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Green roof impact on the quantity and quality of stormwater discharged from urban areas

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Abstract: Green roofs are increasingly popular in both new and modernised buildings. They significantly reduce the outflow of stormwater from buildings and change its composition. Wherever an urbanised area is equipped with a separate sewage system, usually stormwater goes directly to the receiver without treatment, which may affect the quality of water in the receiver. The article presents results of research carried out on the green roof of a building in Lodz, Poland. During rainfall, the flow rate from the roof was measured. With the use of the US EPA software Stormwater Management Model (SWMM) a model of the green roof was created and calibrated using rainfall data from the city's pluviometric network. Based on the measurements of the roof runoff, as well as SWMM modelling, the degree of outfall reduction was determined. Samples of roof runoff were collected to study the characteristics of rainwater, including pH, electrical conductivity, organic compounds, nitrogen, phosphorus, and suspended solids. The results were compared with the quality of runoff from a traditional roof. Except ammonium nitrogen, values of the examined quality indicators was higher in the case of the green roof but the pollution load of almost all contaminants, except phosphorus, were lower due to a significant reduction in the volume of stormwater outflow (62–91%). The quality of stormwater discharged from the green roof improved with its age.

Keywords: green roof, sewerage modelling, stormwater management, stormwater runoff quality, urban drainage

INTRODUCTION

In recent years, green roofs have become increasingly popular in cities, both on new and modernised buildings. Green roofs have many advantages as they improve the aesthetics of cities, microclimate, and above all, they reduce the stormwater outflow to the sewage system. In the era of climate change and increasing problems related to overloading the city's drainage systems, climate adaptation plans assume a widespread implementation of green infrastructure technologies, including green roofs (Carpenter *et al.*, 2016; Shafique, Kimab and Rafiq, 2018; Yao *et al.*, 2020; Zhang and He, 2021). According to Liu *et al.* (2021), since 1981, the research into green roofs has steadily increased with approximately 40.9% of articles focusing on regulating water-related services. The assessment of green roof performance, especially with regard to the functioning of drainage systems in housing estates or city districts, is often based on modelling that uses the US EPA SWMM or other software (Abualfaraj *et al.*, 2018; Palla, Gnecco and La Barbera, 2018; Hamouz and Muthanna, 2019).

Green roofs show different effectiveness in reducing the volume of runoff and peak flow. They are generally considered to provide effective solutions in urban hydrology in various climatic zones. The effectiveness of green roofs depends on many factors, such as extensive or intensive type, structure and age, thickness and sorption capacity of the substrate, species of plants, climate and season, rainfall characteristics, etc. Analyses carried out by Abualfaraj *et al.* (2018) indicated that approximately 55% of the cumulative precipitation on an extensive green roof was captured and retained and the average percentage retained on an event-basis was 77%. Research by Sobczyk and Mrowiec (2016) showed runoff volume reduction between 68.8 and 100%. Based on 3–8 years of field data from four Norwegian locations representing typical cold and wet Nordic climates, Johannessen, Muthanna and Braskerud (2018) found that accumulated retention was 11–30% annually and 22–46% in May through October. Johannessen, Hanslin and Muthanna (2017) observed a considerable retention of stormwater during summer, ranging from 52 to 91%. Based on a dataset of 2,375 original experimental samples, statistical analysis by Zheng *et al.* (2021) shows that the sampled runoff retention rates (i.e. proportion of rainfall retained on per-event basis) range widely (0–100%), with an average of 62%.

