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Research paper

Hybrid system for the purification of street stormwater runoff supplying urban recreation reservoirs

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ABSTRACT

A high percentage of urban areas are covered by impermeable surfaces which reduce infiltration and landscape retention of stormwater. Moreover, the pollution flushed from these areas, particularly after intensive rainfall, is often drained directly to rivers and reservoirs which, in many cases, also serve a recreational function in cities. Stormwater runoff contributes to degradation of aquatic ecosystems and their intensified eutrophication which, in growing seasons, results in toxic cyanobacterial blooms. The hybrid system (combined of engineering and biological measures) tested in this research was constructed in 2013 in Łódź city (POLNAD) to retain and purify stormwater runoff from a street that runed directly to a cascade of recreational reservoirs. The hybrid system consists of an underground separators system that is combined with a sequential sedimentation-biofiltration system (SSBS). In the first two years of the system's operation, it effectively reduced pollution transported to the urban river system by reducing 86.0% of total suspended solids, 71.5% of total nitrogen (TN), 66.7% of total phosphorous (TP), and from 40.7% to 78.3% of PO_4^{3-} and NO_2^{-}, respectively. In addition, the system was able to reduce the hydraulic stress induced by extreme discharges and mitigated discharges for precipitation amounts less than 9 mm. The hybrid system is an example of a nature-based solution measure reducing the negative effects of nutrients transfer, eutrophication and flooding in urbanized areas, as part of the blue-green infrastructure.

1. Introduction

Small urban catchments are strongly affected by intensive land use characterised by high development rates and low permeabilities (Qin et al., 2010). In consequence, stormwater runoff and related pollutants loads are usually primary threats and key factors driving ecological processes in small urban streams and reservoirs (Deletic, 1998; Lee and Bang, 2000; Acharya et al., 2010; Li et al., 2015). Small and shallow impoundments with high catchment to surface area ratios, low mean discharges of the supplying streams, and long water retention times are highly susceptible to accumulations of contaminants. They are also predisposed to intensive secondary pollution – internal loadings, due to microbial loops, because of effective accumulation of sediments and relatively high water temperatures (Sherr and Sherr, 1988; Burford et al., 2007; Acharya et al., 2010). The synergy between the primary, external pollution, and enhanced internal nutrient cycling, makes water quality problems even more oppressive (Acharya et al., 2010). Increasing concentrations of nitrogen and phosphorous (reservoir eutrophication) result in the appearance of toxic cyanobacterial blooms and prevent city inhabitants from using the reservoirs for recreational purposes (Jurczak et al., 2012).

Small urban river pollution, especially that associated with the first flush effect, is often associated with stormwater outflows (Deletic, 1998; Lee and Bang, 2000; Acharya et al., 2010; Luo et al., 2012; Li et al., 2015). Therefore, as demonstrated by Janke et al. (2014), catchment management and land use seriously impact pollution loads exported to aquatic ecosystems. There are several well known concepts for urban catchment management measures such as Low Impact Development (LID), a Best Management Practice in Stormwater (BMP), and Sustainable Urban Drainage Systems (SUDS), which are related to the technical management of urban catchments, stormwater and drainage systems. Recently, also ecological theories such as ecohydrology (Zalewski, 2000; Zalewski, 2011), blue-green infrastructure (Gill et al., 2007; EC, 2013) and Nature Based Solutions (Scott et al., 2016;

Abbreviations: Cond, conductivity; IMGW, Institute of Meteorology and Water Management, National Research Institute; NC, not calculated; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^-, nitrate; PO_4^{3-}, phosphates; SSBS, sequential sedimentation-biofiltration system; Temp, temperature; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids

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Nesshöver et al., 2017) have contributed to practical urban stormwater management. Ecohydrology builds on the possibility of regulating water dynamics and maintaining its quality through the integration of hydrotechnical measures with hydrological and ecological knowledge (Zalewski, 2014). According to this concept, water and pollutants in urban landscapes may be best retained by a combination of conventional methods, supported by blue-green infrastructure and BMPs such as pervious surfaces, swales, green-roofs, plant buffer strips or stormwater infiltration facilities, into one synergistic system (Zalewski and Wagner, 2005; Wagner and Breil, 2013; Liu et al., 2017).

To the extent that sustainable catchment management, especially in highly disturbed urban catchments, is difficult to achieve, there are several measures used to control pollution at stormwater outflows. Conventional measures would usually include oil and grit separators or settlement ponds (Wilson et al., 2009; Tran and Kang, 2013). The efficiencies of pollutant removal for those measures, especially for total suspended solids (TSS), are very high and can reach 98%, depending on flow rate. Biological treatment methods such as constructed wetlands have also proven to be effective in urban catchments (Read et al., 2008; Hatt et al., 2009; Mitsch et al., 2015). Mitsch et al. (2015) demonstrated that six different stormwater treatment wetlands effectively reduced total phosphorus by 60% to 80%. Read et al. (2008) showed the advantage of filtration systems constructed from plants above the soil systems to reduce heavy metals and nutrients from stormwater. Recently, advancing urbanisation and development, together with new challenges resulting from accelerating changes in climate, have stimulated the development of new, integrated approaches based on combined engineering and biological measures (Hatt et al., 2009; Newman et al., 2013). Hatt et al. (2009) tested a biofitration basin treating runoff from a multi-storey car park with an area of 4500 m^2 combined with two sedimentation tanks and biofilters with different filter media. They showed considerable reductions in TSS (89,1%), TN (18,5%), NH_4^+ (96,0%) and heavy metals (80,0–96,1%). In another field study, an oil separating channel with a load bearing box with floating mat and granular stone filter was tested as a macro-pervious pavement system for retaining and reducing oil and suspended solids (Newman et al., 2013). A bioretention system used for treating stormwater runoff was well documented and revised by Davis et al. (2009). The integration of engineering and bioretention systems seems to be a promising direction for improving urban water quality.

This study was aimed at assessing the efficiency of a hybrid system (combined of engineering and biological measures) that consists of an underground separator system combined with a sequential sedimentation-biofiltration system (SSBS), constructed as an innovative BMP solution, to purify and temporarily retain stormwater supplying the cascade of recreational urban reservoirs on a small urban stream. In addition, first and second flush effects were described.

2. Materials and methods

2.1. Sampling site

The city of Łódź is located on the watershed divide of the Vistula and Oder Rivers in Poland, covering an area of 293 km^2. Eighteen small rivers flow through the city. Currently, 47% of the city's area is covered by impervious surfaces, 10% is forested and 0.5% is covered by surface water (Ratajczyk et al., 2017). The city experiences typical stormwater challenges, including high stormwater runoff, extreme river flows, and low surface water quality resulting from primary pollution and enhanced eutrophication. The study was conducted on an upstream stretch of the Bzura River in the north-eastern part of the city of Łódź. Although the river is to a great extent supplied with stormwater, mainly stormwater outflows, it is also the major source of water flowing to a cascade of small man-made reservoirs, which are intensively used for recreation by the city's inhabitants.

