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The influence of green roofs on runoff quality — 6 years of experience

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ABSTRACT

Green roofs have gained global acceptance as a technology that is beneficial for both the environment and the urban population. It is generally believed that green roofs also improve the quality of runoffs. The article presents the results of a 6-years study of water quality in runoffs from extensive green roofs of different constructions with respect to the quality of rainwater and runoff from a reference roof. The research results show that analyzed green roofs are capable of neutralizing runoffs and should not be also regarded as sources of ammonium nitrogen pollution in runoffs. Apart from the positive effects, these green roofs can also have a negative influence on the quality of runoffs. The high total concentrations of nitrite nitrogen, nitrate nitrogen, phosphates, and the content of organic substances that do not undergo biodegradation observed in the runoffs. Based on the results of this research it can be inferred that the influence of green roofs on the runoff quality will improve during the operation period, but not for all quality indicators. There is a need to focus more on the quality of green roof runoff. It should be controllable through better design, management, and maintenance of green roofs.

Keywords: Green roofs; Runoff quality; Substrate; FLL Green Roof Guidelines; Sustainable urban drainage system (SUDS); Rainwater management

1. Introduction

Rainwater drainage is an inseparable operation element of urban areas. Supporting the operation of sewage systems by introducing associated infrastructure solutions securing local retention is a current trend in rainwater management in urban areas. As far as these solutions are concerned, natural methods or solutions based on natural methods are preferred. Green roofs are such systems. They are known to improve the volume and dynamics of runoffs, improve heat, and energy balance of buildings, improve microclimate, air quality, and landscape values of a given area [1,2]. In past research, the green roof runoff quality was considered a fringe issue. It probably results from the common belief that green roofs, owing to their construction and presence of plants, decrease the amount of pollution getting onto their surface in dry or wet atmospheric depositions, which reduces the amount of pollution in runoffs too. Green roofs, however, can influence the runoff quality in different ways. They can reduce the runoff pollution by absorbing and filtering it out, they can also lead to leaching some of the impurities of the substrates, plants, or used fertilizers [3]. Factors influencing the runoff quality from green roofs include substrate types and types of other construction materials of a given green roof (a drainage layer, a downspout), types of maintenance works and fertilizers used, the dynamics of precipitation, a season, presence of local polluters, etc. [4]. The influence of so many factors and additionally the availability of a big number of design solutions for building green roofs make the issue of runoff quality very complex. In recent years, research into the green roof runoff quality has been conducted by a few authors. Most of the studies, however, were based on individual events rather than long-term samplings. According to Buffam et al. [5] and Mitchell et al. [6] assessments that aimed at checking if green roofs act as a source or sink for runoff pollutions should not be based on only a

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few measurements. The reason is that rainwater runoff pollution might be temporary and might not reflect the nature of the phenomenon. For these reasons long-term, systematic sampling is needed to fully evaluate pollutant leaching [3]. Moreover, in the literature, the majority of research into the runoff quality was conducted on the so-called "young" roofs (2–3-years of operation). The variability of some pollution parameters in time allows to assume that the assessment of green roof runoff quality, during the first year of operation, might not be representative for the assessment of runoff quality regarding stable green roofs. Conducting research on "mature" green roofs has an additional advantage as it allows to assess the influence of some construction elements on the runoff quality. The issue of runoff quality in urban areas is essential when it comes to the assessment of potential hazard to the quality of surface and underground water and the operation of sewage systems or local retention solutions accepting green roofs runoffs [7,8].

The aim of the research was to identify the influence of green roofs of different constructions on the quality of rainwater drained off them and to define their role as sustainable drainage systems in the context of drained runoffs. The assessment was based on physico-chemical pollution indicators [phosphates, ammonium nitrogen, nitrite nitrogen, and nitrate nitrogen, sulfates, chlorides, chemical oxygen demand (COD) and (biochemical oxygen demand) BOD_5, pH, and electrical conductivity] measured during the 6-years roof monitoring period. Suggestions concerning the design and maintenance of green roofs, as well as management of runoffs drained off green roofs are also described in the article.

2. Materials and methods

2.1. Study site

The research was conducted on three prototype extensive green roof platforms constructed on a pilot-scale of 2.20 m × 1.00 m × 0.21 m (length/width/height), inclined at 4°. Additionally, one of the platforms, of the same dimensions, was used as a reference roof (without the structural arrangement of green roof and vegetation) (Fig. 1). This reference roof was utilized to identify the influence of green roofs on the change of rainwater runoff quality in reference to a roof of traditional construction. All platforms were located on the roof of one of the buildings on the Science and Education Centre (SEC) of Wroclaw University of Environmental and Life Sciences (south-western Poland). Individual extensive green roofs platforms of different constructions will be henceforth referred to as GR1, GR2, and GR3 (GR – green roof). The reference roof model (control roof) will be referred to as RR. The construction layout of layers used on the roofs is presented in Table 1. The properties of substrates used on the green roofs are presented in Table 2. No fertilizers were used on the sites in the monitoring period.

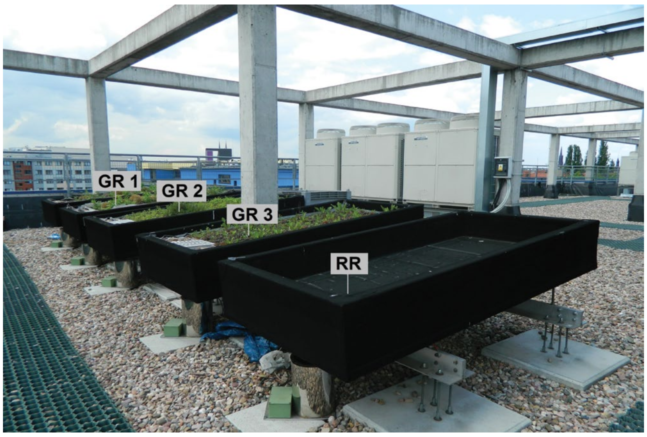

Fig. 1. Study sites located on the roof of SEC.

2.2. Rainwater and roof runoff sampling

The runoff hydrographs were recorded with the device of the original construction. In the same location, the rainfall characteristics were controlled with a OTT Parsivel® laser-based optical disdrometer produced by OTT Messtechnik GmbH & Co. KG, Kempten (Germany). The rainfall was also collected into a plastic container to allow quality analyses. The concentration of phosphates, ammonium nitrogen, nitrite nitrogen, and nitrate nitrogen, sulfates, chlorides, COD and BOD_5, pH, and electrical conductivity were measured for rainwater and runoff samples. The examination of physico-chemical indicators was conducted in the Faculty Laboratory for Environmental Research of the Wrocław University of Environmental and Life Sciences, by means of analytical methods used in Poland. Measurement standards are presented in Table 3. The results of analyses described in this article pertain to the period 2010–2016. During that period, 912 d with the daily rainfall ranging from 0.01 to 91.6 mm were recorded (Fig. 2). Samples for analyses of the quality variation of rainfall and runoffs, if possible, were collected once a month, but not according to any time intervals, due to the randomness of rainfall. Samples for quality analyses were collected after bigger rainfalls (usually rainfall depth of more than 10–15 mm per day). Only rainfall of at least such a depth guaranteed both volume size required to measure selected indicators and the possibility to collect samples on all study sites at the same time (on the same day). Rainfalls with depths lower than 10 mm were on 90% of measurement days retained on green roofs (no runoffs were generated). Rainfall of such a depth constituted over 85% of all recorded rainfall events (see Fig. 2). When it comes to the reference roof, the rate of days with rainfall and no runoffs was much lower (about 30%). Unfortunately, the lack of runoffs on at least one study site on a given day meant that comparison quality runoff between study sites was impossible. For these reasons, in this article quality analyses were based on samples from 52 rainfall that met the aforementioned criteria (208 roof runoff samples in total and 52 rainfall samples). Statistical calculations were made with STATISTICA 13.3 PL software. The normality of water quality data was checked using the Shapiro-Wilk test.

