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Phosphorus leaching from substrates commonly used in rain gardens

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Abstract. Rain gardens are not yet a very popular solution in Poland but their number in cities is steadily growing. They are a measure of adaptation of cities to climate change. Rain gardens can be effective in rainwater retention and delaying runoff or groundwater recharge via infiltration. Among the benefits, also rainwater purification function is often suggested. The aim of the study was (1) to analyze potential phosphorus leaching from construction materials sampled from two rain gardens, and (2) to assess the quality of effluent from multi-layered rain garden in container. Results showed that materials commonly used in filling up rain gardens (sand and gravel) can be a significant source of phosphorus in filtered rainwater. Concentration of phosphorus in both, roof runoff and effluent from multi-layerded rain garden, show different patterns in different series. These preliminary studies show the need of continuous monitoring of existing rain gardens, as well as responsible selection of filter materials for newly built ones.

1 Introduction

Rain gardens, also known as bioretention cells, are green infrastructure solution designed to mitigate problems associated with urban stormwater [1]. Clasical rain garden is a small depression constructed in residential lawn to temporarily hold and soak rainwater coming from a house roof, driveway or other open area [2]. In Poland, rain gardens are not yet very common. For example in Warsaw, there are over a dozen of them [3]. Most of rain gardens in Warsaw are shallow excavations filled with multi-layered substrate (Fig. 1). They are working as an infiltration devices. Other popular construction is a rain garden in container. In this case rainwater is not infiltrated, instead it is discharged into the city stormwater drainage system. Container rain gardens can be a multi-layered or single-layered constructions (Fig. 2-3). Most of Warsaw rain gardens are located close to educational institutions (schools and kindergardens) and receiving rain water from the roofs of buildings.

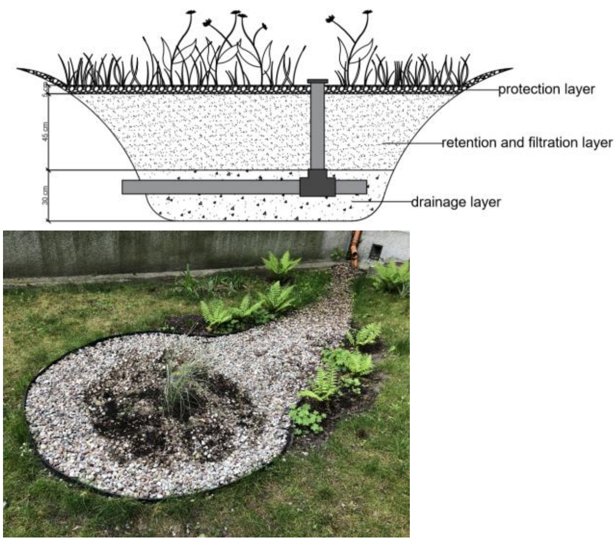

Fig. 1. Multi-layered rain garden located in soil (with infiltration).

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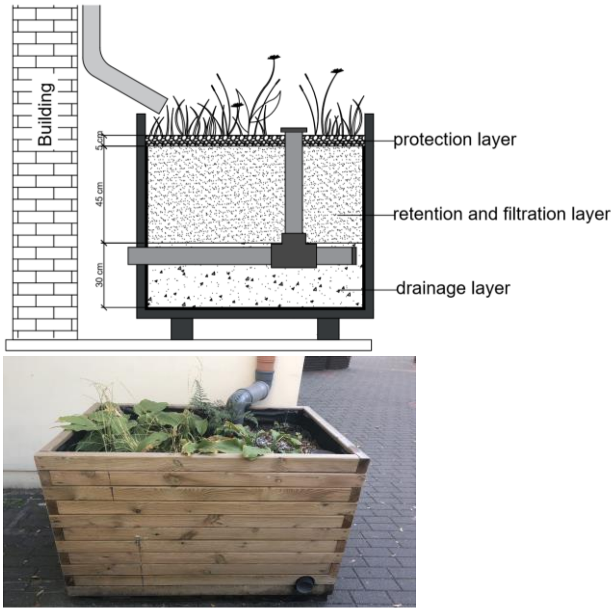

Fig. 2. Multi-layered rain garden in container.