The study was conducted on the stretch of the river directly upstream of the reservoir cascade. A hybrid system was constructed on the river bank with the intention of increasing the efficiency of the purification of the stormwater runoff supplying the river and reservoirs, mitigating high river stormwater discharges, and controlling the first flush effect, which were all to be achieved at low costs of investments and maintenance. The hybrid system collected stormwater from an impermeable, sealed area of approx. 2.8 ha (street and parking slots), which prior to its construction drained directly to the river. This situation caused a gradual deterioration of the water quality in the reservoirs, which are located 250 m below the stormwater outflow and suffered regular summer blooms of toxic cyanobacteria (Jurczak et al., 2012).

The hybrid system was developed and constructed in 2013 within the "Ecohydrologic rehabilitation of recreational reservoirs 'Arturówek' (Łódź) as a model approach to rehabilitation of urban reservoirs" LIFE project (LIFE08 ENV/PL/000517) (LIFE08 ENV/PL/000517, 2008). It was located below Wycieczkowa St., on the right side of the river (coordinates: 51°49′16.3"N and 19°29′12.2"E) (Fig. 1). The hybrid system consists of a functionally integrated engineered system (underground separators) and biological/ecohydrological system (sequential sedimentation-biofiltration system − SSBS). Stormwater is collected from the street by four stormwater drainage inlet pits (Fig. 1a,b), which direct the stormwater into a rotary sedimentation separation tank (Fig. 1a,c) with a volume of 8 m^3, and a lamella oil separator (Fig. 1a) with a nominal flow of 40 l/s. From the separators, the water flows through the outflow (Fig. 1a,d) directly to the SSBS.

The SSBS has an area of 425 m^2 (17 × 25 m), maximum depth of 0.8 m, retention capacity of 0.4 m, and retention volume ranging from 170 m^3 to 220 m^3. The flexible retention capacity has been achieved due to the construction of a weir. The weir is constructed of 3 boards, each with dimensions of 20 × 50 cm. The middle board possesses a slot in its lower part, 40 cm below the upper edge of the weir (Photo in Fig. 1a). It has a length ½ that of the weir and a height 1/10 that of the weir. This construction increases the retention capacity of the SSBS by up to 50 m^3, with only a small effect on the river discharge below the outflow when compared to traditional systems. During a rain event, the retained water is continuously released downstream by the slot. At the same time, the system is still intensively supplied with runoff from the upper catchment and possesses retention capacity up to the upper edge of the uppermost board. Altogether, the construction of the weir allows up to 220 m^3 of rainwater to be retained during a single event, and it does not require manual operation after the reservoir is filled up. Without a slot, the water would overflow the weir after the retained water reaches 170 m^3, and after the rain, the excess water would have to be released manually to assure capacity for the next event. The Intellectual Property Rights for the construction of the system have been protected by patent application No. P.416886.

The SSBS has a sequential construction. The upper part of the SSBS consists of two sedimentation chambers, which constitute approximately 1/3 of the SSBS area (Fig. 1a,e,f). The sedimentation zone is divided into two parts, with a mechanical barrier (Fig. 1a) made of a metal grid. The barrier is fixed to the reinforced ground and covered with a biodegradable geofibre material (400 g/m^2) to increase the effectiveness of the sedimentation process (Fig. 1a). The sedimentation zone is followed by the biofiltration zone of the system (Fig. 1a,g), with a small floating island (6 m^2) located in the outflow part of the SSBS planted with the following aquatic vegetation: *Typha angustifolia* (L.), *Carex riparia* William Curtis, *Glyceria maxima* (Hartm.) Holmb., *Iris*, and *Ceratophyllum demersum* (L.). The biofiltration zone (Fig. 1a,g) constitutes approximately 2/3 of the SSBS. It is separated from the sedimentation part by a dolomite gabion covered with an RG17 coconut mesh mat (900 $g/m^{2} \times 2$) made of coconut fibres 5 cm thick. The sampling sites (stations 1–8) of the hybrid system from the Bzura river are shown in Fig. 1.

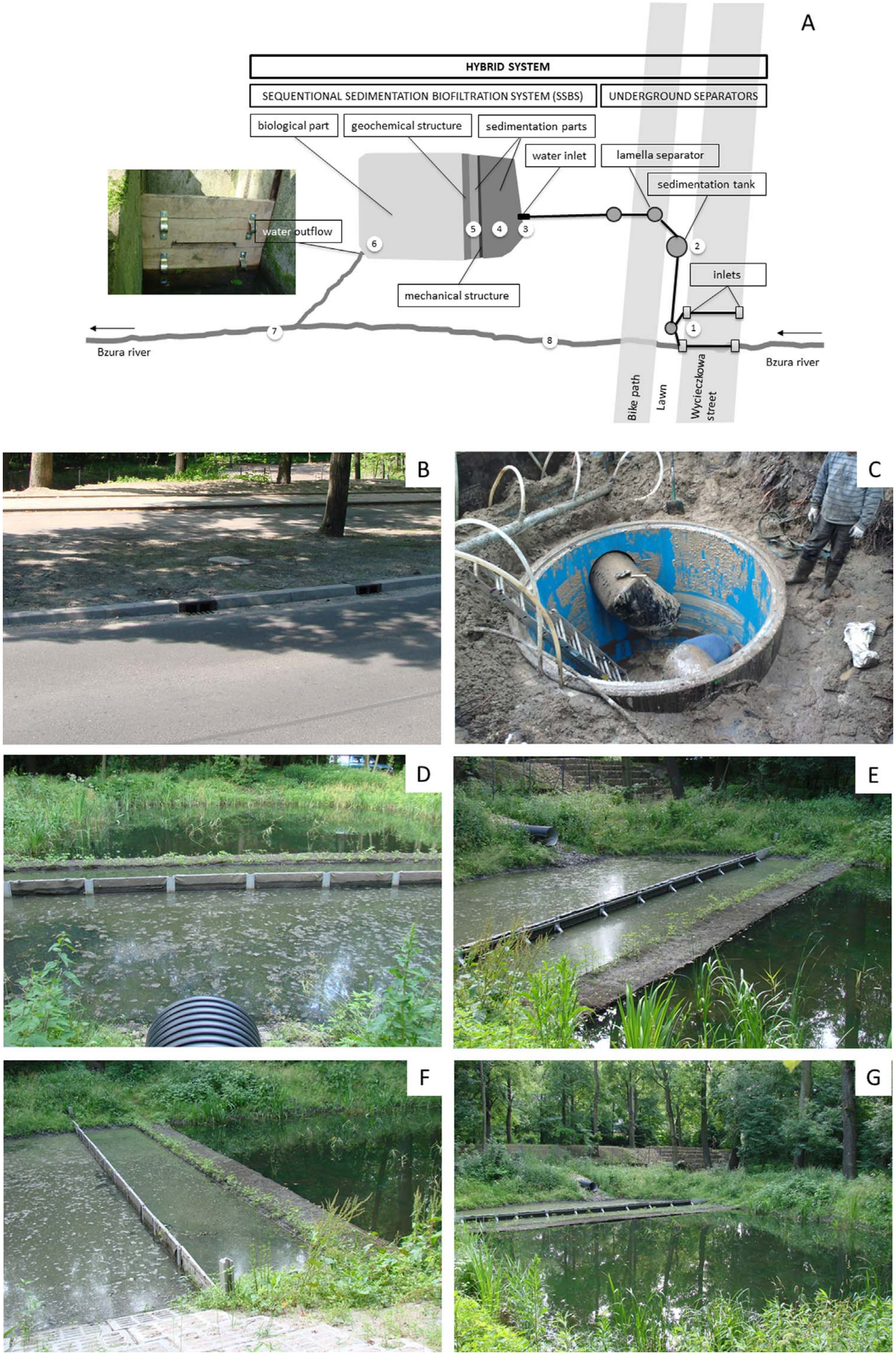

Fig. 1. Arturówek demonstration site in the city of Łódź (Poland). Location of the hybrid system (A) constructed for retention and purification of stormwater transported from Wycieczkowa street to the Bzura River, with its purification stages sampling stations: st. 1–street (inlet of storm drainage system (B)), st. 2–stormwater sedimentation tank (C), st. 3–inflow to the SSBS (D), st. 4–sedimentation zone (E, F) (part 1, above filtration grid), st. 5–sedimentation zone (E, F) (part 2, above geochemical structure), st. 6–biofiltration zone (G), st. 7–river below the hybrid system, st. 8–river above the hybrid system (Photo T. Jurczak).