3. Results and discussion

3.1. Assessment of green roof runoff quality

Shapiro-Wilk tests for the normality of data set distribution were performed and they showed that the normality of

Table 1
The profiles of test sites

Roof types and their reference names	Layer arrangement
RR Reference roof Construction year: 2008	Waterproof membrane: Waterproof membrane EPDM Resitrix SKW with plant preventing properties Thermal insulation layer: XPS extruded polystyrene
GR1 Extensive green roof based on "Nature Roof" solution Construction year: 2010	Vegetation: Sedum acre Yellow Queen, Festuca (Teddybear) Growing medium layer: S1 substrate (10 cm thick) Filter layer: 105 type geotextile fabric Drainage layer: FKD 40 drainage board Proofing layer: RMS 300 protection fleece Waterproof and heat insulation layer: see RR site
GR2 Extensive green roof based on gravel drainage—ready-made solution. Construction year: 2008	Vegetation: Sedum acre Yellow Queen Growing medium layer: S3 substrate (10 cm thick) Filter layer: 105 type geotextile fabric Drainage layer: Gravel drainage - grain diameter of 2–5 cm Proofing layer: RMS 500 protection fleece Waterproof and heat insulation layer: see RR site
GR3 Extensive green roof with internal drainage in substrate. Construction year: 2008	Vegetation: Sempervivum Otello Growing medium layer: S2 drainage substrate (10 cm thick) Proofing layer: RMS 500 protection fleece Waterproof and heat insulation layer: see RR site

Table 2
Characteristics of substrates used in the study

	S1 substrate	S2 substrate	S3 substrate
Area of application	Vegetation layer for extensive green roofs	Drainage material for intensive and extensive roofs	Vegetation-drainage layer for extensive green roofs
Main components	Lava, pumice, green waste compost	Expanded shale (grain size 2–10 mm)	Expanded shale, expanded clay, lava, pumice, crushed brick, Porlith, and green waste compost
Total pore volume	60%–70% volume	n.a.	60%–70% volume
Organic substance	3%–8%	–	1%–3%
pH	6.5–8.5	8.3	6.5–8.5
Water permeability	≤0.6 mm/min	>450 mm/min	≤60 mm/min
Salt content	≤3.5 g/L	≤1.35 g/L	≤3.5 g/L

n.a. – not available

Table 3
Methodology of research into the runoff and rainfall quality pollution indicators on the test sites

Quality indicator	General characteristics	Used methodology
pH	Potentiometric method	PN-90/C-04540.01
Electrical conductivity	Conductometric method	PN-EN 27888:1999
Ammonium nitrogen	Spectrophotometric method	PN-ISO 7150:2002
Nitrite nitrogen	Spectrophotometric method	PN-EN 26777:1999
Nitrate nitrogen	Spectrophotometric method	PN-82C-04576/08
Phosphates	Molybdenum method using tin chloride	PN-EN 1189-2000
BOD_5	Method with dilutions	ISO 5815-1:2003
COD	Cuvette method	PN-ISO 15705:2005
Chlorides	Titration method	PN-ISO 9297:1994
Sulfates	Gravimetric method	PN-ISO 9280:2002

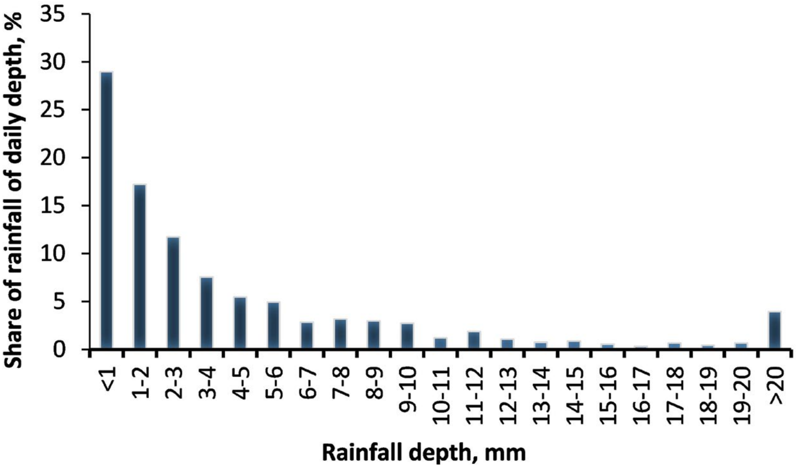

Fig. 2. Share of rainfall of daily depth in period 2010–2016.

distribution hypothesis was not applicable to any of the indicators. As far as data sets with non-standard distribution in sets' statistical description are concerned, medians, percentiles, and minimum and maximum values should be used. Such values for all study sites are presented in Fig. 3. Data in Table 4 describe, for each of the study sites, the percentage of total analyses made for each of the water quality indicators with values higher compared to values calculated in the rainfall on the sampling day.

Based on the research results, one can conclude that there was an increase in the pH value in green roof runoffs compared to the pH of the rainfall and the reference roof runoff. This tendency was observed on most of the sampling days. Rainfall samples collected on the research site had a pH value of 5.3–8.2 (median 6.9 pH). Runoffs from the green roofs had pH values of 5.6–9.0 (with the following medians: GR1 = 7.2, GR2 = 7.4, GR3 = 7.5). Reference roof runoffs (RR) had pH values of 5.0–7.9 (median 6.8). A detailed analysis of the results was performed. It demonstrated that on 74% – 79% of days, pH of the green roof runoffs and on 45% of days pH of the reference roof runoffs were higher than the values registered in the rainfall (Table 4). Rainfalls with pH lower than 5.6 are referred to as acid rains [9]. In the monitoring period, only one of the tested samples of rainfall and runoffs from the green roofs was acid in its nature. When it comes to the reference roof, there were four samples with such a low pH value. Rainfall pH values higher than 5.6 indicated that the air contained substances alkalizing the environment which could have an impact on the pH values of runoffs and rainfall. The presence of ammonia and dust that have chemisorption or sorption binding properties with sulfur monoxides and nitric oxides is considered a factor contributing to the increase of pH. The ability of green roofs to neutralize runoffs has been confirmed by other authors [10,11]. Undoubtedly the influence of green roofs on the increase of pH values of rainfalls is an advantage. It has a positive impact on the condition of drainage pipes and receiving bodies of water in case the runoffs are led directly to them.

The analysis of the electrical conductivity results showed that this pollution indicator, on almost all sampling days, acquired higher values for green roof runoffs than for the reference roof or rainfall. The values of electrical conductivity for rainfall fell within the limits of 13–724 µS/cm (median 75 µS/cm) and 81–2,478 µS/cm for green roof runoffs. The highest conductivity values were obtained in runoffs for GR1 (the roof of the shortest operation period). These values fell in the limit of 98–2,478 µS/cm (median 339 µS/cm). When it comes to roofs GR2 and GR3, the values of electrical conductivity registered in the runoffs were two to five times lower on the same sampling days (81 – 479 µS/cm, median 226 µS/cm for GR2 and 178 µS/cm for GR3). Electrical conductivity of the reference roof runoffs amounted to 17 – 427 µS/cm (median 71 µS/cm). During the 6-years research period, electrical conductivity in roof runoffs was higher than that registered for rainfall for the reference roof (33% of all cases), GR1 (96%), and both GR2 and GR3 (94%) (Table 4). The conducted research confirmed what had been stated in published references dealing with the topic. Specialized literature mentions that during rainwater filtration through the substrate layer of green roofs, electrical conductivity increases [12]. When analyzing rainfall and runoff samples one should not eliminate another factor that could have an influence on electrical conductivity—that is precipitation quality. This influence is noticeable especially in winter and snowmelt periods when along with wet depositions some salts from aerosols purged from the atmosphere could contaminate the samples. During precipitation, the so-called wet deposition covers the surface of substrates and vegetation layers. During antecedent dry weather periods most of the dry depositions reach substrates where it takes part in the decomposition of detritus, undergoes sorption processes or migrates as dissolved substances or suspensions with rainwater soaking off to the construction layout.

