Metal Soil Solution Concentrations Beneath Long-term Operated Bioretention Systems

Concentrations métalliques des solutions de sol en dessous des systèmes de biorétention exploités sur le long terme

Arne Reck[1] and Björn Kluge[1]

[1]Chair of Ecohydrology and Landscape Evaluation, Technische Universität Berlin, D-10587 Berlin, Germany (a.reck@tu-berlin.de)

RÉSUMÉ

À ce jour, nous manquons de résultats systématiques et issus du terrain concernant l'efficacité de rétention des systèmes de biorétention exploités sur le long terme (>20 ans d'exploitation). Nous étudions le risque de rejet de métaux lourds (ML) de trois systèmes de biorétention exploités sur le long terme en milieu urbain en Allemagne, mais dont l'état de pollution et les conditions d’apports diffèrent. Notre méthode de mesure utilise des ventouses installées en dessous de la limite inférieure du système, c'est-à-dire à une profondeur d'environ 30 cm. L'extraction des lixiviats du sol est régulée par une nouvelle approche qui synchronise automatiquement l'échantillonnage de l'eau interstitielle du sol avec les périodes de drainage afin d'analyser de manière fiable le trajet de ML dissous. De plus, l'humidité du sol, les concentrations d'apports et les caractéristiques des précipitations sont enregistrées pour chaque événement afin d'analyser leur effet sur les rejets de ML. Les résultats obtenus à ce jour révèlent une rétention satisfaisante pour deux des trois systèmes étudiés, avec une rétention des métaux de 73 à 93 % par rapport aux concentrations d'apports dissous. Dans le troisième système, les concentrations de Cu et de Zn ont dépassé les valeurs de déclenchement allemandes relatives à la trajectoire sol-eaux souterraines de l'Ordonnance fédérale sur la protection des sols et des sites contaminés (BBodSchV) dans quatre des 12 épisodes de précipitations qui ont provoqué une infiltration profonde.

ABSTRACT

Until today we lack systematic, field-based results regarding the retention effectiveness of long-term operated bioretention systems (>20 years of operation). We investigate the risk of heavy metal (HM) discharge from three long-term operated bioretention systems within urban settings but different pollution status and inflow conditions in Germany. Our measurement approach uses suction cups installed below the systems lower boundary, i.e. in depths around 30 cm. The soil leachate extraction is regulated by a novel approach which automatically synchronises soil pore water sampling with drainage periods to reliably analyse the transport of dissolved HM event-wise. Additionally, soil moisture, inflow concentrations and precipitation characteristics are recorded for each event to analyse their effect on HM discharge. The measurements were started in April 2018 and will be continued at minimum until April 2019 to cover potential intra-annual variations in HM discharge. Results to date show a satisfactory retention performance for two of the three investigated systems with a metal retention of 73-93% compared to the dissolved inflow concentrations. At the third system Cu and Zn concentrations exceeded the German trigger values for the soil-groundwater pathway of the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV) in four out of 12 stormwater events generating deep seepage.

KEYWORDS

Bioretention effectiveness, groundwater degradation, heavy metal discharge, in-situ soil leachate concentration, novel measurement approach

1 INTRODUCTION

Decentralised infiltration of stormwater runoff has clear ecological advantages and is a prerequisite to counteract the increasing level of impervious covers and thus, to reduce the vulnerability of urban areas regarding stormwater flooding (Morgan and Fenner, 2017). Although the construction of bioretention sites is clearly regulated to guarantee the desired stormwater treatment efficiency we lack systematic results of how bioretention systems perform after long-term operation (> 20 years of operation). In particular, the pollutant removal capacity after many years of contaminant accumulation is of high uncertainty (Liu et al., 2014).

Mostly laboratory batch or column experiments are employed to either estimate the timespan until the sorption sites are depleted or the potential liquid phase discharge for a given solid phase contaminant concentration (Jones and Davis, 2013; Paus et al., 2013; Tedoldi et al., 2016). However, almost no field-based soil leachate concentration values of free draining systems exist, especially no time series. Both would be necessary to accurately validate the laboratory experiments and to assess the effect of varying initial and boundary conditions on contaminant discharge. Especially the use of de-icing salts, precipitation characteristics, inflow concentrations and the drainage area type are known to clearly influence the pollution status as well as the sorption and de-sorption kinetics of contaminants in the soil substrate (Bäckström et al., 2004; Göbel et al., 2007; Kluge et al., 2016; Allen et al., 2017).