2.2. Hydrological and meteorological data

Precipitation data was obtained from the meteorological station owned by the Łódź Infrastructure Company, and located on the 38th Centralna street, 1.5 km from the hybrid system. Precipitation was measured with 5 min step. These data were used for the analysis of the efficiency of the system in mitigation of the river discharge at different precipitation ranges. Additionally, data from IMGW meteorological station, located 19 km from the research site, were used for a general characteristic of the precipitation in Łódź.

The Bzura river discharge was measured on the sampling station 7. Discharge was calculated on the basis of the water level in the river, which was automatically recorded by sensors: diver model DI501 and baro model DI500.

2.3. Chemical sampling

Water samples were collected between the 11 March to 7 November 2014 from each zone of the hybrid system (sampling stations 1–6) and from two reference stations located on the Bzura River downstream (st. 7) and upstream (st. 8) of the hybrid system outflow (Fig. 1a). The efficiency of stormwater pollutant removal in the hybrid system was calculated based on data from 10 rain events.

Data from sampling stations 1–6 were used to estimate the efficiency of the treatment of the stormwater flowing through the system at its subsequent stages. The results of the water quality measurements at st. 1 show the quality of the stormwater outflow from the street. We assume this water was previously discharged directly to the river and reservoirs, whereas after the hybrid system had been constructed, it captured and treated the water in the hybrid system prior to discharging it into the river (st. 7). Therefore, the analysis of the results at st. 7 and 8 allowed a comparison of the quality of the river influenced by the stormwater treated by the hybrid system (st. 7) with the river water (st. 8), which was not influenced by street runoff (st. 1).

On the 2 July 2012, an additional 8 stormwater samples for chemical analysis were collected in 10 min intervals between 2:15 am and 3:35 am at sampling station 1. The samples were collected during rainfall to observe the first flush effect.

2.4. Physical measurements and chemical analysis

Physical parameters including: water temperature, oxygen concentration, pH and conductivity were determined *in situ* during water sampling using the WTW Multi 340i (WTW, Weilheim, Germany). Water samples filtered by GF/C membranes were analysed by ion chromatography (Dionex ICS-1000) for the quality and quantity analysis of cations with Ion Pac CS15 column (NH_4^+) and anions with the Ion Pac AS14A column (NO_2^-, NO_3^-, PO_4^{3-}). The analysis of TN concentration was performed in unfiltered water using the persulfate digestion method (method no. 10071; HACH, 1997). Samples for TP analysis were digested with the addition of Oxisolve® Merck reagent (Merck, Darmstadt, Germany) with *Merck* MV 500 Microwave Digestion System, and determined using the ascorbic acid method (Golterman et al., 1978). The analysis of TSS was performed according to PN-EN 872:2007 method by an accredited external laboratory of the Provincial Environmental Protection Inspectorate in Łódź.

2.5. Data analysis

Differences in the nutrient concentrations between sites (st. 1 vs. st. 8, st. 1 vs. st. 6 and st. 7 vs. st. 8) were tested using nonparametric analysis of variance (the Kruskal-Wallis test). When the null hypothesis was rejected, multiple comparisons (the Dunn post-hoc test) were performed (Quinn and Keough, 2002). Also the Kruskal-Wallis test was used to analyse the differences in river flows before and after rain events at station 7. The calculations were made for 12 h before and 12 h after the beginning of the rain event. It was assumed that rainfall up to 9 mm, flowing from the 2.8 ha of impermeable area to the hybrid system, with a runoff coefficient of 0.9, should not cause an increase of river discharge due to the retention capacity of the system (220 m^3). The average, maximum and minimum discharge values were calculated. All analyses were performed in Statistica 10 (StatSoft).

3. Results

3.1. Mitigation of peak flows to the surface water by the hybrid system

Fig. 2 shows the daily precipitation in Lodz city in 2014. During the study period (from April to September 2014), 16 rain events were recorded with precipitation amounts ranging from 3.8 mm to 29.6 mm and durations from 25 min to 395 min (Table 1). Based on those results, it was calculated that during the above rain events the amount of stormwater transported to the hybrid system from the nearby street and parking areas (2.8 ha of sealed surface) ranged from 85 to 740 m^3.

The amount of transported stormwater was compared to the maximum volume of the hybrid system available to retain stormwater (220 m^3). It was assumed that the hybrid system should be able to safely retain stormwater resulting from 9 mm of precipitation during one day. This should efficiently mitigate high flows at the sampling station below the outflow from the hybrid system (station 7). To validate that efficiency, the following categories of precipitation were considered: 4 events with precipitations ranging from 1 to 5 mm, 7 events with precipitations ranging from 5 to 9 mm and 5 events with precipitations exceeding 9 mm.

The results indicate that for most (68.8%) of the stormwater events, all of the inflow volumes (100%) were retained by the hybrid system, and rise in river discharge below the system were not observed (Table 1, Fig. 3). Full retention was observed for rains between 3,4 mm and 8,8 mm and durations between 25 min and 220 min (Table 1). For cases with precipitations exceeding 9 mm and duration from 95 min to 395 min (31.3% of the stormwater events), the river discharges significantly increased during the 12 h after precipitation compared to the values recorded before the rain (Kruskal-Wallis Test: $H (2, N = 16) = 11.10977$, $p = 0.0039$). This increase corresponded to volumes of rainwater varying from 255 m^3 to 740 m^3. In those cases, the proportion of runoff retained in the hybrid system ranged from 29,7% to 86,3% (Table 1).

3.2. Removal of stormwater pollutants in the hybrid system

Concentrations of the physio-chemical parameters at each stage of the water treatment in the hybrid system and the percentage changes in reference to the concentrations recorded at st. 1 for each of the analysed chemical parameters are presented in Table 2. Table 3 shows the statistically significant results of the Kruskal-Wallis test, comparing the nutrient concentrations between stages 1 and 8, 1 and 6, and 7 and 8.