In the runoff quality monitoring period it was noticed that conductivity values of green roof runoff samples were high at the beginning of their operation period. Electrical conductivity decreased during the exploitation period. Electrical conductivity values of runoffs for roofs GR2 and GR3, where the measurement of the quality of runoffs was started after 2-years of operation, were several times smaller

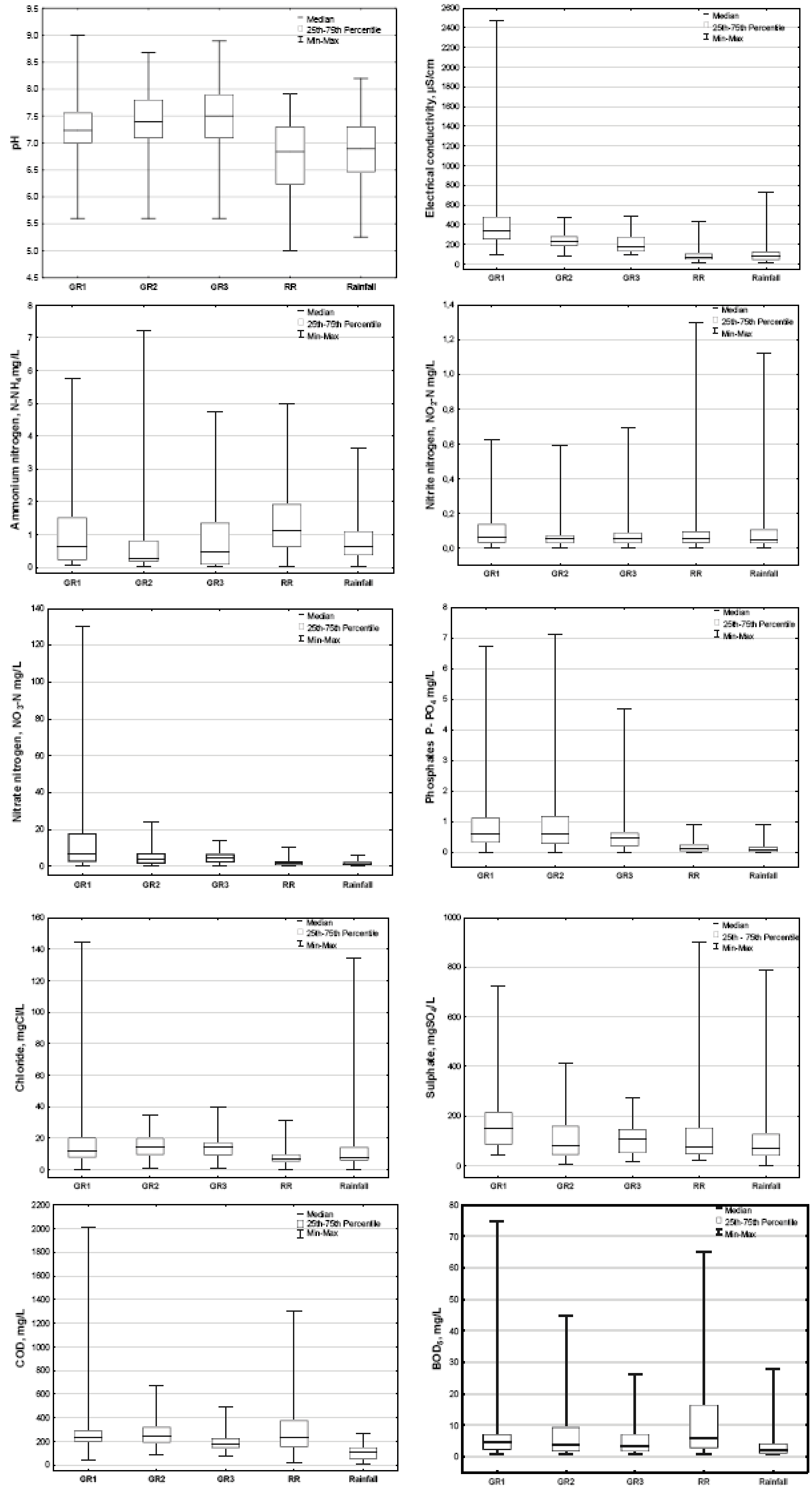

Fig. 3. Box-plot graphs illustrating statistical parameters for pollution indicators concentration measured in roof runoffs and rainfall.

than those of the "younger" roof GR1 where measurements started immediately after the construction (Fig. 4). Based on the results of this research it can be inferred that the influence of green roofs on the runoff quality (including this pollution parameter) will improve during the operation period provided the green roofs operate in similar conditions (city center, no additional fertilizers).

Pollution cumulating on roof surfaces might contribute to the increase of concentration of other impurities drained along with runoffs [13]. The concentration of ammonium nitrogen in rainfall in Poland in the period 2010–2016 (according to data delivered by State Environmental Monitoring) fell in the limit of 0.01–4.51 mg N/L. The concentration in rainfall on the study site located on the SEC of Wroclaw University of Environmental and Life Sciences amounted to 0.03–3.64 mg N/L. One can conclude that the observed range of ammonium nitrogen concentration in own rainfall samples did not deviate significantly from values registered for the same indicator on the territory of Poland in the same period of time. The increased concentration of ammonium nitrogen in the reference roof runoffs, compared to concentrations in rainfall, was observed in 73% of all samples (Table 4). The percentage of such observations for roofs GR1 and GR3 was similar, 51% and 43%, respectively. The smallest increase in ammonium nitrogen concentration compared to the same indicator in rainfall was registered on roof GR2 (29% of cases). The increase of the concentration in the reference roof runoff can be attributed to the deposition of dust containing ammonium salts and any of the following: nitrites, nitrates, chlorates, and sulfates. Pollution cumulated on the roof surface as a result of dry deposition is rinsed off during rainfalls. In the case of green roofs, the mechanism is more complex. The shifts of ammonium nitrogen concentration might be the effects of biochemical transformations undergone by substrates and the binding of an ammonium ion by plants. In the described example green roofs should not be regarded as sources of ammonium nitrogen pollution in runoffs.

Much higher values were observed in rainfalls on test sites compared to values delivered by national monitoring for the sum of nitrite nitrogen and nitrate nitrogen. The range of variation of this indicator in rainfall, calculated on the basis of own research, fell into the limit of 0.04–8.31 mg N/L, whereas the values at research stations performing national monitoring in 2010–2016 amounted to 0.01–4.23 mg N/L. High total values of nitrite nitrogen and nitrate nitrogen in rainfalls on the study site in Wrocław are connected with the fact that the air was polluted with nitrogen oxides produced by the transportation system. The study site is located in the city center of Wrocław, near a national road with huge vehicle traffic. Nitrogen oxides are emitted through exhaust fumes. The exhaust fumes, when in contact with water vapor and influenced by photochemical reactions, convert to nitrites. Huge concentrations of nitrite nitrogen observed periodically in reference roof runoffs and rainfall confirm this conclusion (Fig. 3). According to specialized literature, nitrogen compounds identified in runoffs might also originate from fertilizers [14]. Despite the fact that fertilizers were not used during the operation period of the green roofs, a natural compost was added to both GR1 and GR2 green roofs by the manufacturer. The compost might have been gradually rinsed off the layers. Own research results showed that the highest concentrations of nitrate nitrogen were registered for roof GR1, which had the shortest operation period (the monitoring began immediately after the roof was built). The concentrations ranged from 0.48 to 130 N–NO_3 mg/L (median 7 N–NO_3 mg/L; Fig. 3). Much smaller values were observed for roof GR2. In spite of the fact that the substrate contained a fertilizer, after 2-years of its operation, such huge concentrations of nitrates in runoffs were not identified (from 0.12 to 24 N–NO_3 mg/L, median 4.0 N–NO_3 mg/L). These numbers were close to the values of the same parameter of GR3 (0.16–14.0 N–NO_3 mg/L, median 4.69 N–NO_3 mg/L), which contained no fertilizers in the substrate. A bit lower values were registered in the reference roof runoffs (0.2–10.0 N–NO_3 mg/L, median 1.4 N–NO_3 mg/L). The results of this research allow inferring that occurrences of increased nitrate concentration in the green roof runoffs, when compared to the quality of reference roof runoffs and rainfalls, results not only from the roof age but also from the composition of substrates or wet/