Modern structures and substrates used in green roofs allow to retain almost all precipitation, but usually, particularly in case of previously constructed roofs, part of the stormwater flows to the sewage system. The composition of outflow is different to that of stormwater from traditional roofs. Kok *et al.* (2016) assess that the water quality of the green roof outflow is generally good. Liu *et al.* (2020) observed greater concentrations of suspended solids (SS), chemical oxygen demand (*COD*), and total phosphorus (TP) when compared with rainwater quality. Results obtained by Ferrans *et al.* (2018) confirmed that green roofs have the ability to neutralise potential of hydrogen (pH), but cause the increase of many parameters, like biological oxygen demand (BOD_5), *COD*, total nitrogen Kjeldahl (TKN), nitrates, nitrites, TP, and other. The composition of stormwater runoff from green roofs is not constant (Todorov *et al.*, 2018). Research by Buffam, Mitchell and Durtsche (2016) showed much higher seasonal variation in green roof runoff water quality than among-event variation. Most dissolved element concentrations in runoff were high in summer, positively correlated with temperature. The use of NPK-nutrients in the substrate or in the soil caused much higher values of *COD* and concentrations of nitrogen and phosphorus compounds in runoff water than on non-fertilised green roofs (Teemusk and Mander, 2011). The age of the green roof also has an impact on the quality of stormwater runoff (Mitchell *et al*., 2017; Okita *et al.*, 2018; Burszta-Adamiak, 2020) but according to many researchers the substrate of the green roof could be the most important factor affecting the quality of the stormwater outflow (Kok *et al.*, 2016; Ferrans *et al.*, 2018; Vijayaraghavan *et al.*, 2019; Rocha *et al.*, 2021). However, research by Meng *et al.* (2021) showed that the increase in substrate depth did not significantly affect runoff water quality. Vijayaraghavan, Reddy and Yun (2019) indicate the necessity to consider the sorption capacity of the substrate and phytoremediation potential of plants to improve the quality of runoff from green roofs.

The development of urbanised areas has a significant impact on the water cycle in nature and the pollution of water reservoirs which receive not only outflows from sewage treatment plants. Since the 1990s an integrated approach has been used to ensure good ecological status of receiving water. The approach is based on the analysis of the impact of pollutants from all sources, such as outlets from wastewater treatment plants, combined sewer overflows, stormwater drainage outlets, and surface runoffs (Benedetti *et al.*, 2013). During wet weather, runoff from urban impervious surfaces can significantly contribute to an increase in the pollutant load discharged into water bodies (Sakson, Brzezinska and Zawilski, 2017). Due to the increasingly common use of green roofs and the multitude of factors affecting the quality of stormwater discharged from them, it is necessary to assess the impact of green roofs on the receiving water, especially small urban rivers. The aim of the study presented in this article was to assess the influence of green roofs on the concentration and loads of pollutants discharged with stormwater. The research was carried out on an existing roof in a city with a hybrid sewer system; combined wastewater and stormwater in the center and separate systems in other districts of the city. Stormwater is discharged by over 200 outlets to 18 small rivers almost always without any pretreatment.

MATERIALS AND METHODS

STUDY SITE

The research was carried out on the green roof of a residential building in the city center of Lodz, Poland. It is an extensive roof type of 538 m^2 and the humus layer of 14–26 cm. The roof included the following plants: *Juniperus horizontalis*, *Euonymus fortunei*, *Heuchera*, *Cotoneaster dammeri*, *Cotoneaster nanshan*, *Juniperus sabina*, *Picea pungens*, *Thuja occidentals*, *Carex*, *Pinus mugo* 'Turra', *Celastrus orbiculatus* 'Hercules', *Oenothera*, *Sedum pachyclados*, *Berberis thunbergii* (Photo 1). After precipitations, the excess stormwater from the roof is discharged through a pipe on which a Teledyne ISCO SPA 970 flowmeter and a sampling valve were installed (Photo 2), then the runoff is directed to the municipal sewer system.