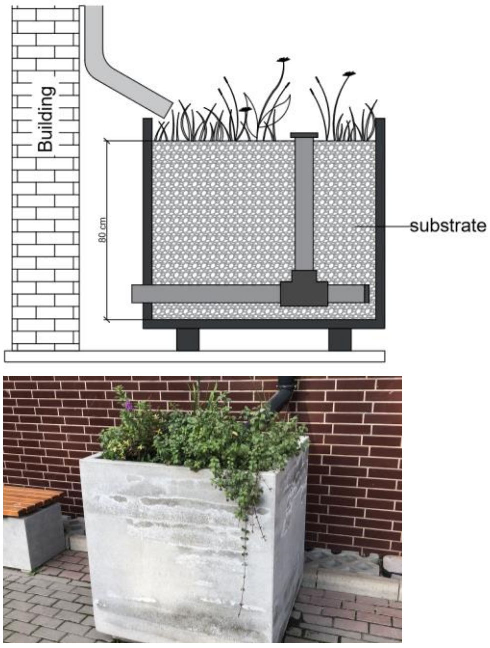

Fig. 3. Single-layered rain garden in container.

Materials commonly used in different layers of rain gardens are set in table 1. In multi-layered rain gardens fertile soil mixed with washed coarse sand supports vegatation and is responsible for water retention. It is usually undelined with drainage layer made of gravel or other coarse material (table 1). In single-layered rain gardens mineral-organic substrate supports vegetation, retains and filter rainwater. In both systems washed gravel or flat stones can be used as a decoration and protection of lower layers against erosion. Rain gardens, similary to green roofs, filter rainwater causing its purification or pollution. Thus materials used in their construction should be careffully tested before filling up the system [4]. The aim of the study was (1) to analyze potential phosphorus leaching from construction materials sampled from two rain gardens, and (2) to assess the quality of effluent from rain garden in container.

Table 1. List of materials used in construction layers of rain gardens.

Layer functions	Layer thickness	Multi-layered rain gardens	Single-layered rain gardens
Decorative & Protection against erosion	3-6 cm	washed gravel or flat stones	washed gravel or flat stones*
Support vegetation & Retention	40-50 cm	fertile soil mixed with washed coarse sand in a 1:3 ratio	mineral-organic substrate
Filtration*	5-10 cm	sand	
Drainage	10-30 cm	washed gravel, volcanic tuff, zeolite, granite grits, dolomite, limestone, crushed brick, opoka, chalcedonite	

* this layer occurs only in some constructions
Sources of information: [5-6]

2 Materials and methods

2.1 Potential phosphorus leaching from rain garden filtration materials

Filtration materials were sampled from two rain gardens. Mineral-organic substrate was sampled from single-layered rain garden in container (Fig. 3). Sand and gravel were sampled from infiltration rain garden located in soil (Fig. 1). All materials were tested for P content. Extracts were prepared according to [7]. All tests were carried out in triplicate. Concentration of phosphorus was analyzed on FiaStar analyzer by ammonium molybdate method in the range of 0.005-1.0 or 0.1-5.0 mg PO_4-P/L. Obtained results were recalculated to unit loads in milligram per kilogram and compared with the limit value of 5 mg/kg [7].

2.2 Quality of roof runoff and effluent from rain garden in container

Phosphorus concentration in roof runoff and effluent was analyzed in samples collected manually from multi-layered rain garden in container (Fig. 2). The rain garden is made in a wooden container with an area of 1 m^2 and collects runoff from the roof of the school building. The container is lined with foil, and the functional layers are made of washed river gravel with a fraction of 8-16 mm, washed sand and fertile soil (Table 1).

Samples of roof runoff and effluent from rain garden were collected during three rainfalls on May 16th, November 4th and November 10th. Each sampling started and ended with collection of roof runoff. Samples of effluent were collected every ten minutes. Volume of each sample was 500 mL. Concentration of phosphorus was analyzed on FiaStar analyzer by ammonium molybdate method in the range of 0.005-1.0 or 0.1-5.0 mg PO_4-P/L.

Data obtained in both experiments were evaluated using analysis of variance with the Statgraphic software at the significance level of 0.05.

3 Results and discussion

3.1 Potential phosphorus leaching from rain garden filtration materials

Phosphorus content measured in hydrochloric acid extracts recalculated to unit loads in milligram per kilogram was the highest in case of fertile soil (Fig. 4). In case of tested mineral materials, coarse sand had higher P content than gravel. Mineral substrate sampled from single-layerd rain garden in container is characterised by a significantly lower P content (at the 95,0% confidence level) as it was made base on limestone (intense bubbling has been observed in reaction with hydrochloric acid).

