, exceptionally high monthly precipitation occurred in May – the maximum sum of 240 mm was registered in 2014 (30.3% of annual rainfall). The minimum monthly rainfall did not exceed 10 mm (X 2013 and VIII 2015).

Relatively low sums of rainfall were also recorded in February (Table 1). According to Kaszewski (2008), the average annual number of days with snowfall in Lublin is 48. However, the average annual number of days with snow cover varies from about 60 to 80 days in the Lublin region. In the analysed period, average annual air temperatures were higher than in the average year over many years (Table 1). This may be a symptom of general climate warming trends. A distinct increase in temperature is visible from year to year. In 2013 and 2014, the coldest month was January. In 2015, a slightly lower temperature was recorded in February; however, throughout the year the average monthly temperature did not fall below 0°C. The highest average air temperatures occurred in the summer months (mainly VII), which is in line with the values for many years.

Table 1. Monthly and annual sums of atmospheric precipitation and average air temperatures during the study period (2013-2015) against the background of average climatic conditions over many years (1971-2010) (CSO 2014, 2015, 2016)

	Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
Precipitation (mm)	2013	62	34	55	46	106	113	88	17	41	7	63	19	651
	2014	67	15	43	54	240	77	76	90	29	24	23	54	792
	2015	51	14	45	28	114	18	43	7	90	47	48	28	533
	1971-2010	32	30	37	39	63	69	82	69	63	43	38	33	598
Temperature (°C)	2013	-4.1	-1.3	-2.5	7.9	14.8	17.8	18.5	18.6	11.5	9.8	5.1	1.3	8.1
	2014	-3.0	1.2	6.0	9.7	13.4	15.6	20.3	17.8	14.2	9.2	4.2	-0.2	9.0
	2015	0.6	0.4	4.7	7.9	12.4	16.7	19.3	21.8	14.6	6.8	4.7	3.3	9.4
	1971-2010	-3.1	-2.0	2.0	8.0	13.5	16.1	18.5	17.7	13.0	7.8	3.0	-1.6	7.7

2.3. Rainwater reservoirs

Drained surfaces are located largely on slopes, which facilitates the gravitational transport of rainwater to reservoirs (use of existing height differences). Their task is to receive, collect and pre-treat liquids. The following self-purification processes may take place in the reservoirs: filtration (only R1), sedimentation, mixing, dilution, sorption, oxygenation, biological reactions (R1 and R2). Such phenomena are common in the aquatic environment.

R1 is a recessed earth structure with an area of 0.34 hectares and a capacity of 9,860 m^3 (significant oversizing). From the north it is closed by a high, grasscovered dyke made of native soil. The reservoir has a permeable bottom overgrown with submerged aquatic vegetation. The design of the structure takes into account the maximum flow rate – 1.5 $m^3 \cdot s^{-1}$ and an instantaneous volume of discharged water – 1,800 m^3 (flow through underground sewers). If necessary, rainwater can be partially transferred from the reservoir using a concrete drain monk. The receiver is a reinforced channel, which is also a girdling ditch (Fig. 2).

R2 is also a recessed earth structure. The object was designed for a maximum flow rate of 1.24 $m^3 \cdot s^{-1}$ and an instantaneous runoff volume of 1,608 m^3 (inflow through underground channels and shallow open gutter) (Fig. 2). The area of R2 is 0.23 ha, and the active volume is 2,013 m^3.