Results of measurements at st. 1 show the quality of the stormwater outflow from the street. In turn, st. 8 represents the quality of the Bzura

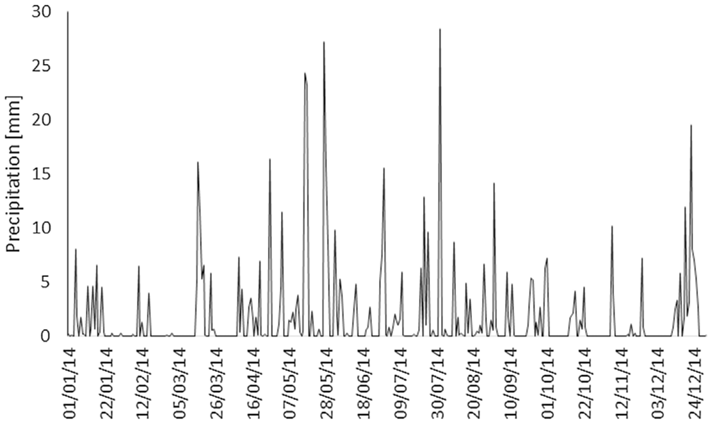

Fig. 2. Daily sum of precipitation in the city of Łódź in 2014 (data from IMGW station located at 19 km from the demonstration site).

Table 1
Precipitation events and river flow data. Q1–mean river flow at the st. 7, within 12 h before precipitation event; Q2–mean river flow at the st. 7, within 12 h after precipitation event; ΔQ − difference between Q1 and Q2; RT − retention time;.

Time of starting of precipitation	Duration of precipitation per day [min]	Daily sum of precipitation [mm]	Volume of runoff from 2.8 ha [m3]	Volume of runoff retained in the hybrid system [%]	Estimated RT in hybrid system for 170/220 m^3 [min]	Q1 [l/s]	Q2 [l/s]	ΔQ [l/s]
2014–04-20 14:40	100	6.9	173	100	59/68	0.763	1.432	0.67
2014–05-12 22:30	125	3.8	95	100	107/124	1.056	1.195	0.14
2014–05-27 18:30	380	29.6	740	29.7	14/16	1.198	17.906	16.71
2014–06-05 17:45	220	8.8	220	100	46/54	0.506	1.108	0.60
2014–06-14 13:55	45	4.6	115	100	89/102	0.156	0.419	0.26
2014–06-28 13:25	25	5.1	128	100	80/92	0.151	1.248	1.10
2014–06-29 20:10	180	7.5	188	100	54/63	0.819	1.546	0.73
2014–07-10 10:40	35	5.7	143	100	72/83	1.848	2.295	0.45
2014–07-23 18:10	200	13.6	340	64.7	30/35	1.476	8.771	7.30
2014–08-01 5:25	330	28.3	708	31.1	14/17	2.227	8.861	6.63
2014–08-09 11:10	140	8.7	218	100	47/54	0.662	0.669	0.01
2014–08-16 5:20	105	4.9	123	100	83/96	0.728	1.052	0.32
2014–08-18 8:00	90	3.4	85	100	120/139	0.205	0.713	0.51
2014–08-31 20:15	95	10.2	255	86.3	40/46	0.622	7.518	6.90
2014–09-21 1:55	130	5.4	135	100	76/87	1.020	1.672	0.65
2014–09-30 21:50	395	12.6	315	69.8	32/37	1.054	2.324	1.27

River without the impact of the stormwater outflow, which is all captured by the hybrid system located on the right side of the river (Fig. 1a). The comparative analysis for st. 1 and st. 8 showed a statistically significant difference in the water quality parameters for TN (H (7, N = 60) = 22,81139 p = 0,0018). This indicates the negative impact of the street runoff on the water quality. The average concentrations of TN and TP at st. 1 were 5.61 and 3.18 mg/l, respectively, and were 3.2-times and 2.4-times higher than the concentrations in the river (st. 8). A statistically significant difference between st.1 and st. 8 were also recorded for NO_3^- (H (7, N = 60) = 15,25575 p = 0,0329), where the average concentrations of that parameter were 1.57 and 0.19 mg/l, respectively. A large difference was also observed for TSS (243.0 mg/l at st. 1 and 5.0 mg/l at st. 8), but due to the low sample size, a statistical analysis for that parameter was not conducted. The smallest differences between those two stations were recorded for the concentrations of NO_2^-, NH_4^+ and PO_4^{3-}. The concentrations of those three parameters were lower by 60.0%, 24.5% and 43.3% at st. 8 than in the stormwater captured at the st. 1, but the results were not statistically significant (Table 3).

The comparative analysis between st.1 and st. 6 shows the overall efficiency of the hybrid system in the removal of nutrients and total suspended solids. The average efficiencies of the hybrid system for the removal of TN and TP were 71.5% and 66.7%, respectively (Table 2), and the results were statistically significant (TN: H (7, N = 60) = 22,81139 p = 0,0018, TP: H (7, N = 60) = 17,00949 p = 0,0173, Table 3). In addition, a high reduction − from 243 mg/l at st. 1 to 34 mg/l at st. 6 was observed for TSS, but due to the low sample sizes, a statistical analysis for that parameter was not possible. The comparison of the results between st. 1 and st. 3 suggests that the underground separator systems were the most efficient section in the hybrid system for TSS removal (94.5%).

In terms of the reduction in PO_4^{3-}, the results indicated an initial increase in the concentration of that parameter in the first stages of the treatment − in the underground separators. The PO_4^{3-} concentrations at the inflow and outflow from the separators (st. 1 and 3) were 0.6 mg/l and 0.59 mg/l, respectively, and the concentrations recorded inside the sediment separator (st. 2) reached high values of 1.33 mg/l. The increases corresponded to the decrease in the oxygen concentration in

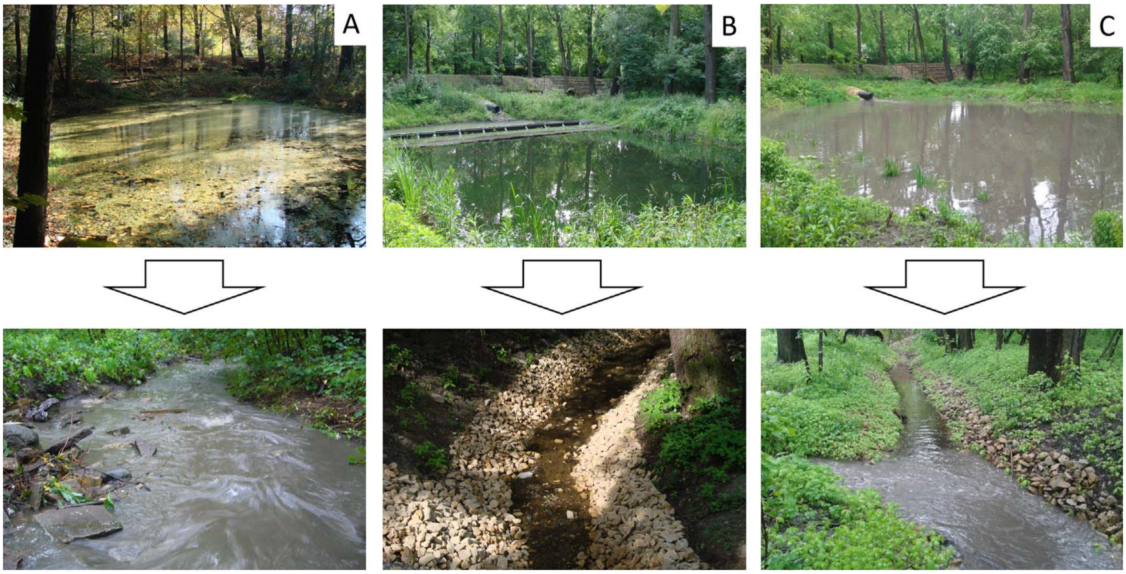

Fig. 3. The impact of the hybrid system on the river discharge during/after rainfall A) before connecting the hybrid system to the street and after intense rainfall of 20.7 mm (2011/07/20), B) after constructing and connecting the hybrid system to the street and after a rainfall of 1.8 mm (2013/06/18), C) after connecting hybrid system to the street and after intensive rainfall of 23.2 mm (2014/05/17) (Photo T. Jurczak).

