Treatment performance of pilot-scale infiltration basins under simulated stormwater events with relevance to groundwater quality

Performances de traitement des bassins d'infiltration à l'échelle pilote dans le cadre d'événements pluvieux simulés ayant une incidence sur la qualité des eaux souterraines

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RÉSUMÉ

Les systèmes d'infiltration des eaux pluviales sont de plus en plus utilisés comme alternative aux drains conventionnels. Cependant, leur utilisation soulève des inquiétudes quant à la pollution des eaux souterraines. Les recherches sur le transport des polluants issus des eaux pluviales vers la zone saturée en milieu urbain restent limitées, et cette étude y contribue en examinant la qualité d'eaux pluviales provenant de deux bassins versants contrastés lors de leur infiltration à travers trois bassins pilotes. Au cours de trois essais, les paramètres physico-chimiques, certains métaux et des micropolluants organiques (par ex. HAP, composés organostanniques, BPA, PFAS) ont été surveillés à l'entrée et à la sortie. Le zinc et certains polluants organiques (BPA, HAP) ont montré des réductions, tandis que le cuivre et les composés organostanniques présentaient des concentrations accrues en sortie. En particulier, les composés MBT et MOT ont été détectés à des niveaux plus élevés, suggérant un lessivage des sols ou matériaux de construction. Des analyses supplémentaires du sol et du potentiel de lessivage aideront à clarifier les sources internes. Ces résultats soulignent que les systèmes d'infiltration peuvent à la fois atténuer et introduire des contaminants, avec des implications pour la qualité des eaux souterraines peu profondes.

ABSTRACT

Stormwater infiltration systems are increasingly implemented as alternatives to conventional piped drainage systems. However, the infiltration of stormwater runoff raises concerns over groundwater pollution. The research on stormwater pollutant transport towards the saturated zone in urban areas is relatively limited, and this study contributes to this area by investigating the quality of stormwater collected from two contrasting catchments on infiltration through three pilot infiltration basins. During three experimental runs, physicochemical parameters, selected metals and organic micropollutants (e.g. PAHs, organotin compounds, BPA, PFAS) were monitored in both the inflow and outflow. Zn and specific organic pollutants (e.g. BPA and PAH) showed reductions, whereas for Cu and organotin compounds we found increases in outflow concentrations relative to inflow. In particular, the organotin compounds MBT and MOT were reported at higher levels in the outflow, indicating leaching from soil media or construction materials within the infiltration basins. Further analyses of the soil media and potential material leaching will help clarify internal contaminant sources. The findings highlight that infiltration systems may both attenuate and introduce contaminants, with implications for the quality of shallow groundwater.

KEYWORDS

groundwater quality, infiltration system, metals, organic micropollutants, urban runoff

1 INTRODUCTION

The infiltration of urban stormwater is increasingly promoted as an alternative to conventional piped drainage systems due to its benefits for e.g. flood mitigation and groundwater recharge. However, urban stormwater can carry complex mixtures of contaminants including metals, nutrients and organic pollutants from diverse anthropogenic sources (Müller et al., 2020), making its infiltration a potential pathway for pollutants transported with runoff to reach – and contaminate - groundwater. Yet, the extent to which this occurs remains poorly understood. In practice, infiltration systems such as detention/infiltration basins and grass swales, commonly use locally available soils, with variability in soil properties influencing pollutant behaviour during subsurface transport. As soil media characteristics play a central role in pollutant retention (Tirpak et al., 2021; Fardel et al 2020), their variability introduces uncertainty in treatment performance. Previous studies have also highlighted that infiltrated stormwater may mobilise contaminants already present in soil (Arora et al., 2023) or reduce background concentrations through dilution (Zubair et al., 2010). The unsaturated zone can act as a filter for hydrophobic contaminants, with retention efficiency influenced by infiltration dynamics and transit time (Tedoldi et al., 2016). However, knowledge gaps remain concerning the behaviour of emerging organic contaminants in infiltrated water pathways, particularly those that are hydrophilic or readily degradable (Pinasseau et al., 2020; Tedoldi et al., 2016), and the extent to which these substances may be transmitted toward groundwater. Assessing pollutant transport during infiltration is therefore essential for understanding potential risks to shallow groundwater and for supporting management decisions regarding stormwater infiltration practices. Thus, the objective of this study is to investigate the quality of infiltrated stormwater in pilot-scale infiltration basins to identify which pollutants are most likely to be transmitted toward shallow groundwater during infiltration.

2 MATERIALS AND METHODS

Three pilot-scale infiltration basins (A, B and C) were constructed in 2021 in Luleå, Sweden, with field investigations conducted in autumn 2025. Each basin measured 6.5 m in length, 1.2 m in top width, and 0.3 m in bottom width, and a longitudinal slope of 1.4%. The systems contained a 0.5 m deep soil media layer underlain by a geomembrane, mimicking conditions with a shallow groundwater table. Infiltrated water was collected by drainage pipes installed directly above the geomembrane and conveyed via PVC piping to individual stainless-steel 500-mL tipping buckets (V2A, UP-Umweltanalytische Produkte GmbH) for continuous flow monitoring. Prior to the runoff simulations, two soil samples from each basin were taken to characterize the media. Particle size distribution was determined by wet sieving and laser diffraction. The media consisted of 76.7% ± 8.5 sand, 22.3% ± 8.3 silt, and 1.0% ± 0.4 clay, corresponding to a loamy sand soil texture.