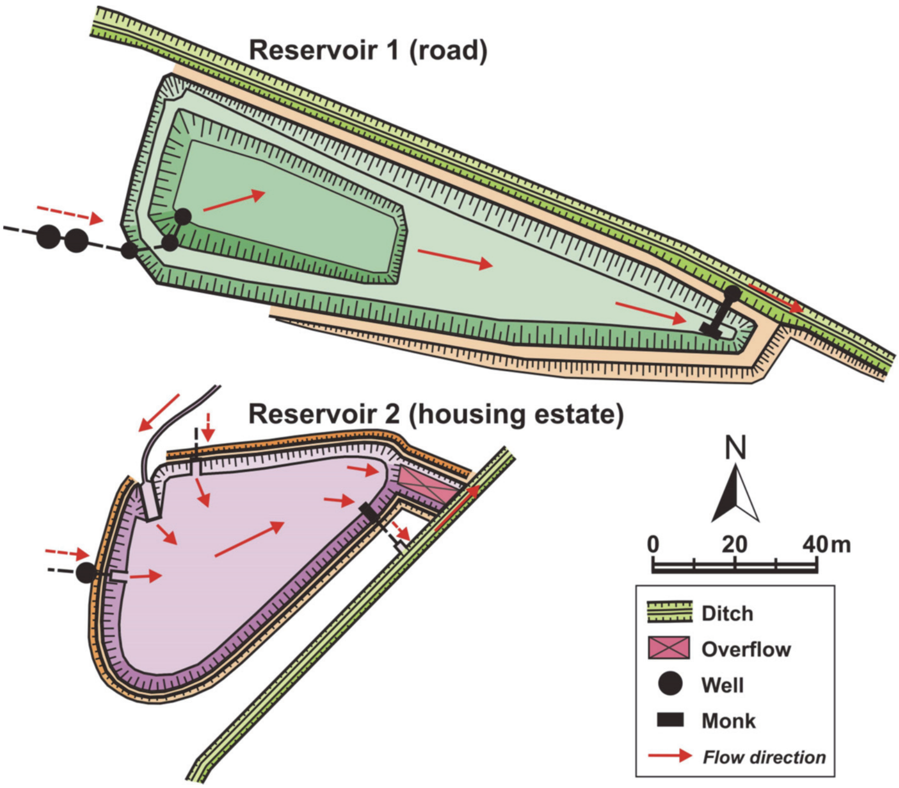
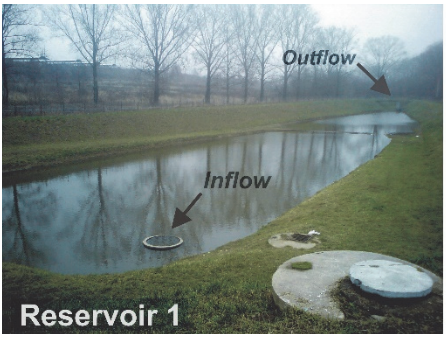


Fig. 2. Schemes of the analysed rainwater reservoirs

R2 bowl was sealed with concrete (geo-grid filled with concrete) for fear concerning the stability of the loess ground and due to the presence of neighbouring residential buildings (Fig. 3). This completely eliminates the infiltration process. The reservoir has the function of a settling tank; however, a layer of sediments has formed on the bottom that enabled the development of aquatic vegetation. Water is discharged into the periodic watercourse after temporary detention. Drainage is possible thanks to the use of a steel riser (monk) and safety overflow.



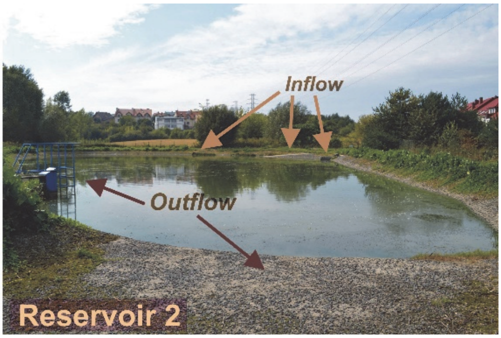


Fig. 3. General view of rainwater reservoirs

Underground rainwater sewers supplying water to the studied reservoirs are equipped with street inlets, inspection chambers and pre-treatment facilities (grit chamber, settling tank, separators). Both reservoirs are protected by a steel fence. The use of objects entails, among other things, regular mowing of vegetation, filling cavities in dikes, maintaining the tightness of weirs, cleaning of separators, grit chambers and settling tank, control and repair of ditch enhancements. During the study period bottom sediments were not removed from reservoirs.