Table 2

Physical and chemical parameters of water in the hybrid system during/after rainfall (mean ± standard deviation, n − sample size, % − percentage changes in comparison to the station 1 values, and compared with the classes of water quality according to Dz, 2016).

Station	temp [°C]	cond [µS/cm]	ph	O_2 [mg/l]	TSS [mg/l]	TN [mg/l]	TP [mg/l]	NO_3^- [mg/l]	NO_2^{2-} [mg/l]	NH_4^+ [mg/l]	PO_4^{3-} [mg/l]
1. street (inlet of storm drainage system)	14.2 ± 3.7 n = 8 0%	203.- 7 ± 12- 7 n = 8 0%	7.8 ± 0.3 n = 8 0%	9.2 ± 1.0 n = 8 0%	243.- 0 ± 0.0 n = 1 0%	5.61 ± 2.19 n = 8 0%	3.18 ± 1.90 n = 8 0%	1.57 ± 1.22 n = 8 0%	0.05 ± 0.08 n = 7 0%	0.49 ± 0.50 n = 7 0%	0.60 ± 0.62 n = 8 0%
2.stormwater sedimentation tank	14.1 ± 3.0 n = 9 0.9%	180.- 6 ± 82- .0 n = 9 11.4%	7.6 ± 0.4 n = 9 3.0%	6.9 ± 2.0 n = 9 24.9%	135.- 8 ± 60- .6 n = 4 44.1%	3.86 ± 2.93 n = 10 31.3%	2.40 ± 2.40 n = 9 24.4%	0.93 ± 0.62 n = 9 40.9%	0.03 ± 0.02 n = 9 52.9%	0.50 ± 0.56 n = 8 NC	1.33 ± 2.87 n = 9 NC
3.inflow to SSBS	14.8 ± 3.3 n = 8 NC	181.- 5 ± 69- .2 n = 8 10.9%	7.8 ± 0.4 n = 8 NC	8.8 ± 1.3 n = 8 5.1%	13.4 ± 0.0 n = 1 94.5%	4.08 ± 3.39 n = 8 27.4%	2.50 ± 2.57 n = 8 21.2%	1.24 ± 1.46 n = 8 21.2%	0.03 ± 0.05 n = 8 37.4%	0.46 ± 0.40 n = 8 5.4%	0.59 ± 0.60 n = 8 2.0%
4.sedimentation zone 1 of SSBS	13.2 ± 3.0 n = 8 7.2%	248.- 5 ± 11- 1 n = 8 NC	7.6 ± 0.2 n = 8 2.2%	7.3 ± 1.5 n = 8 21.1%	57.5 ± 45.4 n = 4 76.3%	3.29 ± 3.02 n = 8 41.4%	1.34 ± 0.79 n = 8 57.9%	1.46 ± 1.78 n = 8 7.0%	0.04 ± 0.03 n = 8 35.5%	0.44 ± 0.38 n = 8 10.4%	0.54 ± 0.33 n = 8 10.2%
5.sedimentation zone 2 of SSBS	12.6 ± 2.5 n = 5 11.4%	354.- 8 ± 96- .4 n = 5 NC	7.4 ± 0.2 n = 5 4.5%	6.0 ± 1.5 n = 5 35.5%	9.8 ± 5.1 n = 2 96.0%	2.04 ± 2.00 n = 5 63.7%	0.93 ± 0.89 n = 5 70.8%	0.45 ± 0.38 n = 5 71.3%	0.04 ± 0.04 n = 4 35.1%	0.35 ± 0.31 n = 5 28.2%	0.41 ± 0.22 n = 5 31.4%
6.biofiltration zone of SSBS	13.7 ± 3.3 n = 10 3.6%	327.- 5 ± 11- 2 n = 10 NC	7.8 ± 0.5 n = 10 NC	7.8 ± 2.3 n = 10 15.2%	34.0 ± 40.9 n = 4 86.0%	1.60 ± 1.20 n = 10 71.5%	1.06 ± 1.51 n = 10 66.7%	0.66 ± 0.84 n = 10 58.1%	0.01 ± 0.01 n = 10 78.3%	0.23 ± 0.18 n = 10 52.6%	0.36 ± 0.19 n = 10 40.7%
Threshold for the 1st class of water quality	**≤22**	**≤549**	**7–7.9**	**≥7.5**	**≤10.8**	**≤3.2**	**≤0.20**	**≤2.2**	**≤0.01**	**≤0.25**	**≤0.065**
Threshold for the 2nd class of water quality	**≤24**	**≤620**	**7–7.9**	**≥6.8**	**≤14.7**	**≤4.9**	**≤0.30**	**≤3.4**	**≤0.03**	**≤0.738**	**≤0.101**
7.river below the hybrid system	14.6 ± 3.5 n = 4 NC	344.- 3 ± 45- .1 n = 4 NC	7.4 ± 0.1 n = 4 NC	5.7 ± 1.1 n = 4 NC	29.4 ± 24.6 n = 2 NC	1.55 ± 0.57 n = 4 NC	1.59 ± 0.85 n = 4 NC	0.60 ± 0.48 n = 4 NC	0.02 ± 0.01 n = 4 NC	0.29 ± 0.19 n = 4 NC	0.33 ± 0.21 n = 4 NC
8.river the hybrid system	14.1 ± 2.6 n = 8 NC	396.- 9 ± 30- .5 n = 8 NC	7.5 ± 0.2 n = 8 NC	7.2 ± 2.7 n = 8 NC	5.0 ± 3.7 n = 2 NC	1.63 ± 0.63 n = 8 NC	0.75 ± 0.46 n = 8 NC	0.19 ± 0.18 n = 8 NC	0.02 ± 0.01 n = 8 NC	0.37 ± 0.48 n = 8 NC	0.34 ± 0.25 n = 8 NC

the surface water in the separator (depth of separator − 3 m, water level − 1.84 m, thickness of sediments − 0.82 m) from 9.2 mg/l at st. 1 to 6.9 mg/l at st. 2, which might have caused anaerobic phosphorus release from sediments accumulated in separator (Table 2). The recorded total efficiency of the hybrid system for the reduction of PO_4^{3-} was therefore relatively low and reached 40.7% for the whole system. However, it is worth mentioning that the free water surface flow by the SSBS proved to be very efficient in reducing PO_4^{3-} and ultimately decreased its mean concentration from 1,33 mg/l to 0,36 mg/l (Table 3).

The most effective removal of TN and TP occurred in the sedimentation zone of the SSBS, where the smallest particles were effectively accumulated. The concentrations of those parameters (TN and TP) decreased by 63.7% and 70.8%, respectively, relative to those for st. 1. In turn, the biofiltration part of the SSBS was most effective in reducing NO_2^- and NH_4^+, where the reduction levels reached values from 35.1% at st. 5 to 78.3% at st. 6 for nitrites and from 28.2% at st. 5 to 52.6% at st. 6 for ammonium.