Photo 1. Green roof during monitoring period (phot.: *Archive of the Institute of Environmental Engineering and Building Installations*)

Photo 2. Measurement of stormwater flow rate and the sampling point (phot.: *Archive of the Institute of Environmental Engineering and Building Installations*)

SAMPLING AND METHODS

The preliminary research on the quality of stormwater discharged from the green roof was carried out 2 years after its construction and samples were collected 6 times. The major survey was conducted 4 years after the construction in the spring-summer period (April–June 2016). The test samples were collected 10 times during rainfall with different characteristics. Each time during the runoff, 3 samples of rainwater were collected. They were transported to the laboratory and tests were performed on a mixed sample. At that time, the quality of stormwater discharged from a neighbouring building with traditional roof covered with galvanised sheet was also analysed. The following indicators were tested: potential of hydrogen (pH), electrical conductivity (*EC*), biological oxygen demand (BOD_5), chemical oxygen demand (*COD*), ammonium nitrogen (NH_4-N), total nitrogen Kjeldahl (TKN), total phosphorus (TP), and total suspended solids (TSS). The scope of laboratory tests performed and methods are presented in Table 1. The table also presents formal requirements for the quality of wastewater discharged into water and soil, as well as quality requirements for rivers. With the use of the US EPA SWMM software, and based on the design of the building and rainwater system, a model of a green roof was developed. The model was made in 2014 based on the measurement of stormwater runoff from the green roof and rainfall data from the city's pluviometric network. The network was equipped with A-STER TPG-037-H230-AM rain gauges. Precipitation was recorded in 5-minute time steps. The green roof model and the comparison of hydrographs showing modelled and observed data are presented in Figure 1. Model results were evaluated using Nash–Sutcliffe model efficiency coefficient (*NSE*). It was considered satisfactory (>0.5). Table 2 shows calibration parameters for the green roof model.

With the use of the model and rainfall data from 2016–2020, the stormwater runoff from the green roof was determined for the period. Based on the rainfall data, the outflow from a traditional roof in the same area was determined (runoff coefficient was assumed to be 0.95), and the outflow reduction for the green roof

Table 1. Parameters of stormwater runoff quality – analysis methods, emission standards, and requirements for river water of good quality

No.	Parameter	Analytical method	Discharge into water and soil according to Rozporządzenie (2019)	Requirements for water of good quality according to Rozporządzenie (2021) (lowland sandy-clay river)
1	pH	PN-EN ISO 10523:2012; potentiometric method	6.5–12.0	6.7–8.1
2	*EC*	PN-EN 27888:1999; conductometric method	–	<553 $\mu S \cdot cm^{-1}$
3	TSS	PN-EN 872-2007-1; gravimetric method	35 $mg \cdot dm^{-3}$	<18.5 $mg \cdot dm^{-3}$
4	BOD_5	PN-EN 1899-2:2002; dilution technique	15 mg $O_2 \cdot dm^{-3}$	<3.7 mg $O_2 \cdot dm^{-3}$
5	*COD*	PN-ISO 6060-2006; titration method	125 mg $O_2 \cdot dm^{-3}$	<30 mg $O_2 \cdot dm^{-3}$
6	NH_4-N	PN ISO 5664:2002; titration method	10 mg NH_4-$N \cdot dm^{-3}$	<0.553 mg NH_4-$N \cdot dm^{-3}$
7	TKN	PN-EN 25663:2001; titration method	–	<1.4 mg $N \cdot dm^{-3}$
8	TP	PN-EN ISO 6878:2006; UV/VIS spectrometry	1 mg $P \cdot dm^{-3}$	<0.3 mg $P \cdot dm^{-3}$

Explanations: *CD* = conductivity, TSS = total dissolved solids, BOD_5 = biological oxygen demand, NH_4-N = ammonium nitrogen, TKN = total nitrogen Kjeldahl, TP = total phosphorus.
Source: own elaboration.