This study aims to investigate the potential of heavy metal (HM) discharge of three long-term operated bioretention systems in urban settings with different inflow conditions and pollution status. Therefore, we (i) test a newly developed measurement approach for in-situ drainage water sampling; (ii) analyse the time series of the received soil leachate samples to check for critical HM concentrations and to evaluate the retention performance; and (iii) use generalized additive mixed models (GAMM) to test the effect of initial and boundary conditions on HM discharge from long-term operated bioretention systems.

2 METHODS

2.1 Experimental Sites

Soil leachate was sampled in-situ at three bioretention sites in Germany. One system is located in Berlin (“BS 1”, north-eastern part of Germany) and the other two in the Ruhr valley of the federal state of North-Rhine-Westphalia (central-western part of Germany, sub-urban setting “BS 2” and urban setting “BS 3”). All three systems are constructed according to the German Association for Water, Wastewater and Waste technical standard (DWA-A 138, 2005), consist of a 10 cm topsoil and 20 cm subsoil layer, and are operated since 20-25 years. Site “BS 1” receives stormwater runoff areally from the adjacent residential road and paved sidewalks. Site “BS 2” receives the stormwater runoff from different point inflows draining the area of a commercial logistic company. Site “BS 3” receives stormwater via one single inflow point connected to a roof with zinc gutters. Mean temperature and annual precipitation sum is 10.2 °C and 579.2 mm for “BS 1” as well as 10.7 °C and 949 mm for “BS 2” and “BS 3”.

2.2 Monitoring Stations

The soil leachate sampling was realised using a novel soil water sampling approach to automatically extract soil water during drainage periods to analyse the draining water qualitatively (Reck et al., submitted). This approach samples soil water using suction cups in a discontinuous operation mode regulated by the actual soil moisture. Only if the actual soil moisture exceeds field capacity plus offset, the vacuum starts regulating and soil water will be extracted. Additionally, a SMS notification is sent in the case if soil water is collected.

Each experimental site was equipped with the advanced in-situ soil water sampling system connected to ten suction cups with a nylon membrane to avoid sorption processes. The suction cups were installed radially around an excavated access shaft and incorporated horizontally into the soil substrate at an angle of 45° at two points per experimental site. At the sites with point inlets (“BS 2”, “BS 3”) the first point for suction cups installation was set in direct vicinity to the inflow point and the second point around ten meters behind the first point. For site “BS 1” both points were set at a central position of the swale depression with ten metre distance between both points as well. Before suction cup installation the bottom of the constructed bioretention media horizon was located for each point using a boring rod to ensure a correct installation depth of the porous membrane (25-45 cm depth). After installation, the access shaft was covered with a vertically embedded plastic pipe to protect the suction tubes and to house the soil water collection bottles under soil-like conditions. To analyse the inflow heavy metal concentration, a part of the stormwater runoff was redirected from the inlet point to a collection shaft equipped with a sampling bottle. From this bottle an aliquot was taken each time soil leachate was sampled. Additionally, each experimental site was equipped with one tipping-bucket rain gauge, installed one metre above ground.

2.3 Sample Analysis

Soil leachate was always analysed as a composite sample from the five suction cups per sampling point. Inflow was shaken and split up into two samples. One aliquot was filtered through a 45 µm membrane and the other aliquot was digested with nitric acid to determine both dissolved and total heavy metal concentrations. After field collection all samples were acidified with HNO_3 and stored by 4°C until analysis. The heavy metal concentrations of the samples were determined by atomic emission spectrometry with inductively coupled plasma (ICP-OES). Values below the limit of detection were set to zero and values below the determination limit were set to half the determination limit.