2.4. Sampling and analysis

The analysis of rainwater quality variables was conducted seasonally for three years (12 measurement terms, 24 samples). The same number of samples was taken each year. The periods between rainwater runoffs were consistently selected. Samples were collected on the same day in both reservoirs (time difference: half an hour). The intake was carried out 1 meter from the shore in the middle of the length of the reservoirs (the side with inflow), using a sampling bailer. Both reservoirs contained water on all measurement dates. The research was carried out in the Laboratory of Water and Wastewater at the University of Life Sciences in Lublin. The following indexes were determined in the water samples: temperature, electrolytic conductivity (by conductometry), pH (by potentiometry), total suspended solids (by drying and weighing), dissolved oxygen (O_2), 5-day Biochemical Oxygen Demand – BOD_5 (by dilution), Chemical Oxygen Demand – COD (by dichromate method), ammonium ions (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-), phosphates (PO_4^-), sulphates (SO_4^-), iron (Fe^+), potassium

(K^+), and chlorides (Cl^-) (photometric determination). Chemical components (e.g. nutrients) were determined by means of photometers: MPM 2010 (WTW) and LF 300 (Slandi). Physical properties were determined using a multi-parameter Thermo Orion meter. In assessing the quality of rainwater, the extreme and average values of the analysed indicators were determined for each checkpoint. The statistical variability of obtained results was determined based on the values of standard deviation and coefficient of variation. The non-parametric Mann-Whitney test was used to compare the variable quality of rainwater in both reservoirs (significance levels $\alpha = 0.05$ and $\alpha = 0.10$). The percentage differences in the content of contaminants in the analysed objects were also determined.

3. Results and discussion

The quality of rainwater collected in reservoirs 1 and 2 is characterised by high variability (Table 2). The variability shown in this article is compatible with results obtained in other rainwater management facilities in the region (Zubala 2013, 2018). Significant differences were found in the case of conductivity, NH_4^+, NO_2^-, PO_4^-, SO_4^-, Fe^+, K^+, Cl^- (different distributions of values of the analysed features) (Table 2). Higher values of conductivity, NH_4^+, SO_4^- and Cl^- were observed in reservoir 1 (R1), receiving rainwater from a part of the national road. The percentage differences in mean values of given variables were recorded between reservoirs: 63.8, 24.9, 58.0 and 65.0%. The reservoir 2 (R2), which is supplied with rainwater from the housing estate, was more contaminated with NO_2^-, PO_4^-, Fe^+ and K^+. When comparing both reservoirs, the percentage differences of average concentrations were particularly high in the case of the last three indicators – they amounted to 282.8, 167.7 and 235.7% respectively. Despite the fact that on most measurement dates, COD and NO_3^- values were higher in rainwater R1, there were no incompatibilities in the distribution of these characteristics in statistical analysis. The high variability coefficients in R1 were characteristic of suspended solids, NH_4^+ and K^+ (above 100%), while in R2 of suspended solids and NO_3^- (NO_3^- as much as 205.6%). In both reservoirs, the smallest variation related to the pH value (about 10%).

Table 2. Characteristic values of rainwater quality indicators in reservoirs 1 and 2 (R) in 2013-2015 (statistical significance of differences in quality variables was determined for α = 0.05 and α = 0.10 – Mann-Whitney test)