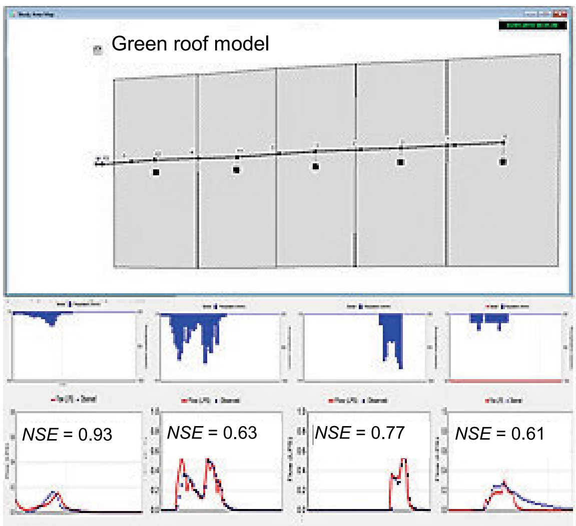

Fig. 1. Green roof model and the hydrographs of modelled and observed data with precipitation; source: own elaboration

Table 2. Parameter of green roof in SWMM

Parameter	Value
Vegetation volume	0.1
Surface roughness	0.1
Soil porosity (volume fraction)	0.5
Field capacity (volume fraction)	0.35
Wilting point (volume fraction)	0.05
Conductivity ($mm \cdot h^{-1}$)	200
Conductivity slope	30
Suction head (mm)	80
Drainage void fraction	0.5
Roughness	0.4

Source: own elaboration.

was calculated. On the basis of the average volume of the runoff in 2016–2020 and average concentrations of pollutants, the amount of discharged loads was determined.

RESULTS AND DISCUSSION

The results of the 2016 research on the quality of runoff from the green roof carried out for the roof are presented in Table 3. The table also provides the main parameters of precipitation during which samples were taken, including rainfall depth (*H*) and maximum rainfall intensity (i_{max}). Values of the indicators were generally low, especially *EC*, BOD_5, and TSS. Considering results of other studies, the results obtained were typical for extensive green roofs. Taking into account average indicator values, the values specified in requirements for sewage discharged into water and soil were not exceeded. In the case of 3 phenomena of rainfall, the permissible value of the total phosphorus concentration was exceeded. Moreover, when comparing the results with requirements for surface waters of good quality, an increased concentration of TP was observed, as well as high values of *COD* and TKN. Both the average pH value and the pH value for some individual phenomena were lower than permissible values for discharge into water of good quality. Other studies most often demonstrate the ability of green roofs to neutralize rainwater (Kok *et al.*, 2016; Liu *et al.*, 2021).

The indicators were characterised by variability during the research period. pH and *EC* were showed low variability ($CV < 0.25$), TP had an average variability ($0.25 \le CV < 0.45$), all other parameters (BOD_5, *COD*, NH_4-N, TKN, and TSS) high variability ($0.45 \le CV \le 1$). As regards the quality of stormwater runoff, Pearson correlation coefficients were determined. These are given in Table 4. The results indicate that there are no strong correlations between the indicators. Some moderate positive

Table 3. Results of testing the composition of stormwater runoff from green roof and rainfall parameters

Date in 2016	pH	*EC* (μS·cm^{-1})	BOD_5	*COD*	NH_4-N	TKN	TP	TSS	*H* (mm)	i_{max} (dm^3·s^{-1}·ha^{-1})
			mg·dm^{-3}							
08 Apr	6.86	195	4.8	61	0.12	8.50	0.64	25	3.2	6.7
04 May	6.94	210	2.9	93	0.23	18.60	0.97	6	8.1	129.9
04 May	6.67	180	8.1	69	0.20	8.40	1.00	2	16.9	43.3
30 May	6.07	145	6.0	75	0.11	5.54	0.76	6	12.9	253.1
30 May	6.09	160	5.2	47	0.23	9.10	1.21	5	14.1	156.5
31 May	5.88	250	2.2	63	0.52	1.82	0.97	14	3.2	11.7
01 Jun	6.04	190	2.0	14	0.065	1.54	1.00	2	3.4	16.7
15 Jun	6.72	230	3.2	33	0.18	1.40	0.62	8	9.7	116.6
16 Jun	6.6	290	0.6	96	0.10	1.54	1.42	12	3.3	13.3
20 Jun	6.31	300	0.6	120	0.035	5.30	1.16	3	6.5	23.3
Min.	5.88	145.00	0.6	14	0.04	1.40	0.62	2	3.20	6.70
Max.	6.94	300.00	8.1	120	0.52	18.60	1.42	25	16.90	253.10
Mean	6.42	215.00	3.56	67.1	0.18	6.17	0.98	8.3	8.13	77.11
Median	6.46	202.50	3.05	66.0	0.15	5.42	0.99	6.0	7.30	33.30
SD	0.38	52.17	2.43	31.29	0.14	5.37	0.25	7.10	5.11	83.41
CV	0.06	0.24	0.68	0.47	0.77	0.87	0.26	0.86	0.63	1.08