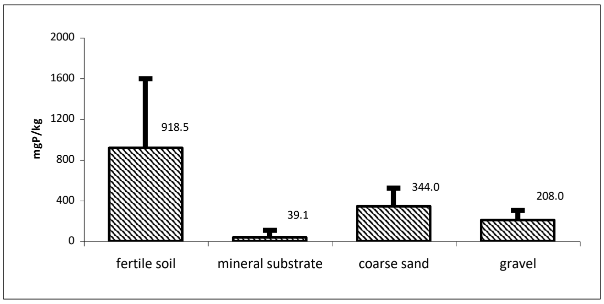

Fig. 4. Phosphorus content in tested rain garden components.

Sand, gravel and limestone are also popular mineral compounds of green roof substrates. Sands and gravel are marked on the list of the risky green roof substrates components as materials with high or very high risk of application connected with phosphorus release and potential eutrophication of urban receivers. Limestone was characterised as a material with low risk of application [4].
Base on construction projects of analyzed rain gardens it was possible to calculate the mass of materials used for filling up functional layers. Using results from Fig. 4 and bulk density of tested materials total potential leaching of phosphorus was estimated (Table 2). Rain garden in soil has the volume more than four times larger than the garden in container but its phosphorus release potential is almost twenty times higher. This is mostly due to sand and gravel used for filling up the protection and retention layer. In case of this garden it was not possible to sample drainage material, but application of P reactive drainage would limit P release [8-10].

Table 2. Potential phosphorus leaching from analyzed rain gardens.

Material	Bulk density [kg m^{-3}]	Volume [m^3]	Potential leaching [g]
Rain garden in soil (with infiltration)			
Fertile soil	870	0.16	127.8
Sand	1620	0.80	446.1
Gravel	1600	1.20	398.2
Total		2.16	972.1
Single-layered rain garden in container			
Mineral substrate	1160	0.50	22.6
Organic substrate	870	0.03	25.4
Total		0.53	48.0

3.2 Quality of roof runoff and effluent from multi-layered rain garden in container

Concentration of phosphorus (PO_4-P) in samples of roof runoff and effluent from multi-layered rain garden (Fig. 2, Table 2) collected during three rainfalls in May and November 2019 are presented on Figures 5-7. Roof runoff was collected at the beginning (roof runoff 1) and at the end (roof runoff 2) of each series. Samples of effluent from rain garden were collected every ten minutes, first sample just after “roof runoff 1” and the last one just before “roof runoff 2”. Unfortunatelly, sampling series do not cover all rainfall. First serie in May was started in the middle of rain event. Second serie started about 25 minutes after the begining of the rainfall but was continued to the end of the roof runoff. Third serie started with the start of the rainfall but was not continued to the end of the rainfall.

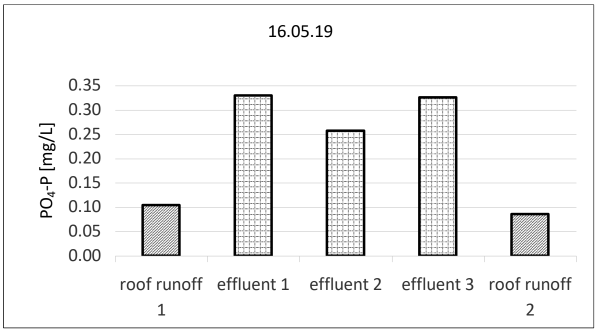

Fig. 5. Phosphorus concentration in roof runoff and effluents from multi-layered rain garden on 16th of May 2019.

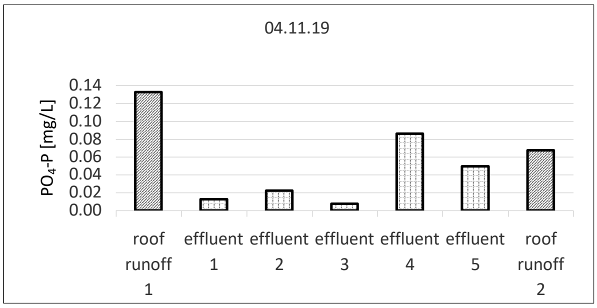

Fig. 6. Phosphorus concentration in roof runoff and effluents from multi-layered rain garden on 4th of November 2019.