Table 4
Characteristics of result sets of the analyzed runoff quality indicators

Quality indicator	Percentage of results where values for a given runoff quality indicator were higher than values calculated for rainfall, %			
	GR1 (*N* = 52)	GR2 (*N* = 52)	GR3 (*N* = 52)	RR (*N* = 52)
pH	79	79	74	45
Electrical conductivity	96	94	94	33
Ammonium nitrogen	51	29	43	73
Nitrite nitrogen	59	50	54	49
Nitrate nitrogen	88	80	82	43
Phosphates	86	82	82	50
BOD_5	60	53	53	71
COD	98	100	98	96
Chlorides	67	82	65	22
Sulfates	70	60	54	64

N, number of rainfall and runoff samples collected in 2010–2016.

dry deposition as well as many other factors. Bacterial activity and nitrification-related nitrogen transformations within the substrate originating from the bacterial activity can be one of the factors. These processes were beyond the scope of detailed analyses in this article.

So far these have been no legal regulations or even guidelines about the green roof runoff quality standards. Because of this fact, for the purpose of comparison, the results of the research can be analyzed against the treated sewage standards described in the decree of the Minister of Maritime Economy and Inland Navigation dated the 12th July 2019—on conditions that must be fulfilled when discharging sewage to waters or to the ground and on substances that have a particularly negative effect on the water environment (Journal of Laws 2019 item 1311). The decree defines the requirements for sewage discharged to surface waters. For sewage treatment plants of 10,000–100,000 P.E. (Population Equivalent), total nitrogen is defined as a sum of organic nitrogen, nitrate nitrogen, nitrite nitrogen, and ammonium nitrogen. The sum should not exceed the value of 15 mg N/L and for sewage treatment plants of more than 100,000 P.E., the value should not be higher than 10 mg N/L. The upper quantile value (75% of the results) of the sum of nitrate nitrogen, nitrite nitrogen, and ammonium nitrogen, calculated on the basis of own research, for green roof runoffs amounted to 24.2 mg N/L (GR1), 9.9 mg N/L (GR2), and 9.8 mg N/L (GR3). These concentration levels are close to the value required for the total nitrogen limit of treated wastewater from the agglomeration of more than 100,000 P.E. (GR2 and GR3). As far as GR1 roof is concerned (the shortest operation period), the upper quantile value for the sum of nitrate nitrogen, nitrite nitrogen, and ammonium nitrogen was above the limited defined for sewage treatment plants of more than 10,000 P.E. Taking into account the fact that rainwater contains organic nitrogen, which was beyond the scope of own research, one can conclude that rainwater drained from the green roofs located in areas with huge vehicle traffic can constitute a vital source of nitrogen compounds in waters discharged to drainage systems or receiving body of surface water.

Research into the concentration of biogens in roof runoffs conducted by other authors demonstrate diverse results, but the majority of them confirm that green roofs are sources of various forms of nitrogen in runoffs [10,15]. In this research, the percentage of nitrite nitrogen values higher than the limit, measured in green roof runoffs against the concentration values registered in rainfalls was 50%–59%. Higher concentration values of nitrate nitrogen contained in runoffs generated off GR1, GR2, and GR3 roofs, compared to rainfall were registered in 80%–88% of cases (Table 4). This share was smaller for the reference roof runoffs. In the total number of reference roof runoff analyses, in 49% of the results, there was an increased concentration of nitrite nitrogen and in 43% of the results there was an increased concentration of nitrate nitrogen—compared to the composition of rainwater. Most probably the location of the study sites (city center, near the communication route) caused the increased results. It contributed to air pollution by nitrogen oxides, which during antecedent dry weather periods as well as during rainfall, reached the roof surfaces and affected the quality of runoffs directly. The research of Wu et al. [16] showed that there is an

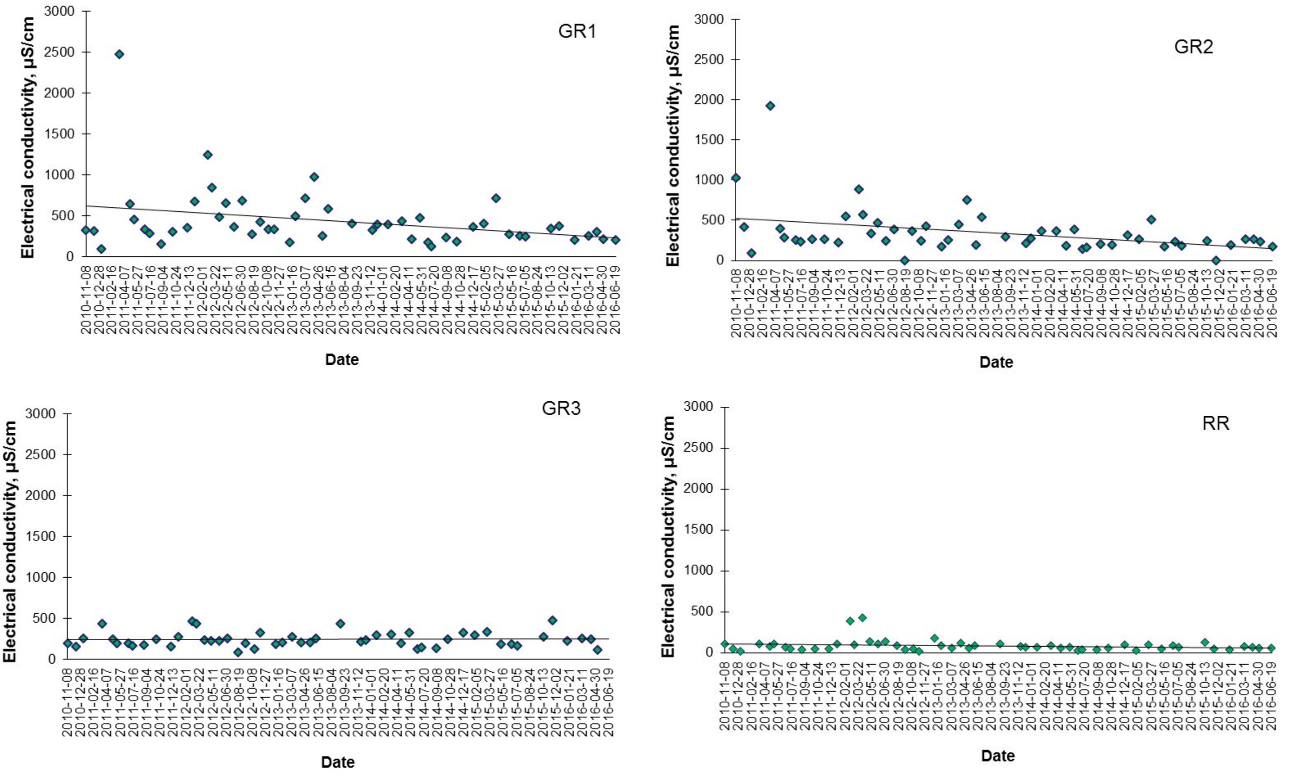

Fig. 4. Changes of electrical conductivity values for roof runoffs during their operation.

important impact of local pollution sources on runoff quality in urban areas. According to this research, even 70%–90% of the total load of nitrogen compounds contained in runoffs might originate from dry and wet atmospheric deposition. Additionally, the substrate thickness might affect the high concentration of nitrate nitrogen in green roof runoffs. The thickness of the substrate layer of the examined green roofs was only 10 cm. Such substrate thickness is characteristic for extensive green roofs, but when it comes to the capability of handling biochemical processes that could influence the transformation of nitrogen accumulated in substrates, this thickness might not suffice.