Variables	R	Min.	Max.	Average	Median	Standard deviation	Variation coefficient	Important difference
Temperature (°C)	1	1.0	26.0	12.8	14.0	9.2	72.5	–
	2	1.0	25.5	13.3	14.5	9.2	69.2	
Conductivity ($\mu S\cdot cm^{-1}$)	1	265	3,985	1,122	841	1,051.3	93.7	+
	2	60	1,373	406	276	373.2	92.0	(α=0.05)
pH	1	7.6	10.1	8.8	8.8	0.9	10.6	–
	2	7.9	9.9	8.6	8.4	0.7	7.8	
Suspension ($mg\cdot dm^{-3}$)	1	4	114	29	18	35.4	120.8	–
	2	5	121	38	24	38.5	100.4	
O_2 ($mg\cdot dm^{-3}$)	1	2.4	13.7	8.9	9.5	4.2	47.2	–
	2	5.4	12,9	9.7	10.8	2.9	29.7	
BOD_5 ($mg\cdot dm^{-3}$)	1	1.4	13.1	7.1	6.9	3.9	55.2	–
	2	3.2	10.5	6.5	5.4	2.6	41.0	
COD_{Cr} ($mg\cdot dm^{-3}$)	1	13	173	61	47	44.6	73.7	–
	2	7	181	60	42	54.8	91.9	
NH_4^+ ($mg\cdot dm^{-3}$)	1	0.052	2.281	0.558	0.202	0.7	130.2	+
	2	0.258	0.876	0.419	0.387	0.2	38.4	(α=0.05)
NO_3^- ($mg\cdot dm^{-3}$)	1	0.102	1.659	0.594	0.323	0.6	98.3	–
	2	0.088	2.181	0.290	0.115	0.6	205.6	
NO_2^- ($mg\cdot dm^{-3}$)	1	0.056	0.625	0.254	0.161	0.2	72.1	+
	2	0.059	0.691	0.374	0.372	0.2	51.6	(α=0.10)
PO_4^- ($mg\cdot dm^{-3}$)	1	0.010	0.100	0.051	0.048	0.03	53.7	+
	2	0.018	0.561	0.197	0.170	0.1	71.7	(α=0.05)
SO_4^- ($mg\cdot dm^{-3}$)	1	3	36	13	9	9.8	78.5	+
	2	2	9	5	6	2.4	45.3	(α=0.05)
Fe^+ ($mg\cdot dm^{-3}$)	1	0.24	1.33	0.54	0.46	0.3	57.1	+
	2	0.14	3.77	1.44	1.05	1.1	74.6	(α=0.05)
K^+ ($mg\cdot dm^{-3}$)	1	1.3	21.9	4.6	2.4	5.7	124.2	+
	2	1.4	48.2	15.4	12.0	12.2	78.8	(α=0.05)
Cl^- ($mg\cdot dm^{-3}$)	1	20.4	98.0	65.4	77.7	25.7	39.3	+
	2	6.4	78.6	22.8	14.1	21.7	95.0	(α=0.05)

Rainwater quality forecast is difficult to perform due to a variety of factors and phenomena within the drained catchment and in sewerage systems. Their dynamics and variability may determine the variability of the content of pollutants in rainwater reservoirs. A relationship between the method of use, as well as the degree of pollution of urban space and the quality of outflow rainwater has been demonstrated in some papers (Goonetilleke et al. 2005, Liu et al. 2013). Existing weather conditions or the construction and operation of a rainwater retention system may also be of great importance (Gong et al. 2016, Zubala 2018).

Rainwater collected in the studied reservoirs was characterised by poor quality on most measurement dates. The indicator decreasing water quality in R1 was conductivity. The highest values were achieved in the winter months with a maximum of 3,985 $\mu S \cdot cm^{-1}$ in 2015 (Table 2). In the winter of 2013, the conductivity value was 2,321 $\mu S \cdot cm^{-1}$, and in 2014 – 825 $\mu S \cdot cm^{-1}$. Although the conductivity in R1 decreased in the subsequent months of a given year, in spring 2013 and 2015 its level exceeded 1,000 $\mu S \cdot cm^{-1}$. The average conductivity value in rainwater of R2 was only 406 $\mu S \cdot cm^{-1}$ and only on one measurement date it exceeded 1,000 $\mu S \cdot cm^{-1}$ (1,373 $\mu S \cdot cm^{-1}$ in March 2015). Such high conductivity is associated with meltwater runoff, carrying high loads of pollutants. According to Ociepa et al. (2015) such phenomena are linked primarily with the long time of snow retention and gradual accumulation of subsequent portions of pollutants, including measures to protect roads against glazed frost. During these periods a significant increase in the content of chlorides was also observed, which is especially true for R1. The maximum level of Cl^- in R1 was 98.0 $mg \cdot dm^{-3}$, and in R2 78.6 $mg \cdot dm^{-3}$. Sodium chloride (NaCl) is widely used in Poland to reduce slipperiness after snowfall. The necessity to ensure transport safety means that it is likely to use much more salt within the national road than in a housing estate. Consequently, in R1, the average concentration of Cl^- was 65.4 $mg \cdot dm^{-3}$, and in R2 only 22.8 $mg \cdot dm^{-3}$. The average annual content of Cl^- did not decrease in R1 below 75 $mg \cdot dm^{-3}$ in 2013 and 2015. Placing large doses of salt on drained surfaces can have a negative impact on the environment (Corsi et al. 2015, Rivett et al. 2016). The increase of salt concentration in the soil prevents the roots of plants from taking up water, causing them to dry up. It can also be destructive to soil decomposers and disturb the functioning of freshwater ecosystems (rainwater receivers).