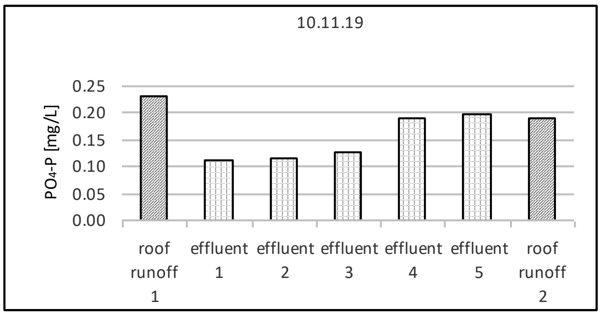

Fig. 7. Phosphorus concentration in roof runoff and effluents from multi-layered rain garden on 10th of November 2019.

Concentration of phosphorus in both, roof runoff and effluent from multi-layered rain garden, show different patterns in different series. In May, PO$_4$-P concentrations of effluent were higher than roof runoff, showing leaching of phosphorus from the rain garden. In November however, all effluents concentration were lower than in first roof runoff. The concentration distribution of PO$_4$-P in five consecutive samples was also different in series sampled in November, with no visible trend in second serie and with increasing concentration values in third serie.

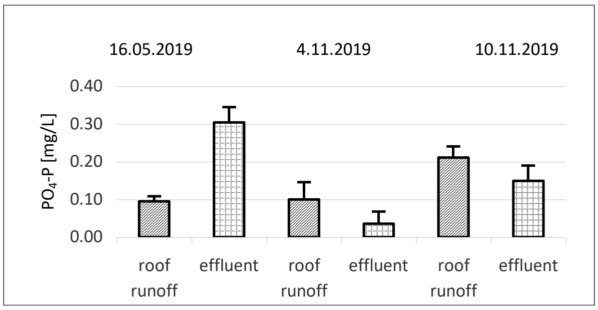

Fig. 8. Mean PO$_4$-P contrations in roof runoff and effluents from multi-layered rain garden in three sampling series.

In analysed rainfalls, differences between mean PO$_4$-P concentrations in roof runoff and effluents were statistically significant (at the 95,0% confidence level) only in first serie (Fig. 8). Analyzed multi-layered rain garden can be both a source and a filter for phosphorus. Some studies reported that phosphorus concentration in rain garden effluent decreasing over time. Dietz and Clausen [11] observed rain garden effluent for 16 months. During this period concentration of TP was gradually decreasing, but even at the end of this period it was still higher than TP concentration of influent (roof runoff). Retention for TP was "-110.6%", indicating that more phosphorus left the system than entered. The review made by Phong and Ramirez-Avila [12] reports that average TP removal is highly variable, ranging from "-398%" to 99% removal. From 9 analysed studies 4 show that phosphorus is released from rain garden. Other studies report that rain gardens retain phosphorus. Davis et al. [13] found removal of 81% for TP. Brown et al. [14] monitored two sets of loamy-sand-filled bioretention cells of two media depths (0.6 m and 0.9 m) with low P-Index. Estimated annual pollutant load reduction for total phosphorus was 10% for the 0.6-m media cells and 44% for the 0.9-m media cells, respectively. Hsieh et al. [15] also reported total phosphorus removal of 85% (on mass basis) for high conductivity soil filtration media. Since the volume of incoming and outgoing rainwater was not measured in this study, it is not possible to determine the load of incoming and outgoing phosphorus. This preliminary study shows that there is a need of monitoring existing rain gardens, as well as responsible selection of filter materials for newly built ones.

4 Conclusions

Rain gardens are not yet a very popular solution but their number in cities is steadily growing. They will also be more and more popular, because of growing interest in implementing blue and green infrastructure to adapt cities to climate change.

Rain gardens can be effective in rainwater retention and delaying runoff or groundwater recharge via infiltration. Among the benefits, also rainwater purification function is often suggested, but the studies of water quality and construction materials presented in this paper do not confirm this thesis. Examination of the phosphorus content in construction materials sampled from rain gardens showed the significant potential of these materials for the release of phosphorus into filtered rainwater. This creates a threat to the quality of rainwater receivers in cities. In new rain garden designs, filter materials with a low risk of phosphorus release should be used. Existing and newly built rain gardens, especially those which discharge to the urban water bodies (in container solutions), should be monitored for the effluent quality to avoid their contribution to urban water pollution.

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