Increased concentration of phosphates, chlorides, and sulfates were observed in runoffs of the controlled extensive green roofs. The indicated concentrations of phosphates were 5 – 7 times higher in green roofs runoffs than in the reference roof runoffs and rainfall. The values fluctuated between 0.03 – 6.73 mg P–PO_4/L, 0.03 – 7.14 mg P–PO_4/L, 0.01 – 4.67 mg P–PO_4/L for GR1, GR2, and GR3, respectively (Fig. 3). These values were higher than those observed by Gregoire and Clausen [17] and Aitkenhead-Peterson et al. [18]. Phosphates concentrations in runoffs analyzed in this article, compared to those observed in rainfall, were higher on 50% of all sampling days for the reference roof and 82%–86% for the green roofs (Table 4). According to Moran et al. [19] and Rowe [20] rainwater drained off green roofs might have a higher concentration of phosphorus in leachates, especially when compost is used to create substrates. In the example, analyzed substrates of GR1 and GR2 roofs contained compost. The runoffs of these roofs contained the highest concentration of phosphates. The pH of precipitation can affect the phosphorus content in the runoff [3]. Phosphates have the strongest soil particle binding capacity at pH 6–7, and in this range, it is mostly adsorbed on soil particles. In higher pH values (such were noted in the analyzed runoffs), phosphates could easily transfer to runoffs. Köhler et al. [21] and Karczmarczyk et al. [22] proved that the reduction of phosphorus compounds can increase with time. The phenomenon of phosphates concentration decrease in runoffs was also noticed in the analyzed roofs (Fig. 5).

Chlorides and sulfates concentration values in runoffs and rainfall showed that increased concentration of these parameters appears more frequently in green roof runoffs, especially GR1 roof with the shortest operation period (Fig. 3). The highest concentration values of both chlorides and sulfates appeared in GR1 runoffs, especially at the beginning (up to 1-year) of its operation period. Periodically high concentration values of both chlorides and sulfates were observed in rainfall, and in the case of sulfates in both rainfall and reference roof runoffs. Variability ranges in rainfalls on the study site fell into the limit of 0.3–134.0 mg Cl/L for chlorides (median 7.2 mg Cl/L) and 1.4–786.0 mg SO_4/L for sulfates (median 69.1 mg SO_4/L). The concentration of chlorides for green roofs amounted to 0.1–144.6 mg Cl/L, whereas the concentration of sulfates 4.9–721.6 mg SO_4/L. Median values for both pollution parameters in green roof runoffs were two times higher compared to those indicated in the reference roof runoffs and rainfalls. When analyzing individual sampling days, one can infer that the concentration of chlorides in green roof runoffs was over the limit in 65% – 82%

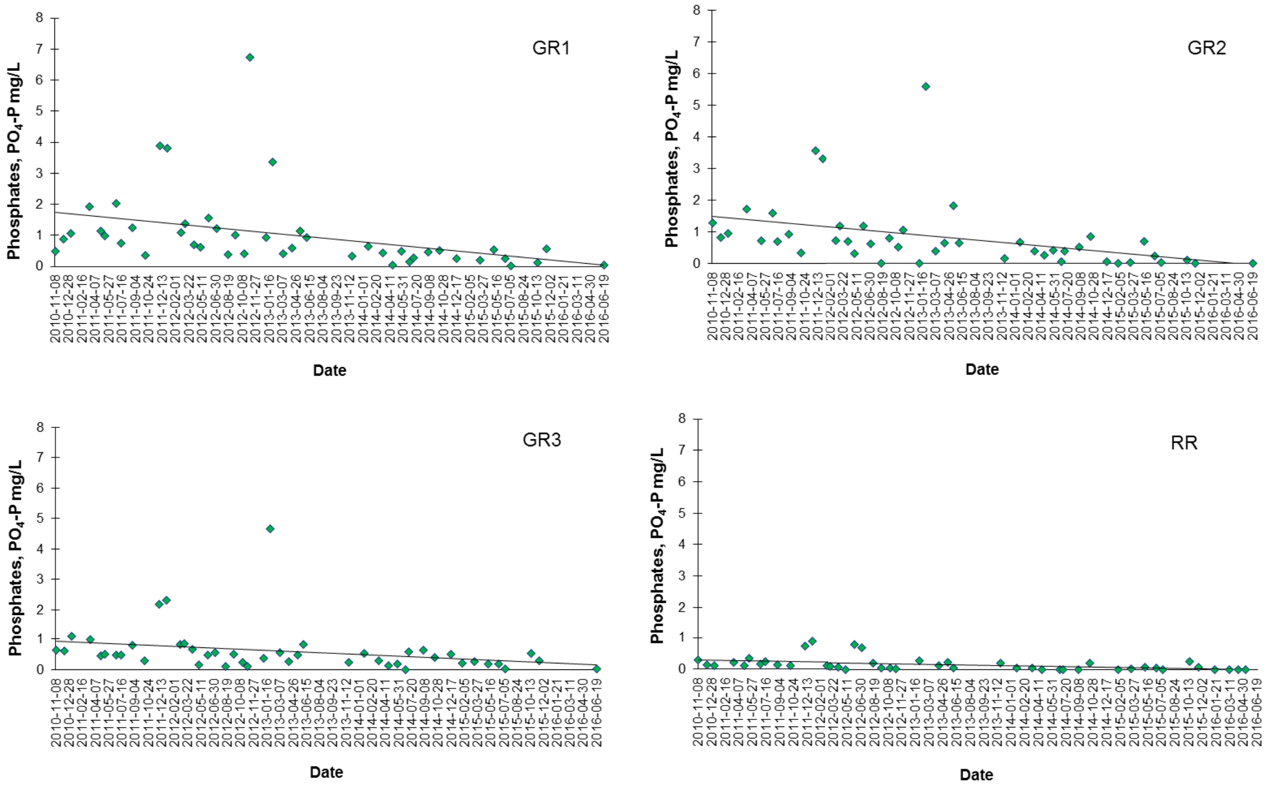

Fig. 5. Changes of phosphates concentration for roof runoffs during their operation.

of samples compared to the concentration in rainfall. When it comes to sulfates, such excess appeared in 54%–70% of all green roof runoffs over rainfall samples (Table 4). Based on this, it can be stated that salt leaching from substrates has an influence on the increase of chloride content in green roof runoffs and on electrical conductivity. Water evaporation from substrates leads to changes in pore water salinity. The salinity increase rate depends on the volume of evaporated water during antecedent dry weather periods [23]. In precipitation periods the contained salts are rinsed off provided that sparingly soluble mineral and mineral-organic compounds failed to precipitate. Increased chloride anion concentration registered periodically results from the fact that these substances migrate with precipitation. During winter and early spring, salinated dust, which are the consequence of using sodium chlorides and calcium chlorides to counteract black ice in areas for pedestrians and motor traffic in cities, in form of dry deposition in antecedent dry weather periods reach roof surfaces, and during precipitation, they are rinsed off to drainage. It is supported by the fact that on the same sampling days increased concentration of chlorides was observed in rainfall and runoffs of the reference roof (22% of samples), where runoff was initiated immediately after precipitation stopped (without earlier, at least partial accumulation of chlorides in substrates). The analysis of all measurement results of chlorides allows concluding that the registered concentration values, despite excessive values when compared to rainfall, are high. Taking into account good solubility of chlorides in water as well as their high prevalence in the environment and additional anthropogenic use of salt in winter, the level of a dozen mg Cl/L in runoffs should not be seen as alarming. Chloride concentration levels measured in the research for green roofs and rainfalls are much lower than those registered by other authors in runoffs from roads [24]. Still, the traditional roof runoffs analyzed by Vialle et al. [25] contained lower concentrations of chlorides than those measured in runoffs of the green roofs examined in this article.