Maximum concentrations of TP and TN observed in the runoff from the street (sampling station 1) during the study reached 6.17 mg/l (2014/07/23) and 10.5 mg/l (2014/04/08), respectively. The respective maximum concentrations of those two parameters observed in the river upstream the outflow from the hybrid system (st. 8) were at the levels of 1.1 and 2.8 mg/l and were over 4-times lower. The concentrations of TP and TN in the outflow from the hybrid system for those two individual events reached 1.27 mg and 2.2 mg/l, respectively, which corresponded to high reductions in TP and TN of 79.4% and 79.0%.

The comparative analysis between st.7 and st. 8 showed no significant differences in any of the water quality parameters (Table 3), which indicates the high efficiency of the stormwater treatment by the hybrid system. The results show that the effluent from the hybrid system does not negatively influence the water quality below its outflow in comparison to the “unimpacted” river upstream of its outflow. This indicates that the hybrid system purified the stormwater to concentrations of TSS, TP, NO_3^- and NO_2^- that were close to those at the upstream sampling site (st. 8), and for TN, NH_4^+ and PO_4^{3-} concentrations were even lower than in the Bzura River.

3.3. Dynamic of nutrient transport by stormwater runoff within a rain event

The dynamics of the nutrient concentrations during high rain events were observed for the event on the 2 July 2012. The observations were made for the 45 mm and 135 min duration rain event. The event occurred before project implementation, which allowed the extent of the first flush effect on the stormwater outflow on the Bzura River to be identified.

Concentrations of nutrients transported from the street to the river during that rainfall in the first 20–30 min were the highest, indicating the first flush effect. During that period, the TP concentrations increased from 1.05 to 1.39 mg/l, and those for TN increased from 8.3 to 9.9 mg/l (Fig. 4a). Within the next 20–30 min, the concentrations of those two parameters (TP and TN) decreased to 0.35 and 2.7 mg/l, respectively. Reductions in NO_3^-, NH_4^+ and PO_4^{3-} were also observed throughout the rain event (Fig. 4b). However, in the next 90 min marked from the beginning of the rainfall, unexpected increases in the concentrations of TP and TN to 0.48 and 3.8 mg/l were observed. We refer to these observations as the “second flush” effect.

4. Discussion

4.1. Stormwater retention and discharge mitigation

The results confirmed that the hybrid system, which has a flexible retention capacity extending up to 220 m^3, was able to retain stormwater drained from the 2.8 ha sealed street and parking area and effectively mitigated the peaks in river discharge for rainfalls below 9 mm (Fig. 5). During those rains, only small (statistically insignificant) increases in river discharge were observed as a result of the gradual release of inflowing stormwaters through the slot in the weir. That mechanism allowed stormwater release to be delayed and extreme stormwater discharges in the river to be avoided. For precipitations exceeding 9 mm (5 events of the 16 observed), the discharges exceeded capacity of system and could not be stored at full volume. In those cases, the river discharges after the rain events were significantly (5.5 times) higher than before the precipitation (Fig. 2) due to water overflowing the weir.

Table 3
Comparison of TSS and nutrient concentration between stations 1 and 6, 1 and 8, 7 and 8 (bold fonts − statistically significant results for the Kruskal-Wallis test with $p < 0.05$; * − too low sample size for statistical analyses).

Station	TSS* [mg/]	TN [mg/]	TP [mg/]	NO_3^- [mg/]	NO_2^- [mg/]	NH_4^+ [mg/]	PO_4^{3-} [mg/]
st1	243.0	5.61	3.18	**1.57**	0.05	0.49	0.60
vs	5.0	**1.63**	0.75	**0.19**	0.02	0.37	0.34
st8							
st1	243.0	**5.61**	**3.18**	1.57	0.03	0.49	0.60
vs	34.0	**1.60**	**1.06**	0.66	0.01	0.23	0.36
st6							
st7	29.4	1.55	1.59	0.60	0.02	0.29	0.33
vs	5.0	1.63	0.75	0.19	0.02	0.37	0.34
st8							

Results of the Kruskal-Wallis test for TN: H (7, N = 60) = 22,81139 p =,0018 TP: H (7, N = 60) = 17,00949 p =,0173 and NO_3^-: H (7, N = 60) = 15,25575 p =,0329.

Hatt et al. (2009) tested a system consisting of two sedimentation tanks combined with a sub-surface flow biofilter (45 m^2 of the free water surface system area). They reported that between 15 and 83% (33% on average) of the inflow volume from the catchment area of 4500 m^2 was retained by the system. There were no events for which all the volume was retained. Another example comes from research by Trowsdale and Simcock (2011), who drained stormwater from a road area of 11600 m^2 to the Paul Metthews bioretention system, which employed a sub-surface flow biofilter and which had a total retention capacity of 200 m^3. They reported retaining stormwater in the range of 14% to 100% (average 41%) in the bioretention system, but during large or short-duration rain events, most of the runoff was directed to the bypass system. The hybrid system in this research appeared to be comparatively very efficient in retaining stormwater runoff from the impervious area, retaining 100% of the runoff for most events (11/16). Runoff volume from more intensive precipitation events was retained within the range of 29.7–86.3%.

4.2. Treatment efficiency

The treatment efficiency varied under different parameters, depending on the applied method. Separators are usually very efficient for TSS removal (Wilson et al., 2009). For example, high efficiencies in reductions of TSS by underground separators were demonstrated by Tran and Kang (2013), who installed a bypass with a hydrodynamic separator at the stormwater outflow from a catchment that achieved reductions in the range of −31% to 98% (average: 58%). In our case, the observed TSS reduction with stormwater retained from the street to the underground separator system was, as expected, also high (94,5%) but was, however, based only on one measurement and could not therefore be compared with other data.

There are very few results that show the efficiencies of underground separators (separation tanks or hydrodynamic separators) in nutrient removal. In our research, we considered the efficiencies for TN and TP to be high, and they reaching 27.4% and 21.2%, respectively. For NO_3^- and NO_2^- at the outflow from the underground separators (st. 3), the efficiencies reached 21.2% and 37.4%, respectively. In the case of