A worrisome high pH was found in the analysed rainwater. The average value in R1 was 8.8 and 8.6 in R2. The maximum values were about 10 in both reservoirs (Table 2). Alkalization of rainwater is probably due to the presence of alkaline dust and salinity within the basins. The processes occurring in the sediments of the sewerage system and the studied reservoirs may also be of great importance. The sediments have not been removed from the reservoirs from the moment they were put into operation. A thick layer accumulated on the bottoms, which is moved during intense water flows. This is evidenced by a significant increase in turbidity during and after violent storm and meltwater runoff. The highest concentration of suspended solids in both reservoirs were found in the first year of the study (2013). Maximum concentration were 114 (R1) and 121 $mg \cdot dm^{-3}$ (R2). The amount of suspended solids in water R2 was higher than that in R1 in most measurement date. For R2 catchment a major problem was inadequate securing of construction sites and unpaved roads located on a steep slope (especially in 2013). As a result of water erosion, larger quantities of loess dust penetrated into the sewage system and the reservoir, which may be confirmed by the yellow colour of rainwater in some periods. Increased suspension content was usually observed in winter and spring (thaws, pollutants wash-off after winter). The lowest mean annual concentrations of the analysed component were recorded in 2014. In R1 and R2 its values were 10.5 and 15.5 $mg \cdot dm^{-3}$, respectively. The year 2014 was characterised by heavy rainfall. Total rainfall significantly exceeded the average for many years (Table 1). Relatively large runoff occurred in November 2013 (63 mm). It is likely that suspended solids were washed off from drained surfaces and contaminants were partially diluted in retention reservoirs (inflow of clear liquids) during those periods (Lee et al. 2002, Liu et al. 2013). The reduction of average values in 2014 also referred to other variables: conductivity, NH_4^+, NO_2^-, SO_4^-, Fe^+, K^+ and Cl^-. On respective dates, the conductivity was only 60 $\mu S \cdot cm^{-1}$ (R2), the concentration of the suspension did not exceed 5 $mg \cdot dm^{-3}$, and NO_2^- 0.06 $mg \cdot dm^{-3}$ (R1 and R2). Fe^+, K^+ and Cl^- decreased to: 0.14 (R2), 1.3 (R1) and 7.0 $mg \cdot dm^{-3}$ (R2).

Some authors have shown strong affinity between suspended solids in rainwater and nutrients (Song et al. 2019, Vaze & Chiew 2004). According to them, nitrogen and phosphorus (N, P) are most often transported with finer and slower settled fractions. It was found that the concentration of N and P increased with an increase in the concentration of suspended solids and in water turbidity. In the reservoirs analysed in this work, similar connections were observed only on a few measurement dates. In the case of R1, they mainly concerned NH_4^+ and NO_2^-, while in R2 – NO_2^- and PO_4^-. R1 was more loaded with NH_4^+ than R2 (on average 24.9%), while higher concentrations of NO_2^- and PO_4^- were found in R2 (on average 47.0 and 282.8%). In R1 rainwater the average concentrations of most nutrients were higher in winter than in summer. Relatively high percentage differences were found for NH_4^+ (70.0%) and PO_4^- (40.7%). The average NO_2^- values remained at a similar level in both seasons. The only increase in pollution in the summer season was observed in 2015 and it concerned mineral forms of nitrogen. Different phenomena occurred in R2. The average concentrations of NH_4^+, NO_2^- and PO_4^- in summer time were higher than in winter. Differences reached even several hundred percent depending on the year and component. Downward trends in summer were found only in the case of NO_3^- (on average