The concentration of organic compounds referred to as COD fell into the limit of 9–264 mg O_2/L (median 107 mg O_2/L) in rainfall, 22–1,305 mg O_2/L (median 240 mg O_2/L) in reference roof runoffs and 44–2,015 mg O_2/L in green roof runoffs (median 234 mg O_2/L for GR1, 241.5 mg O_2/L for GR2 and 178.9 mg O_2/L for GR3; Fig. 3). BOD_5values were lower. In the reference roof runoffs, they amounted to 0.9–65 mg O_2/L (median 6.0 mg O_2/L) and 0.9–75.0 mg O_2/L (median around 3.3 – 4.5 mg O_2/L) for green roof runoffs (Fig. 3). Oxygen index indicators (BOD_5 and COD) in green roof runoffs showed that the biggest number of cases where the concentration in roof runoffs was over the limit when compared to rainfall was for the COD parameter (on 96% – 100% of sampling days). As far as $BOD_5$is concerned, a higher concentration in green roof runoffs appeared in 51%–60% of all collected samples. For both oxygen index parameters excesses have also been identified in reference roof runoffs compared to rainfall (96% of samples for COD and 71% of samples for BOD_5; Table 4). Maximum values of COD and BOD_5 that were identified in green roof runoffs were higher than those that are required according to the ordinance of the Minister of Maritime Economy and Inland Navigation dated the 12th July 2019 on conditions that must be fulfilled when discharging sewage to waters or to the ground and on substances that have a particularly negative effect on the water environment (Journal of Laws 2019 item 1311). According to the law, the highest allowed values of the pollution indicators for sewage treatment plants with P.E. lower than 2,000 should not exceed 40 mg O_2/L for BOD_5 and 150 mg O_2/L for COD. For sewage treatment plants with higher P.E. the required values are even lower, which is 25 or 15 mg O_2/L for BOD_5 and 125 mg O_2/L for COD. When it comes to COD, on 83% of sampling days the result values were over the limit described in the decree—150 mg O_2/L for reference roof runoffs and on 96%, 92%, and 74% sampling days in green roof runoffs for GR1, GR2, and GR3, respectively. Increased values of COD in green roof runoffs support the notion of substrates' influence and organic substances and fertilizers contained in them. The smallest number of excessive values was observed in GR3 runoffs (74%). The substrate composed in the layers set of this roof contained neither compost nor fertilizers that are sometimes added by manufacturers. A big share of sampling days when COD values of over 150 mg O_2/L were identified in reference roof runoffs proves that the composition of substrates is not the only source of pollution by organic substances. The reference roof during antecedent dry weather periods was a point where organic pollution accumulated, for example, bird droppings factors might have had an influence on the results gathered from runoffs. Dust pollution of anthropogenic origin (transportation) contributed to high COD values both for the reference roof and green roofs because of the location of the sites. Results of research made by other authors confirm this statement [26]. As for the BOD_5, on 9.4% of the sampling days reference roof runoffs contained more BOD_5 than the limit put forward in the decree (40 mg O_2/L). For the green roof runoff percentage of the results over the limit was lower, 3.8% for GR1, 1.9% for GR2, and 1.9% for GR3. For the lower limit described in the decree (15 mg O_2/L) the percentage values for BOD_5 in the runoffs amounted to 28.3% (reference roof), 11.3% (GR1 and GR2), and 7.5% (GR3). The obtained values indicate that dry deposition, which in antecedent dry weather periods gets to the roof surfaces, is the main source of organic pollution. During rainfalls, it is completely rinsed off the reference roof. In the case of green roofs, some of these substances undergo transformations within the construction layers of the roofs and some of them are rinsed off with runoffs, which allows to partially reduce the concentration of this pollution in green roof runoffs.

As far as a potential influence on receiving water bodies accepting green roof runoffs is concerned, it is vital to analyze the relation between COD/BOD_5 values. It makes it possible to identify the biodegradability of organic substances contained in waters. This interrelation increases with the increase in the percentage share of organic substances that do not undergo biochemical transformations. The COD/BOD_5 ratio in the examined runoff samples of the reference roof did not exceed 1.29–332.0 values. For green roofs, the same relation was more distorted. The number of compounds that are difficult to biodegrade was increasing. The quotient of these two indicators totaled 2.64–447. On 93% of sampling days, the relation of COD/BOD_5 in the reference roof runoffs was higher than 2.5. For GR1 roofs the same situation happened on 98% of days and for both GR2 and GR3 in all (100%) cases. It can be assumed that pollution found in the examined roof runoffs is difficult to biodegrade. The obtained COD/BOD_5 results imply that compounds difficult to biodegrade biochemically outnumber other compounds in the runoffs. Organic compounds might originate from rainwater or might be the products of elution from the substrates. Similar distribution of samples shares in green roof runoffs and rainfall, where the COD/BOD_5 ratio values exceeded 2.5, supports this fact.

3.2. Recommendations for further action

The research results showed that the issue of the quality of green roof runoffs should not be marginalized. With the existing need to apply this type of solutions to ensure sustainable management of rainwater in cities, attention should be paid not only to the assessment of their functioning in terms of the amount of retained water, but also the quality of discharged runoffs. Runoffs from the rooftops are transported through a sewer system or are discharged directly into a receiving water body. The consequence of the pollution of water to which runoffs are discharged may be a limitation of their use for municipal, recreational, and industrial purposes, as well as a threat to the condition of aquatic ecosystems. To keep urban water bodies in high environmental and aesthetic value, runoff quality from green roofs should be controllable through better design, system management, and maintenance. The current state of knowledge allows the use of some methods to minimize the occurrence of undesirable impurities in runoffs. One of the possible steps is to attempt to amend the composition of substrates used on green roofs. Vijayaraghavan and Joshi [27] added cocopeat as an organic fraction in vegetative roofs, Kwon et al. [28] studied the use of scoria as an adsorbent, Jang et al. [29] investigated the adsorption capability of a variety of mulches and Romera et al. [30] found the use of seaweeds as excellent biosorbents. Results of this research apply only to the effectiveness measurement of the reduction of the concentration of various metal ions in runoffs. Author's previously conducted research [31] proved that the concentration of metals in the examined runoffs was extremely low or beyond the quantification limits. In general, green roofs were a sink for heavy metals. Alsup et al. [32] and Gnecco et al. [33] formulated a similar conclusion. Based on this the author advises that more important is to undertake actions that aim at minimizing the presence of nitrogen and phosphorus compounds in the green roof runoffs, at reducing salinity and presence of substances that are difficult to biodegrade (referred to as COD/BOD_5 in this article). One of the measures to prevent excessive P leaching from green roofs to urban receivers can be the implementation of a specially-prepared low P-emission substrate [34]. The research of Clough et al. [35] and Kuoppamäki et al. [36] indicated that biochar used in the substrate layer of green roofs not only reduces the concentration of metal ions in runoffs but can also contribute to nutrient retention. Component selection will vary with respect to ease of sourcing component materials, cost of components, nutrient-retention capacity, and environmental sustainability [37]. Another idea to improve runoff quality is to select plants that have high phytoremediation ability. However, to date, no studies have been published regarding the phytoremediation property as an important factor in selecting plant species for vegetative roofs.