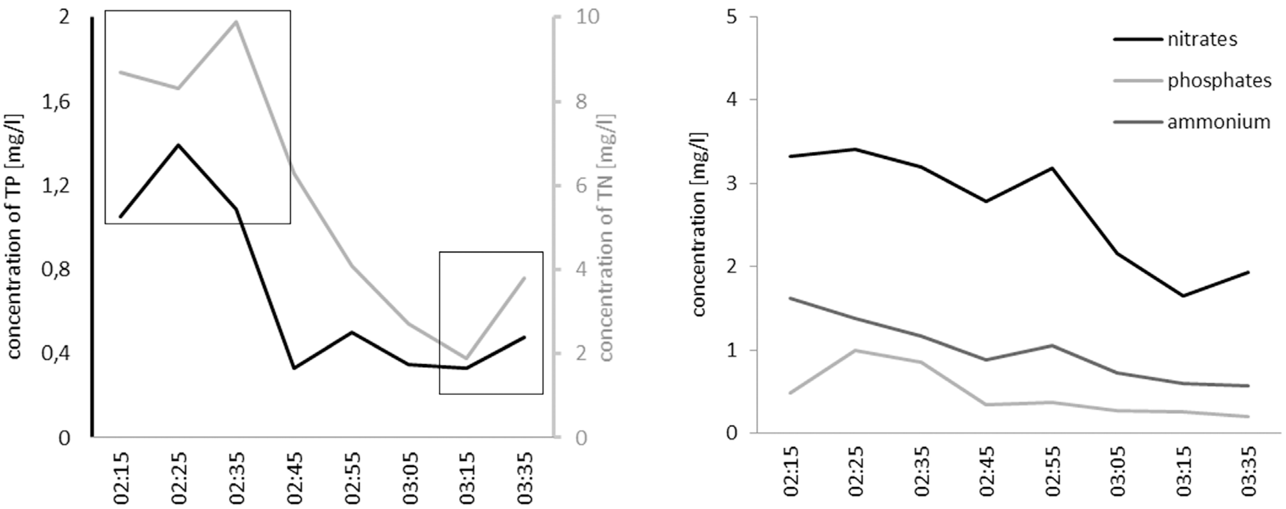

Fig. 4. Nutrient concentration changes in the street stormwater outflow during rainfall of 45 mm and 135 min (02.07.2012). First and second flush effect are marked with boxes.

PO_4^{3-} and NH_4^+, the efficiencies reached only 2.0% and 5.4%, respectively. We observed that the concentration of PO_4^{3-} increased at st. 2 by a factor of two (from 0.62 mg/l to 1.33 mg/l) and then again decreased to a concentration of 0.59 mg/l at st. 3 in the outflow from the underground part of the hybrid system. This trend corresponded to decreases in the concentration of oxygen in the underground separator and might have been the reason for the release of phosphorus from the sediments. Breault and Granato (2000) suggested that during periods of low oxygen concentrations in separators, metals and nutrients adsorbed in sediments can become desorbed and dissolve into solution. A similar situation was observed by Newman et al. (2013), who recorded unexpectedly very high concentrations of TP (13–38 mg/l) in underground separating flow chambers retaining and treating stormwater from a car park.

The SSBS tested in this research, as a free-water surface flow system (Vymazal, 2007), was designed to work in complement with underground separators to increase efficiency of the removal of nutrients transported with stormwater runoff. In the case of TP and TN, the highest reductions in their concentrations were observed in the two first sedimentation basins of the SSBS. The metal grid constructed in the sedimentation section of the SSBS covered with a biodegradable geofibre increased the effectiveness of the sedimentation process. In addition, nitrate concentrations were also reduced in the sedimentation section of the SSBS, where the average concentration decreased from 1.46 mg/l to 0.45 mg/l. In the biological part of the SSBS, we observed increases in nitrates up to 0.66 mg/l. Despite the 46.8% reduction in nitrates in the SSBS, the average concentration of that parameter in the outflow from the SSBS was still 3 times higher than in the river above the system. The increase in nitrate concentrations in the biological part of the SSBS corresponded to the decrease in ammonium concentrations. A similar correlation was reported by Hsieh et al. (2007) and Cho et al. (2009) in the reservoir's vegetation zone, and it may be a result of nitrification processes. Aquatic plants in the biofiltration part of the SSBS and the floating island (6 m^2) installed at the outflow from the system contributed to the accumulation of nutrients in periods of stable water flow (dry weather). During the flow of stormwater through the hybrid system, the biological section also worked as a barrier to sediments. In addition, floating mats are more resistant to water level changes in small stormwater retention systems than for typical wetland constructions. Studies conducted by Lynch et al. (2015) confirmed that the floating mats used in this type of waterbody are able to remove from 25 to 40% of TN and from 4 to 48% of TP from water.

Furthermore, Winston et al. (2013) tested a wet pond with an area of 500 m^2 in North Carolina, at which four floating islands were tested

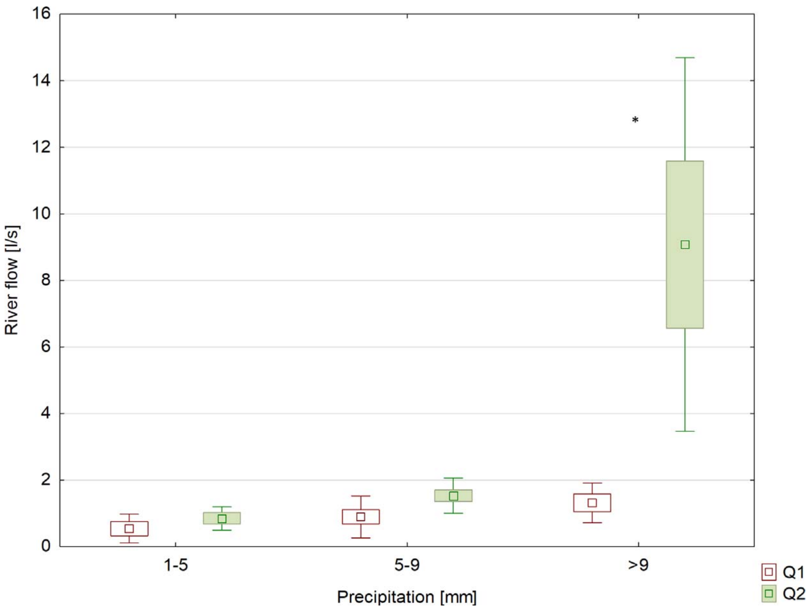

Fig. 5. Comparison of the river discharge below the hybrid system (sampling station 7), for 12 h before (clear bar) and after rain (green bar) for precipitation between 1 and 5 mm, between 5 and 9 mm and above 9 mm. Statistical significant value is marked by asterisk (Kruskal-Wallis test for ΔQ: H (2, N = 16) = 11.10977 p = 0.0039).

as floating treatment wetlands for stormwater retention (depth of 0.53 m and depth at the permanent pool of 0.93 m) and purification of stormwater drained from a parking area of 2.37 ha. The construction of floating mats in the existing wet retention pond increased the efficiency of the removal of TSS from 88.9% to 94.8% and those of TN from 59.4% to 87.7% and TP from 57.7% to 87.1%. Studies conducted by Tanner and Headley (2011) confirmed the efficiency in reducing phosphorus (almost 100%) of floating mats installed on stormwater reservoirs. Small floating mats appear to be more effective in reducing nutrients from stormwater systems, especially with significant fluctuations in water levels. Studies carried out by Read et al. (2008) demonstrated that vegetation used to treat stormwater significantly reduced the concentrations of total dissolved nitrogen (79%), phosphorus (22%) and TSS (98%) in comparison to those in the control zone without vegetation. They also demonstrated that specific species have different capacities for absorbing nutrients from water, and only five species of 20 tested, e.g., Sedge *Carex* (L.), which was also used in our SSBS, effectively eliminated ammonium ions from stormwater. In addition, Mitsch et al. (2015) observed reductions in total phosphorus ranging from 17% to 51% via vegetation treatment, depending on plant species.