86.0%). It is difficult to determine the reason for the increase in the concentration of nutrients in water of R2 in summer. According to some authors, the outflow of N and P from the catchment during the growing season should be smaller than in winter (Arheimer et al. 1996, Birgand et al. 2007). This is related to the ability to capture nutrients by autotrophs that form biogeochemical barriers in the basin. However, the share of biologically active areas is strongly reduced within the territory where the studied reservoirs are located. The drainage area is also small, and the take-over and transport of rainwater into the sewage system are very fast. The natural and economic systems analysed in the literature are more extensive and are characterised by a large variety of spatial development forms. In the studied rainwater reservoirs, the risk of eutrophication was mainly due to high NO_2^- concentrations. The maximum values were between 0.6 and 0.7 $mg \cdot dm^{-3}$. Relatively high average annual concentrations fell in 2013 (R1 and R2) and 2015 (R2) – exceeded 0.44 $mg \cdot dm^{-3}$. There was also a disturbing increase in NH_4^+ (maximum 2.28 $mg \cdot dm^{-3}$ in R1) and PO_4^- (maximum 0.56 $mg \cdot dm^{-3}$ in R2) on certain measurement dates. During those periods, the outflow of rainwater into ditches should be blocked (use the reserve capacity).

The average O_2 content in the analysed rainwater was satisfactory and was 8.9 (R1) and 9.7 $mg \cdot dm^{-3}$ (R2). In all years, high saturation of O_2 in R1 was maintained in winter and spring (7.8-13.7 $mg \cdot dm^{-3}$), and in R2 in winter, spring and summer (7.0-12.9 $mg \cdot dm^{-3}$). The worst condition was observed in autumn. The average O_2 concentrations were then 4.9 (R1) and 5.7 $mg \cdot dm^{-3}$ (R2). High levels of dissolved oxygen were found after many days of intense rainfall, taking place immediately before the liquid samples were taken. During the study, a gradual decrease in the average annual oxygen content in the examined rainwater was observed. Biochemical processes occurring in the growing layer of bottom sediments, as well as the elevated temperature of the retained liquid might be the cause (Dojlido 1995). During the tests, the average annual air temperature gradually increased (Table 1). This may result in negative phenomena within rainwater reservoirs in the future – for example, the intensification of anaerobic processes and the emission of gaseous pollutants into the atmospheric air. The presence of odours was noticeable in the vicinity of R2 in the warm months of the last year of research. If the weather trends persist, this nuisance may be significant if more rainwater reservoirs are built. This particularly applies to the territory of housing estates and travel service areas. Water was characterised by the greatest turbidity in this period. The phenomena characteristic of phytoplankton bloom have been observed (Fig. 4).

Fig. 4. Increase in turbidity of rainwater in the analysed reservoirs during the warm season

Despite the relatively high average concentration of dissolved O_2, BOD_5 and COD reached alarming levels in the analysed rainwater. The average values of these indicators were 7.1 and 61 $mg \cdot dm^{-3}$ in R1, and 6.5 and 60 $mg \cdot dm^{-3}$ in R2 (Table 2). In both reservoirs, a particularly high demand for O_2 occurred in spring and summer. In the warm season in R1, the average BOD_5 and COD values were higher by 34.7 and 184.1% compared to the cool season. In R2, these differences were even higher and amounted to 38.6 and 231.3%, respectively. The obtained results may indicate a high load of organic pollutants (Dojlido 1995). Artificial oxygenation using mechanical, chemical (Imhoff & Imhoff 2006) or biological methods could be a way to eliminate oxygen problems. Floating treatment wetlands are becoming increasingly popular among biological methods. At the same time, they demonstrate high efficiency in the elimination of other contaminants, e.g. N and P (Chang et al. 2012, Wang & Sample 2014). It is also important to successively remove bottom sediments, which unfortunately was not implemented in the case of the analysed objects. Sludge quality tests should be undertaken in order to determine the environmental hazard on their part and possible participation in secondary pollution of retained rainwater.