3 RESULTS AND DISCUSSION

To date soil leachate was sampled in total for 39 single drainage events caused by stormwater runoff infiltration into the three experimental systems. Results from the monitoring sites are presented for the first six months in Figure 1 exemplarily for the metals Cu and Zn at site “BS 2”. Precipitation input and soil moisture respond correlate clearly and demonstrate the proper functioning of the tested, novel measurement approach to collect “real” soil drainage water (Figure 1a). The highlighted segments of the soil moisture curve mark the drainage periods when soil leachate extraction is initiated. Both, dissolved inflow and soil leachate concentrations vary clearly over time (Figures 1b-d). The maximum and median inflow concentrations for Cu and Zu are 121 and 4429 µg l^{-1} as well as 41 and 2348 µg l^{-1} respectively. At point 1 the maximum and median concentrations of Cu and Zn in the soil leachate are 37 and 220 µg l^{-1} as well as 11 and 154 µg l^{-1} respectively. The latter values confirm a proper retention performance of site “BS 2” with concentration values clearly below the German trigger values (50 µg l^{-1} for Cu and 500 µg l^{-1} for Zn). Compared to the median stormwater runoff concentrations at the inlet point the metal retention is 73% for Cu and 93% for Zn. At point 2, soil leachate was sampled only in a third of the events since stormwater runoff reaches there just in case of higher precipitation sums. Accordingly, the median leachate concentrations are half the values (6 µg l^{-1}) for Cu and more than five times lower (29 µg l^{-1}) than Zn values at point 1 (Figure 1d).

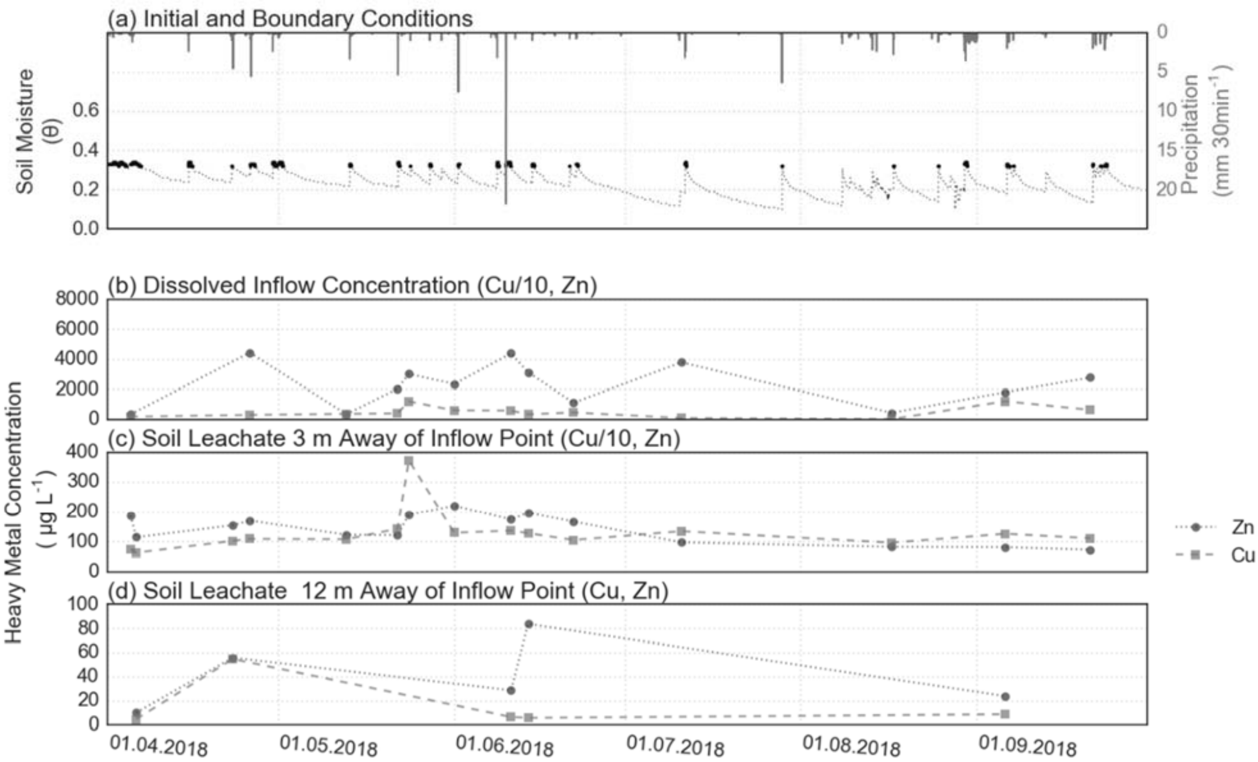

Figure 1: First results of the soil leachate sampling campaign demonstrated at site „BS 2“ for the metals Cu and Zn. (a) Time series of precipitation and soil moisture of the bioretention media soil at a depth of 25-30 cm. Soil leachate extraction is always triggered if the actual soil moisture exceeds the set threshold as indicated by the black and solid highlighted segments of the soil moisture curve. (b) Dissolved heavy metal input and the respective soil leachate concentration (c-d). Note that not all threshold excesses in (a) were analysed and (d) has less points of soil leachate samples than (c) because stormwater runoff not always reached point 2.