So far green roof designers have been focusing on substrate selection in terms of its physico-chemical properties suitable for vegetation and safe for the durability of construction of a building with a green roof. The reason for this is the substrate requirements mentioned in the German guidelines for green roofs FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.) [38], which are the foundation of green roof projects. According to the guidelines, substrates intended for green roofs should not contain more than 20% of organic substances and their thickness should not exceed 20 cm. Such conditions require fertilizers to be added to substrates during the production stage and during operation period in order to ensure proper vegetation. These practices do not usually have a positive influence on the quality of runoffs. The research of Teemusk and Mander [14] and Vijayaraghavan et al. [23] demonstrated that the quantity of nitrogen and phosphorus that is rinsed off green roofs depends on the nature of precipitation. Concentrations of most chemical constituents in green roof runoffs were higher in first-flush runoff samples than in the samples that followed. Taking these dependencies into account to minimize the leaching of nitrogen and phosphorus compounds from green roofs, it is recommended to limit irrigation shortly before rainfalls and during wet periods. Precise irrigation and synchronized nitrogen supplies to crops [39] can also lead to a decrease in the presence of nutrients in runoffs. Nevertheless, types of fertilizers used for green roofs to decrease the amount of some contents in runoff water must be taken into consideration. Controlled release fertilizers should be used instead of conventional fertilizers in green roof maintenance works.

Due to the increasing interest in constructing bioretention systems as solutions supporting dewatering of cities, another challenge in improving the runoff quality should be the development of quality standards for runoffs drained from the systems to local retention and infiltration. Green roofs are included in such systems. As long as water quality issues remain outside the design phase there is a large potential for green roofs to be contra-productive towards the improvement of urban runoff quality. The lack of standards regulating the quality of green roof runoffs forces some authors to refer, for the purpose of comparison, to norm values, for example, the norm on the quality of drinking water [23], the quality of surface waters or quality of sewage drained to receiving bodies [40]. All these comparative analyses allow only to estimate the size of the problem but do not oblige green roof designers or substrate manufacturers to follow the runoff quality results. For these reasons, all construction elements of vegetated roofs shall be tested for their influence on passing water quality before the full-scale installations take place. These recommendations should be reflected in the guidelines, based on which green roofs are designed and built in the whole world.

Another important challenge for local retention system designers, including green roofs, is a management method of the rainwater drained of the systems. In the countryside, it is possible to use green roof runoffs for the irrigation of plants, which thereby obtain the necessary nutrients. A combination of a green roof with a pond, acting as a rainwater retention reservoir, is a common solution in newly-constructed residential areas. However, shallow and small in volume, urban rainwater ponds are the most sensitive type of receiver and may respond dramatically even to small inputs of phosphorus, resulting in excessive algae and plant growth. Alternatively, another possibility is to treat green roof runoffs in constructed wetlands [41]. Residential areas, however, usually do not have enough space available for this kind of solution. For these reasons, bio-retention systems accepting roof runoffs are suggested as they need less space, which is rain gardens. Unfortunately, the research of Dietz and Clausen [42] showed that rain gardens reduce the peak flow rate and increase the lag time of runoffs, but they do not work well as bio-retention systems for treating runoffs. They reported that mass retention for nitrate nitrogen, total nitrogen, total Kjeldahl nitrogen, and organic nitrogen was <36%. The only nutrient that was retained well by the system was ammonium nitrogen at 84.6%. The mechanisms responsible for the decrease were denitrification in the soil and adsorption of ammonium nitrogen to soil particles. The retention of total phosphorus was 110.6%, which indicates that more phosphorus left the system than entered it. Davis et al. [43] share this point of view. They made research into rain garden runoffs under laboratory conditions and reported concentration reductions of more than 68% of the total Kjeldahl nitrogen and 87% of ammonia nitrogen. For nitrite and nitrate nitrogen reductions were generally low (24%). According to the authors, it was the effect of processes taking place inside the rain gardens and self-produced nitrite and nitrate nitrogen in the bio-retention system. The problem of managing runoffs with integrated bio-retention systems (e.g., green roofs + rain garden, green roof + infiltration trench) requires further research in order to be able to either confirm or reject their expedience.

4. Conclusions

The research conducted with three extensive green roofs located in the city center, near transport routes, showed that such constructions are capable of neutralizing runoffs and sustain ammonium nitrogen in the structure. Higher pH values and lower concentrations of ammonium nitrogen in green roof runoffs, when compared to reference roof runoffs and rainfall during the 6-years monitoring period, support this observation. Apart from the positive effects, the research results show that green roofs can also have a negative influence on the quality of runoffs. The value increase of pollution indicators, that is electrical conductivity and concentration of chlorides, sulfates, nitrate nitrogen, and phosphates in runoffs might have a negative impact on the environment. Particularly disadvantageous for runoff receivers are high total concentrations of nitrite nitrogen, nitrate nitrogen, phosphates, and the content of organic substances that do not undergo biodegradation. The more urban area becomes green this way, the bigger this influence will be. As far as single green roofs located in city centers are concerned, their influence on sewage systems or water receivers might remain unnoticeable. Looking prospectively, in case of larger investments (e.g., green roofs of an entire housing estate), roofs containing substrates that were not verified against runoff quality can bring several impurities to the sewage system and underground and surface water.

The most likely factors shaping the quality of roof runoffs are substrate properties or dry and wet atmospheric depositions. The research results allowed us to observe that whenever no additional fertilizer is used on a green roof, the negative impact of the substrate composition decreases the longer the operation period is (green roof age). A decrease of phosphates concentration and electrical conductivity of green roofs with longer operation periods (GR2 and GR3) compared to runoffs of a "younger" green roof (GR1) confirm the trend. Apart from these parameters, the declining trends in pollution concentration in the analyzed period were not identified. Most probably it results from the influence of other impurities, such as nitrites, nitrates, chlorides or sulfates and other factors, such as location, seasonal variability of pollution concentration in the air.

Despite the fact that the quality of runoffs got worse, green roofs should not be excluded from the rules of sustainable rainwater management in urban areas, because, as emphasized in numerous publications, they play an important role in improving the quality of the urbanizing environment and may be justified by a broad range of other benefits. Even when taking into account other benefits, the question of runoff quality should not be trivialized. Possible ways of improving the quality should be considered at the design stage of green constructions. There is an urgent need to pay more attention to the selection of substrate components, green roof maintenance methods, and runoff management.

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References

[1] L.F.M. Francis, M.B. Jensen, Benefits of green roofs: a systematic review of the evidence for three ecosystem services, Urban For. Urban Greening, 28 (2017) 167–176.

[2] E. Burszta-Adamiak, J. Stańczyk, J. Łomotowski, Hydrological performance of green roofs in the context of the meteorological factors during the 5-year monitoring period, Water Environ. J., 33 (2019) 144–154.

[3] Y. Li, R.W. Babcock, Green roofs against pollution and climate change. A review, Agron. Sustainable Dev., 34 (2014) 695–705.

[4] J. Czemiel Berndtsson, Green roof performance towards management of runoff water quantity and quality: a review, Ecol. Eng., 36 (2010) 351–360.

[5] I. Buffam, M.E. Mitchell, R.D. Durtsche, Environmental drivers of seasonal variation in green roof runoff water quality, Ecol. Eng., 91 (2016) 506–514.

[6] M.E. Mitchell, S.F. Matter, R.D. Durtsche, I. Buffam, Elevated phosphorus: dynamics during four years of green roof development, Urban Ecosyst., 20 (2017) 1121–1133.

[7] F.K.F. Geronimo, M.C. Maniquiz-Redillas, L.H. Kim, Fate and removal of nutrients in bioretention systems, Desal. Water Treat., 53 (2015) 3072–3079.