With the exception of the slight odour nuisance in the case of R2 (last year), during the study period no negative environmental impact of the analysed reservoirs was observed. Although R1 is an earth reservoir, made of local loess material, no over-standard deformations and displacements of individual elements as well as subsidence of adjacent land were found. No cracking and traces of caving were noticed in the body of the embankments. This may indicate a lack of intensive infiltration of rainwater into the ground and dikes. Despite the large inclination of slopes, erosive damage is also not observed. Dense vegetation effectively protects their surface (Fig. 3 and 4). R2 is a tight, concrete reservoir in which no infiltration takes place. This means that the risk of the described phenomena is very low. During the research period, no influence of R2 waters on the lowest located objects of the housing estate was found. Natural gravel and stones were sunk in the fresh concrete during construction, which improves the aesthetics of the reservoir. Shrub and tree planting also positively influenced its landscape values (Fig. 3 and 4). R2 should in principle perform the function of a classic open settling tank due to its sealing. However, after more than ten years of operation, its bottom completely captured the aquatic vegetation by succession (Fig. 5). The deposition of a thick layer of sediments with a loess suspension was a favourable factor. Currently, the reservoir resembles an artificial marsh ecosystem. Such solutions are considered as factors enhancing biodiversity in a poor, urbanised landscape (Herrmann 2012, Kazemi et al. 2011, Le Viol et al. 2009, Zubala 2018).

Fig. 5. Intensive plant development on the sealed bottom of reservoir

The basic principles of maintaining and operation of the analysed reservoirs are respected. As a result, no problems were observed in the operation of individual devices and the entire systems (including correct tightness of hydraulic closures and patency of inflow sewers). Supervision over the flow of rainwater is carried out properly. The need to remove bottom sediments from reservoirs should be considered. Their presence may hinder the precise control of the quality of collected and pre-treated rainwater (re-suspension and secondary pollution). Improving the quality of rainwater in the future would allow them to be used for economic and environmental purposes in the immediate vicinity of reservoirs (e.g. surface cleaning, green areas irrigation). According to many authors, this is an element of integrated and rational management of water resources (Mitchell et al. 2007, Pennino et al. 2016, Tao et al. 2014, Yu et al. 2013).

4. Summary

Retention and treatment of rainwater in the place of their formation contributes to reducing the load on sewage systems. However, it should be remembered that the very construction and operation of rainwater reservoirs can also be associated with environmental impact and irreversible changes in ecosystems (terrain relief, soils, surface and underground waters, landscape). The intensity of these processes depends on many factors, which are sometimes difficult to determine before putting the object into use. For this reason, it is necessary to constantly monitor and evaluate the functioning of existing infiltration reservoirs, settlers and constructed wetlands. This article shows a high variability of rainwater quality collected in the Lublin agglomeration reservoirs. Among the analysed indicators, suspended solids, NH_4^+, NO_3^- and K^+ were characterized by a significant differentiation of values (above 100%). The lowest variation was found for pH (approximately 10%). Rainwater from the section of the national road had higher conductivity, NH_4^+, SO_4^- and Cl^- than the water from the housing estate. In the second case, there was a greater load of NO_2^-, PO_4^-, Fe^+ and K^+. The analysed rainwater was characterized by poor quality on many measurement dates. Conductivity was a major threat, mainly related to meltwater runoff from the national road (maximum 3985 $\mu S \cdot cm^{-1}$). Alarmingly high was the pH (maximum 10.1) and the concentration of suspended solids (maximum 121 $mg \cdot dm^{-3}$). In some cases, an increase in the content of nutrients was observed – especially NO_2^-, NH_4^+ and PO_4^-. During these periods, the outflow of rainwater from reservoirs should take place under special control due to the risk of eutrophication. The relationships between the quality of retained waters and weather conditions or seasons of the year was also noted. For example, in the year with the highest precipitation sums, the average concentration of suspended solids, NH_4^+, NO_2^-, SO_4^-, Fe^+, K^+ and Cl^- decreased in the reservoirs. The conductivity was similar. This phenomenon results from rinsing the basin and diluting contaminants in reservoirs. In cold seasons, there was always an increase in the concentration of dissolved oxygen, as well as the values of conductivity and Cl^-. In spring and summer, the demand for oxygen increased (BOD_5 and COD) and oxygen deficits occurred. In the following years, a decrease in the average annual oxygen content in rainwater was observed. This may be related to biochemical processes occurring in the thick layer of bottom sediments and increasing average annual air temperatures and heating of retained waters. There is a periodic odour nuisance in the case of a reservoir in a housing estate. The use of open rainwater reservoirs near human settlements may be problematic if these trends persist and the sediments are not systematically removed.