The median soil leachate concentration of Cu and Zn at site “BS 3” are 41 and 167 µg l^{-1}. In five out of 12 deep seepage events the measurements slightly exceed the German trigger values which corresponds with the high median inflow concentrations of Zn (1512 µg l^{-1}) but not for Cu (20 µg l^{-1}). Until yet the reason of the high inflow concentrations is unclear because the Zinc roof gutters were installed more than twenty years ago, and leaching rates of Cu and Zn normally decrease sharp within the first year of installation (He et al., 2001).

At site “BS 1” soil leachate was only sampled four times since measurement initiation due to a prolonged drought period in Berlin. Compared to the other two sites, soil leachate shows the lowest median HM concentration for Zn (19 µg l^{-1}) and moderate concentration values fur Cu (33 µg l^{-1}).

4 CONCLUSION

The testing of the advanced soil leachate sampling system demonstrates a satisfying performance at all three experimental sites. Since the majority of soil leachate concentration values are below the trigger values we can attest a proper HM removal capacity for all three sites even after long-term operation. If the measurements will be completed in April 2019 we will complement our data by employing generalized additive mixed models (GAMM) to test the effect of varying initial and boundary conditions on the HM retention/discharge behaviour of long-term operated bioretention systems. The syntheses of all results will be used to better evaluate the lifecycle of bioretention systems and thus to promote the application of decentralised infiltration in urban areas.

ACKNOWLEDGEMENTS

We gratefully acknowledge the Ministry of Environment, Agriculture, Nature and Consumer protection of North-Rhine-Westphalia for funding as well as the site owners for permitting all the measurements in their facilities.

LIST OF REFERENCES

Allen, D., H. Haynes, S. Arthur, 2017. Contamination of Detained Sediment in Sustainable Urban Drainage Systems. *Water* 9(5). 355.

Bäckström, M., S. Karlsson, L. Bäckman, L. Folkeson, B. Lind, 2004. Mobilisation of heavy metals by deicing salts in a roadside environment. *Water Research* 38(3). 720–732.

DWA-A 138, 2005. *Planung, Bau und Betrieb von Anlagen zur Versickerung von Niederschlagsabwasser* [Design, construction and operation of rainwater drainage systems] (in German). German Association for Water, Wastewater and Waste e.V., Hennef, Germany.

Göbel, P., C. Dierkes, W.G. Coldewey, 2007. Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology* 91(1-2). 26–42.

He, W., I.O. Wallinder, C. Leygraf, 2001. A comparison between corrosion rates and runoff rates from new and aged Copper and Zinc as roofing material. *Water, Air and Soil Pollution: Focus* 1(3/4). 67–82.

Jones, P.S., A.P. Davis, 2013. Spatial Accumulation and Strength of Affiliation of Heavy Metals in Bioretention Media. *Journal of Environmental Engineering* 139(4). 479–487.

Kluge, B., A. Markert, M. Facklam, H. Sommer, M. Kaiser, M. Pallasch, G. Wessolek, 2016. Metal accumulation and hydraulic performance of bioretention systems after long-term operation. *Journal of Soils and Sediments* 18(2), 431-441.

Liu, J., D. Sample, C. Bell, Y. Guan, 2014. Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. *Water* 6(4). 1069–1099.

Morgan, M., R. Fenner, 2017. *Spatial evaluation of the multiple benefits of sustainable drainage systems*. Proceedings of the Institution of Civil Engineers - Water Management 1–14.

Paus, K.H., J. Morgan, J.S. Gulliver, T. Leiknes, R.M. Hozalski, 2013. Assessment of the Hydraulic and Toxic Metal Removal Capacities of Bioretention Cells After 2 to 8 Years of Service. *Water, Air, & Soil Pollution* 225(1).

Reck, A., E. Paton, B. Kluge (submitted): Advanced in-situ soil water sampling system for monitoring solute fluxes in the vadose zone. *Advances in Water Resources*.

Tedoldi, D., G. Chebbo, D. Pierlot, Y. Kovacs, M.-C. Gromaire, 2016. Impact of runoff infiltration on contaminant accumulation and transport in the soil/filter media of Sustainable Urban Drainage Systems: A literature review. *Science of The Total Environment* 569-570. 904–926.