[8] N. Sultana, S. Akib, M.A. Ashraf, M.R.Z. Abidin, Quality assessment of harvested rainwater from green roofs under tropical climate, Desal. Water Treat., 57 (2016) 75–82.

[9] A.K. Singh, G.C. Mondal, S. Kumar, K.K. Singh, K.P. Komal, A. Sinha, Precipitation chemistry and occurrence of acid rain over Dhanbad, coal city of India, Environ. Monit. Assess., 125 (2007) 99–110.

[10] Q. Zhang, L. Miao, X. Wang, D. Liu, L. Zhu, B. Zhou, J. Suna, J. Liu, The capacity of greening roof to reduce stormwater runoff and pollution, Landscape Urban Plann., 144 (2015) 142–150.

[11] X. Wang, Y. Tian, X. Zhao, The influence of dual-substrate-layer extensive green roofs on rainwater runoff quantity and quality, Sci. Total Environ., 592 (2017) 465–476.

[12] M. Köhler, M. Schmidt, Study of Extensive Green Roofs in Berlin. Part III. Retention of Contaminants, 2003. Available at: http://www.roofmeadow.com/wp-content/uploads/Study-of-extensive-green-roof-in-Berlin_rev2.pdf

[13] M.B. de Macedo, C.A.F. do Lago, E.M. Mendiondo, Stormwater volume reduction and water quality improvement by bioretention: potentials and challenges for water security in a subtropical catchment, Sci. Total Environ., 647 (2019) 923–931.

[14] A. Teemusk, U. Mander, The influence of green roofs on runoff water quality: a case study from Estonia, Water Resour. Manage., 25 (2011) 3699–3713.

[15] J.C. Berndtsson, L. Bengtsson, K. Jinno, Runoff water quality from intensive and extensive vegetated roofs, Ecol. Eng., 35 (2009) 369–380.

[16] J.S. Wu, C.J. Allan, W.L. Saunders, J.B. Evett, Characterization and pollutant loading estimation for highway runoff, J. Environ. Eng. ASCE, 124 (1998) 584–592.

[17] B.G. Gregoire, J. Clausen, Effect of a modular extensive green roof on stormwater runoff and water quality, Ecol. Eng., 37 (2011) 963–969.

[18] J.A. Aitkenhead-Peterson, B.D. Dvorak, A. Voider, N.C. Stanley, Chemistry of growth medium and leachate from green roof systems in south-central Texas, Urban Ecosyst., 14 (2011) 17–33.

[19] A. Moran, B. Hunt, G. Jennings, A North Carolina Field Study to Evaluate Green Roof Runoff Quantity, Runoff Quality, and Plant Growth, World Water & Environmental Resources Congress, 2003, doi:10.1061/40685(2003)335.

[20] D.B. Rowe, Green roofs as a means of pollution abatement, Environ. Pollut., 159 (2011) 2100–2110.

[21] M. Köhler, M. Schmidt, F.W. Grimme, M. Laar, V.L. De Assuncao Paiva, S. Tavares, Green roofs in temperate climates and in the hot-humid tropics, Environ. Health, 13 (2002) 382–391.

[22] A. Karczmarczyk, A. Bus, A. Baryła, Phosphate leaching from green roof substrates—can green roofs pollute urban water bodies?, Water, 10 (2018) 199.

[23] K. Vijayaraghavan, U.M. Joshi, R. Balasubramanian, A field study to evaluate runoff quality from green roofs, Water Res., 46 (2012) 1337–1345.

[24] Ż. Polkowska, Quality of highway runoff water from the urban region, Ecol. Chem. Eng., 13 (2006) 305–322 (in Polish).

[25] C. Vialle, C. Sablayrolles, M. Lovera, M.-C. Huau, S. Jacob, M. Montrejaud-Vignoles, Water quality monitoring and hydraulic evaluation of a household roof runoff harvesting system in France, Water Resour. Manage., 26 (2012) 2233–2241.

[26] D.J. Bliss, R.D. Neufeld, R.J. Ries, Storm water runoff mitigation using a green roof, Environ. Eng. Sci., 26 (2009) 407–418.

[27] K. Vijayaraghavan, U. Joshi, Can green roof act as a sink for contaminants? A methodological study to evaluate runoff quality from green roofs, Environ. Pollut., 194 (2014) 121–129.

[28] J.S. Kwon, S.T. Yun, J.H. Lee, S.O. Kim, H.Y. Jo, Removal of divalent heavy metals (Cd, Cu, Pb, and Zn) and arsenic(III) from aqueous solutions using scoria: kinetics and equilibria of sorption, J. Hazard. Mater., 174 (2010) 307–313.

[29] A. Jang, Y. Seo, P.L. Bisho, The removal of heavy metals in urban runoff by sorption on mulch, Environ. Pollut., 133 (2005) 117–127.

[30] E. Romera, F. González, A. Ballester, M.L. Blázquez, J.A. Munoz, Biosorption with algae: a statistical review, Crit. Rev. Biotechnol., 26 (2006) 223–235.

[31] E. Burszta-Adamiak, Green Roof as an Element of Sustainable Urban Drainage Systems in Urban Areas, Monograph No. CLXXV, Publisher Wrocław University of Environmental and Life Sciences, Wroclaw, ISBN 978–83–7717–187–5, 2014.

[32] S. Alsup, S. Ebbs, L. Battaglia, W. Retzlaff, Green roof systems as sources or sinks influencing heavy metal concentrations in runoff, J. Environ. Eng.-ASCE, 139 (2013) 502–508.

[33] I. Gnecco, A. Palla, L.G. Lanza, P. La Barbera, The role of green roofs as a source/sink of pollutants in storm water outflows, Water Resour. Manage., 27 (2013) 4715–4730.

[34] A. Karczmarczyk, A. Baryła, P. Kożuchowski, Design and development of low P-emission substrate for the protection of urban water bodies collecting green roof runoff, Sustainability-Basel, 9 (2017) 1795.

[35] T. Clough, L. Condron, C. Kammann, C. Müller, A review of biochar and soil nitrogen dynamics, Agronomy-Basel, 3 (2013) 275–293.

[36] K. Kuoppamäki, M. Hagner, S. Lehvävirta, H. Setälä, Biochar amendment in the green roof substrate affects runoff quality and quantity, Ecol. Eng., 88 (2016) 1–9.

[37] T.S. Jennett, Y. Zheng, Component characterization and predictive modeling for green roof substrates optimized to adsorb P and improve runoff quality: a review, Environ. Pollut., 237 (2018) 988–999

[38] FLL, Green Roof Guidelines - Guidelines for the Planning, Construction and Maintenance of Green Roofs, Landscape Development and Landscaping Research Society e. V. Bonn, Germany, 2018.

[39] X.P. Chen, Z.L. Cui, P.M. Vitousek, K.G. Cassman, P.A. Matson, J.S. Bai, F.S. Zhang, Integrated soil–crop system management for food security, Proc. Natl. Acad. Sci. U.S.A., 108 (2011) 6399–6404.

[40] J.C. Berndtsson, T.T. Emilsson, L. Bengtsson, The influence of extensive vegetated roofs on runoff water quality, Sci. Total Environ., 355 (2006) 48–63.

[41] S.D. Lloyd, T.H.F. Wong, C.J. Chesterfield, Water Sensitive Urban Design - A Storm water Management Perspective. 02/10, Cooperative Research Centre for Catchment Hydrology, Melbourne, 2002.

[42] M.E. Dietz, J.C. Clausen, A field evaluation of rain garden flow and pollutant treatment, Water Air Soil Pollut., 167 (2005) 123–138.

[43] A.P. Davis, M. Shokouhian, H. Sharma, C. Minami, Laboratory study of biological retention for urban stormwater management, Water Environ. Res., 73 (2001) 5–14.