Explanations: *H* = rainfall depth, i_{max} = maximum rainfall intensity, *SD* = standard deviation; *CV* = coefficient of variation, other as in Tab. 1.
Source: own study.

Table 4. Pearson correlations for quality parameters of stormwater runoff from green roof; $p < 0.05$

Parameter	pH	*EC*	BOD_5	*COD*	NH_4-N	TKN	TP	TSS	*H*	i_{max}
pH		0.12	0.11	0.25	–0.26	**0.50**	–0.23	0.28	0.03	–0.12
EC			–0.81	**0.53**	–0.02	–0.33	**0.43**	0.13	–0.58	–0.61
BOD_5				–0.25	0.09	0.33	–0.40	–0.07	**0.79**	**0.44**
COD					–0.13	0.33	**0.41**	0.01	–0.03	–0.04
NH_4-N						0.04	–0.06	0.21	–0.01	–0.04
TKN							–0.05	–0.05	0.33	0.31
TP								–0.34	–0.07	–0.27
TSS									–0.54	–0.32
H										0.63

Explanations as in Tab. 3.
Source: own study.

Pearson correlations were observed between *COD* and *EC*, between TKN and pH, between TP and *EC*, and between TP and *COD* (Fig. 2). A linear relationship between *COD* and TP in the runoff from a green roof was also observed by Liu *et al.* (2020). No clear correlation was observed between the quality of green roof runoff and precipitation characteristics. Only in the case of BOD_5, significant correlations were found with the rainfall parameters, both with H and i_{max}.

The indicator that should attract special attention in the analysis of the quality of green roof runoff is phosphorus. Its concentration is high compared to a traditional roof. The results clearly show that the green roof is a source of increased levels of phosphorus leaving the substrate. Although other studies also confirm that green roof substrates are a significant source of phosphorus in runoff, its concentration vary (Karczmarczyk *et al.*, 2018; Liu *et al.*, 2020; Rocha *et al.*, 2021). Seters van *et al.* (2009) observed significantly higher concentrations of TP in the runoff from a green roof compared to a conventional roof. According to Rocha *et al.* (2021), phosphorus leaching increases during the dry season. Studies results obtained by Mitchell *et al.* (2017) suggest that extensive green roofs are likely to act as environmentally significant sources of P for 10 or more years after installation.

The average values of basic quality parameters obtained in the 2016 studies for a green 4-year-old roof are compared with the results obtained for this roof 2 years earlier and with a traditional roof (Fig. 3). In the case of 4 indicators (BOD_5, *COD*, TKN, and TP), an increase in their concentration compared to the traditional roof can be clearly noticed. However, their concentration in the roof runoff 4 years after its construction was clearly lower than after 2 years. Only in the case of ammonium nitrogen the concentration was higher after prolonged use and lower than in the case of a traditional roof. In order to determine the exact influence of the roof age on the leaching of substrate components and the duration of the process, it would be necessary to extend the test period.

The green roof significantly limited the stormwater outflow to the sewage system. The runoff volume reduction was varied in the range of 62–91% (Tab. 5). The roof's ability to stormwater absorption depended not only on the amount of rainfall, but also on the characteristics of the phenomenon and the antecedent dry weather period. This is shown in Figures 4a (2017) and 4b (2020). Sometimes the outflow from the green roof took place after rainfall less than 5 mm. This occurred when relatively small precipitation was preceded by rainfall that exhausted the retention capacity of the green roof.