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Abstract

Three-year observations made it possible to assess the degree of pollution and variability in quality of rainwater collected in two reservoirs in the Lublin agglomeration (south-eastern Poland). The studied objects are characterised by different construction, size, hydraulics and type of drained surface. In particular, a large variation in water quality indicators was observed for suspended solids, NH_4^+, NO_3^- and K^+. Higher conductivity, NH_4^+, SO_4^- and Cl^- was found in the reservoir receiving rainwater from the national road, compared to the water from the housing estate. In the second reservoir, a higher load of NO_2^-, PO_4^-, Fe^+ and K^+ was observed. Among the analysed variables, the most disturbing values were recorded for conductivity, pH, suspended solids, oxygen indicators, NO_2^-, NH_4^+ and PO_4^-. The liquid flowing into the reservoirs during snowmelt was characterised by high pollution. In the year with the highest sum of atmospheric precipitation, there was a reduction in medium concentrations of many quality variables (flushing effect, dilution of pollutants). An increase in oxygen demand and oxygen deficits were observed in warm seasons. An emission of inconvenient odors in the vicinity of the reservoir in the housing estate was also observed. These phenomena may be intensified in the case of improper use of the system (e.g. when bottom sediments are not removed) and further increase of air temperatures. Under such conditions, the possibility of using open rainwater reservoirs near human settlements becomes questionable.

Keywords:
rainwater, water pollution, retention reservoir, environmental protection

Ocena zmienności jakości wód opadowych i funkcjonowania zbiorników retencyjnych na terenie zurbanizowanym

Streszczenie

Na podstawie trzyletnich obserwacji dokonano oceny stopnia zanieczyszczenia oraz zmienności jakości wód deszczowych gromadzonych w dwóch zbiornikach na terenie aglomeracji Lublina (Polska południowo-wschodnia). Badane obiekty charakteryzują się różną budową, wielkością, hydrauliką i rodzajem powierzchni odwadnianej. Szczególnie duże zróżnicowanie wskaźników jakości wody dotyczy zawiesiny, NH_4^+, NO_3^- i K^+. W zbiorniku na wody deszczowe z drogi krajowej stwierdzano wyższą przewodność, NH_4^+, SO_4^- i Cl^- niż w wodach z osiedla mieszkaniowego. W drugim zbiorniku obserwowano większe obciążenie NO_2^-, PO_4^-, Fe^+ i K^+. Wśród analizowanych zmiennych najbardziej niepokojące wartości osiągała przewodność, pH, zawiesina, wskaźniki tlenowe, NO_2^-, NH_4^+ i PO_4^-. Wysokim zanieczyszczeniem charakteryzowała się ciecz dopływająca do zbiorników w trakcie roztopów. W roku z najwyższą sumą opadów atmosferycznych nastąpiło zmniejszenie średnich koncentracji wielu zmiennych jakości (przemycie zlewni, rozcieńczenie zanieczyszczeń). W ciepłych porach roku obserwowano wzrost zapotrzebowania na tlen i pojawianie się deficytów tlenowych. Stwierdzono też emisję odorów w sąsiedztwie zbiornika w osiedlu mieszkaniowym. Przy niewłaściwej eksploatacji systemu (m.in. brak usuwania osadów dennych) i dalszym wzroście temperatur powietrza zjawiska te mogą nasilać się. W takich warunkach możliwość stosowania otwartych zbiorników wód deszczowych w pobliżu siedzib ludzkich staje się wątpliwa.

Słowa kluczowe:
woda deszczowa, zanieczyszczenia wód, zbiornik retencyjny, ochrona środowiska