Comparing the results achieved for the SSBS to the efficiencies of sub-surface wetlands, we achieved comparable results in terms of nutrient removal, but the SSBS reached higher retentiveness and flood protection capabilities. Birch et al. (2005) tested an infiltration basin (31 × 16 m) with an area of 450 m^2 that was constructed using filtration media consisting of a 1:6 mixture of zeolite and coarse, pure quartzitic sand for purifying stormwater collected from a catchment area of 2.7 ha (ratio of the catchment area to the system area: 1.7). The efficiencies of that system for the removal of TP and TN were 51% and 65%, respectively. In our SSBS system (comparable ratio of catchment area to treatment system area: 1.5), the efficiencies for TP and TN between st. 3 and st. 6 reached 57.6% and 60.8%, respectively.

Hatt et al. (2009) combined sedimentation tanks and different types of sub-surface flows in biofiltration systems (Monash University system), but only the efficiencies of the sub-surface flow biofiltration systems were reported in his paper. The average efficiencies for TSS and NH_4^+ reduction reached 89.7% and 33.3%, respectively. In our SSBS system, TSS was reduced by a minimum of 75% (reduction calculated based on the results from st. 2 and st. 6), and NH_4^+ was reduced by 50%. Hatt et al. (2009) did not observe reductions for TP, TN, PO_4^{3-} and NO_x. The SSBS system tested in our studies achieved the following reductions: TP, 57.6%, TN, 60.8%, PO_4^{3-}, 39%, NO_2^-, 66.7% and NO_3^-, 46.8%.

In turn, three wet detention ponds with volumes of 175 m^3 (Odense), 267 m^3 (Aarhus) and 305 m^3 (Silkeborg) retained stormwater from impervious catchment areas of 11.4 ha, 25.8 ha and 8.8 ha, respectively (Istenič et al., 2012). They reached efficiencies in the removal of TSS, TN and TP at levels of 68.8%, 59.4%, and 41.4% for the Odense, 91.6%, 69.6%, and 50,0% for the Aarhus and 94.6% 79.2%, and 90.9% for the Silkeborg. In addition, in the Odense system, a sorption filter dosed in iron sulphate was tested in the outflow; they observed system performance increases as great as 91.6%, 65.6% and 90.3%.

The hybrid system reduced TSS transported from Wycieczkowa Street to the Bzura River by 86.0%, and TN was reduced by 71.5%, nitrite by 78.3%, nitrate by 58.1%, ammonium by 52.6%, TP by 66.7% and phosphates by 40.7%. According to the applicable Polish regulation, the system achieved a good water status for all of analysed chemical parameters, with the exception of TP, PO_4^{3-} and TSS (Table 2) which exceeded thresholds for a good water status (Dz, 2016). However TP and PO_4^{3-} had also exceeded thresholds for a good water status in the Bzura River above the hybrid system.

4.3. *“Second flush” effect*

Our results confirmed occuring the first flush effect in a small urban catchment. During 135 min of rainfall, the highest concentrations of TN and TP were observed during the first 20 min of the stormwater outflow from the street, and minimum concentrations were observed after 30–60 min from the beginning of the rain event. The highest concentrations of TN and TP in stormwater outflow from the street during the studies reached 10.5 and 6.17 mg/l, respectively. Luo et al. (2012) recorded comparable ranges of concentrations: 23.4 mg/l for TN and 6.4 mg/l for TP. Slightly lower concentrations of TN and TP were found in stormwater during studies performed by Hatt et al. (2009), Mitchell et al. (2012) and Zhou et al. (2013), which showed the impacts of catchment size and its management on the pollution loads exported from catchments (Lee and Bang, 2000).

The first flush effect is a well-documented phenomenon (Deletic, 1998; Lee and Bang, 2000; Lee et al., 2004) and can be described as a significantly higher concentration of pollutants in the early stage of rainfall runoff when compared to that in the later stage. The concentrations transported with increasing discharge also change seasonally, depending on the selfpurification ability of the river (Wagner and Zalewski, 2016). This has also been confirmed by studies performed by Li et al. (2015), who demonstrated that retaining the initial 40% of runoff volume from the catchment contributed to the removal of as much as 58% of TN, 61% of TP and 55% of TSS. Similar dependencies observed in the above studies suggest that retaining and, as a consequence, removing loads transported in the first flush of the stormwater runoff might significantly improve the quality of the surface water ecosystems into which they discharge. On the other hand, large amounts of pollutants discharged into receiving waters in short periods of time may cause serious damage to water environments (Wang et al., 2017).

Acharya et al., 2010 demonstrated that the initial 30% of runoff transported 44% of TN, 34% of TP and 35% of TSS; however, in the case of TSS, a second increase in concentration was also observed. Qin et al. (2016) also described the first flush effect, but they also modelled middle and final flush effects for outflows of stormwater from urban areas. Through analysis, they found that more than 1/3 of the pollutant loads were washed off during the middle and final flushes.

Li et al. (2009) described a “second flush effect” for heavy metals during short duration rain events of medium rainfall and bimodal rains. In turn, Li et al. (2015) observed a “secondary flush effect” during one bimodal rain event in Dongguan city in China when the pollutant concentrations peaked slightly after the rainfall intensity peak.

The relation between the rainfall times and TN and TP concentrations in our study was also complex. The first flush effect most likely resulted from the transport of pollutants by stormwater runoff from the impermeable areas enclosed by curbs (e.g., streets and car park). When the intense rainfall continued, the drainage system was not able to accommodate the large volume of water, causing the inflow to choke and flooding the adjacent areas (including the green areas) located behind and above the curbs. Given that the rainwater mostly infiltrated in those adjacent areas during the first stages of the rain, the flooding from the streets intensively leached the accumulated nutrients. As a consequence, a subsequent, second load of pollutants was transported to the stormwater drainage system (st.1) and further into the river. We call this the “second flush effect”, but further research is required as only one measure of that increasing concentration was recorded. Wang et al. (2017) tested different types of rainfall on the first flush effect of common urban surfaces. They suggested that grasslands should be built around asphalt roads and watertight tiles to attenuate the first flush effect, but the grasslands should be located in lower lying areas to avoid the second flush effect.

5. Conclusions

The goal of the study as to test the efficiency of the new hybrid system (combined of engineering and biological measures) for stormwater retention and purification. The innovation of the system is in the integration of engineering measures with ecological biotechnologies, which increase the efficiency of stormwater purification in urban limited space.

Similar constructions are currently tested in Radom city (Poland), as an example of nature-based solution for adaptation of the city to climate changes (retention of extreme city and small urban river floods, and purification of more often and intensive stormwater runoffs).

The current study has shown that hybrid systems effectively reduced nutrients transported with stormwater runoff from impermeable urban areas to the river and downstream reservoirs. The underground part of the system mainly reduces suspended matter, sand and petroleum substances, while the ground, biological part of the system reduces the fine particulate organic matter and assimilates them into the food chain.

Due to the specific construction of the weir, the hybrid system stabilised the river discharge downstream of the system during rainfall.

The system proved to be efficient in spite of its relatively small surface area, therefore it can be used successfully in cities, where land is often expensive or its availability is limited.

The system is cost-efficient. Relatively low cost of the construction (approx. 70,000 €) allows to achieve good results in water quality improvement for a long time at relatively low investments. For comparison, the cost of the sediments removal from a reservoir of 10 ha is approx. 250.000 €, and must repeated every few years. The hybrid system, if maintained properly and systematically, provides long-term prevention measure for eutrophication and siltation, instead of treatment of the already degraded system.

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