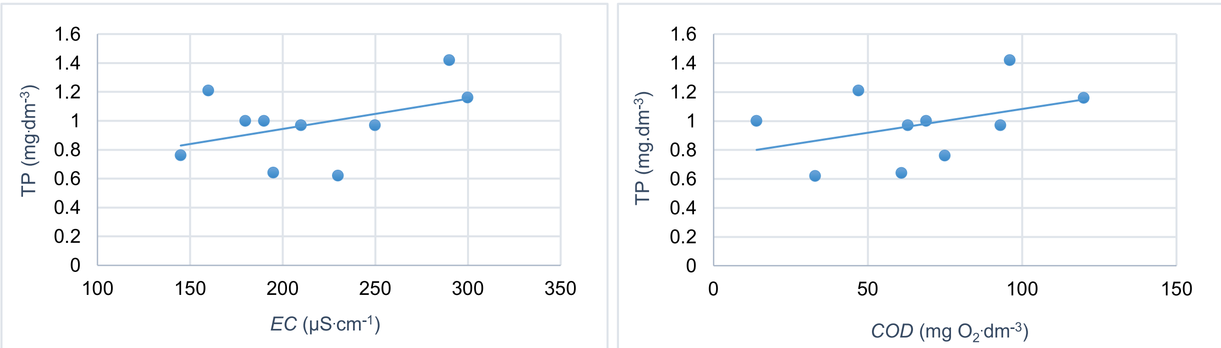

Fig. 2. Dependence of phosphorus concentration on electrical conductivity (*EC*) and chemical oxygen demand (*COD*) in the outflow from a green roof; source: own study

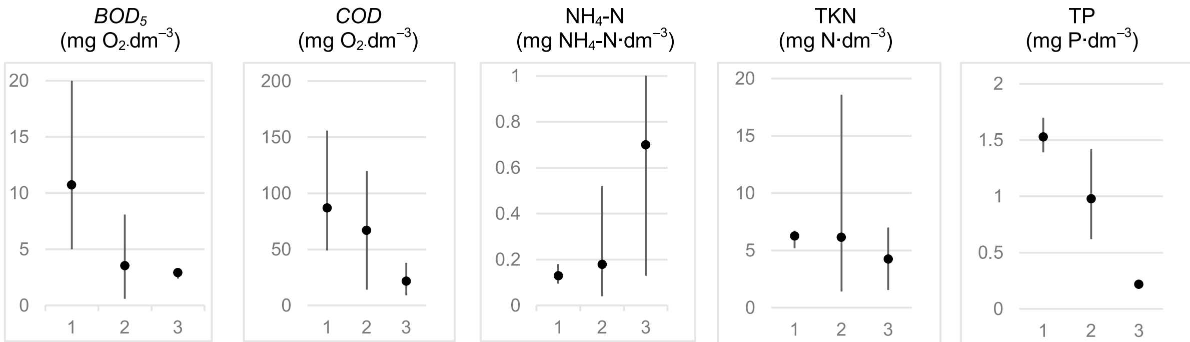

Fig. 3. Mean (min–max) value of stormwater runoff parameters: *1* = from green roof in 2014, *2* = from green roof in 2016, *3* = from traditional roof in 2016; BOD_5 = biological oxygen demand, *COD* = chemical oxygen demand, NH_4-N = ammonium nitrogen, TKN = total nitrogen Kjeldahl, TP = total phosphorus; source: own study

Table 5. Stormwater runoff from the green roof in comparison with a traditional roof in 2016–2020

Parameter	Value in				
	2016	**2017**	**2018**	**2019**	**2020**
Runoff from traditional roof (m^3)	340	249	320	414	386
Runoff from green roof (m^3)	85	24	62	157	129
Reduction (%)	75	91	81	62	67

Source: own study.

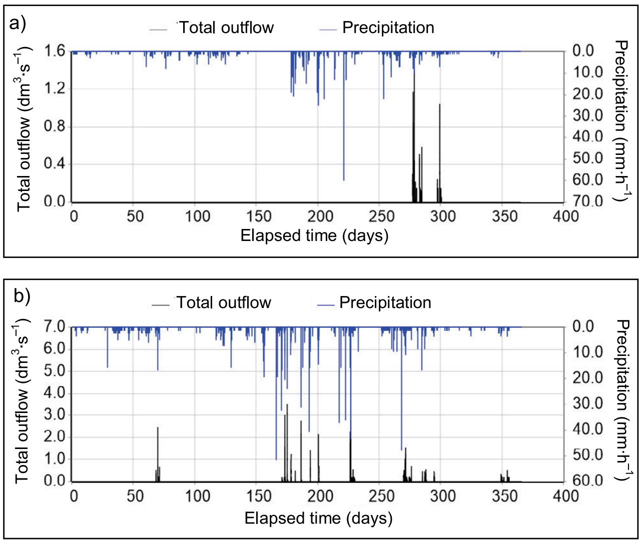

Fig. 4. Examples of green roof functioning during precipitation in: a) 2017, b) 2020; source: own study using SWMM

Although the stormwater quality indicators for the green roof were higher compared to the traditional roof, pollution loads were lower for most indicators due to a significant reduction of the runoff volume (Fig. 5). Only in the case of phosphorus, the load discharged from the green roof was slightly higher compared to the traditional roof of the same area. Similar results were obtained by Seters van *et al.* (2009): loads of most chemical variables in green roof runoff were lower than in the runoff from the conventional roof, except calcium, magnesium, and total phosphorus.

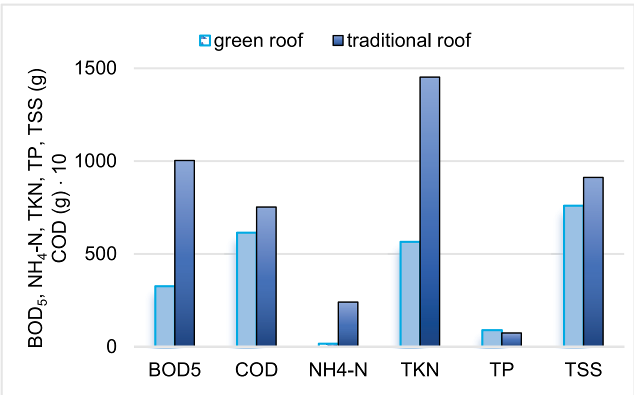

Fig. 5. Annual loads of pollutants discharged from green and traditional roof of the same area; TSS = total suspended solids, other as in Fig. 3; source: own study

CONCLUSIONS

The research has shown significant effectiveness of the green roof in limiting the outflow of stormwater to the sewage system (>60%). However, the reduction was different depending on the characteristics of precipitation. Stormwater runoff from the green roof was characterised by a higher concentration of pollutants, except for ammonium nitrogen, compared to the traditional roof. Values of indicators tested decreased with the age of the green roof. The load of discharged pollutants was lower in the case of the green roof than in the case of a traditional roof. The largest differences were observed for BOD_5, NH_4-N and TKN. Only the load of phosphorous was slightly higher. Hence, it can be concluded that widespread implementation of green roofs in cities probably will not increase pollution of water receivers. The component of stormwater runoff from green roofs that should be controlled is total phosphorus, the concentration of which is significantly higher than in the stormwater runoff from traditional roofs. However, it should be emphasized that the quality of runoff from green roofs depends on many factors, such as substrate, plants, climate, maintenance, and it changes with roof age. Therefore, it is necessary to continue research into this type of roofs, especially in existing buildings considering major differences in the outflow and limited operating experience.

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