The basins received three controlled inflows of stormwater runoff collected from two catchments: a residential catchment including a road section with approximately 2,000 vehicles/day (run 1 and 2) and a mixed road–industrial catchment with approximately 6,000 vehicles/day (run 3). Stormwater for runs 1 and 2 were collected during the same precipitation event; the water for run 1 was collected first, followed by the water for run 2, which was collected 15 minutes later. For each run, stormwater was collected and stored in IBC tanks for several days, and subsequently homogenized by recirculating the water through a high-flow centrifugal pump, ensuring thorough mixing prior to application. Runoff simulations were simultaneously performed with each basin receiving a total inflow volume of around 250 L per run. In order to quantify pollutant concentrations of the inflow water, one sample for each basin was collected directly from the inlet hose throughout the duration of the stormwater application. For the outflow of infiltrated water, volume-proportional composite samples were collected from each outlet point using the tipping buckets coupled with automated samplers (ISCO 6712), producing two composite samples per run and basin that represented the early (1) and late (2) outflow phase, defined as the first and second halves of the total outflow volume.

The water samples were analysed for conventional physicochemical parameters, including pH, conductivity, turbidity, alkalinity, total suspended solids (TSS), total organic carbon (TOC), dissolved organic carbon (DOC), chemical oxygen demand (COD), chloride, sulphate, total and dissolved fraction of various metals, as well as for 16 polycyclic aromatic hydrocarbons (PAH16), 10 organotin compounds (OTC), bisphenol A (BPA) and 35 Per- and polyfluoroalkyl substances (PFAS), including ultra-short PFAS (PFAS analysis pending). Conductivity and pH were measured immediately in field, and samples for dissolved metals were filtered on-site. All remaining samples were cooled to 4 degrees C and transferred to commercial laboratories (ALS Scandinavia AB and Eurofins Environment Testing Sweden AB) within 48 hours after completed experimental runs. Due to ongoing data interpretation, only a selected set of representative parameters is presented in the abstract.

3 RESULTS AND DISCUSSION

Figure 1 illustrates the concentrations of selected metals (zinc (Zn), copper (Cu) and chromium (Cr) in dissolved (<0.45 µm) and total form), conductivity and organic micropollutants (BPA, PAH16, OTC monobutyltin (MBT), OTC dibutyltin (DBT) and monooctyltin (MOT)) measured during the three runoff experiments in the inflow (in) and early (1) and late (2) infiltration phase of the basins A, B and C. Across the selected pollutants, inflow concentrations varied between the three runs, consistent with differences in catchment characteristics and phase of event. For instance, run 3 (stormwater collected from a road–industrial catchment) had the highest inflow concentrations for several pollutants, particularly BPA, PAH16 and total Cr. While inflow conductivity varied between runs, the outflow consistently converged toward 150–250 µS/cm. High inflow conductivity from the residential catchment (350 – 782 µS/cm) decreased toward this range, whereas low inflow conductivities from the road–industrial catchment (60-96 µS/cm) increased.

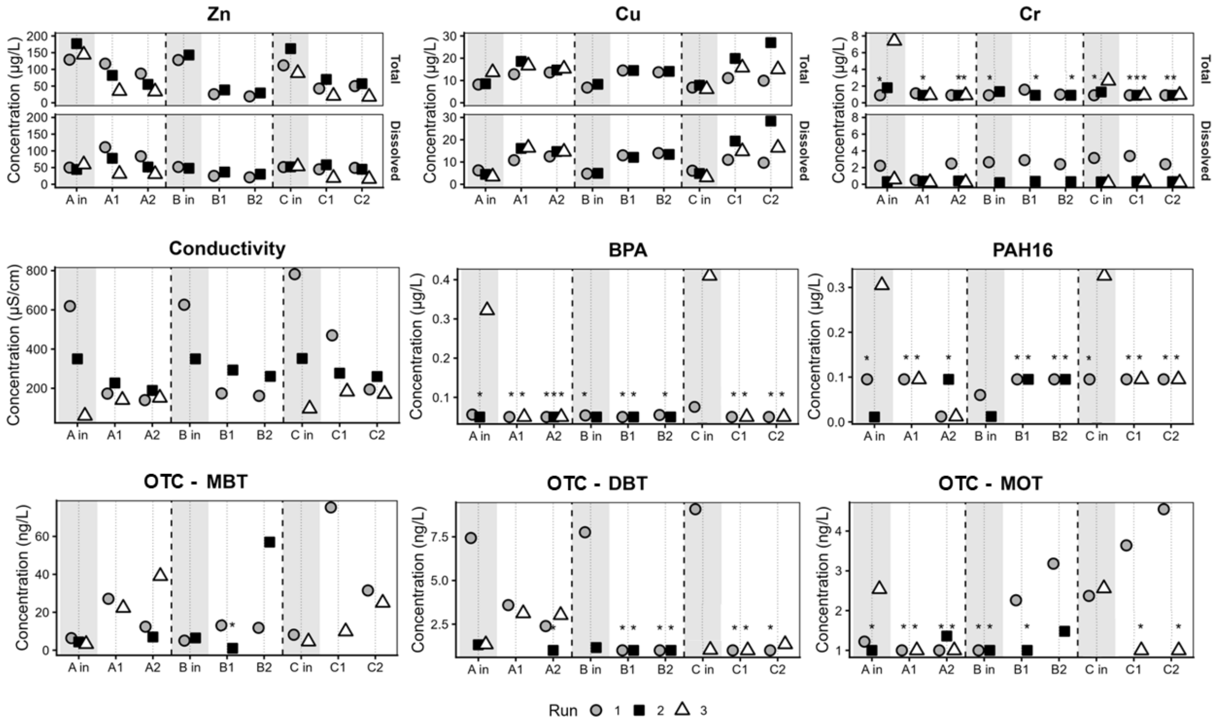

Figure 1: Concentration of metals (Zn, Cu, Cr), conductivity, BPA, PAH16, and organotin compounds (MBT, DBT, MOT) measured in the inflow (in; grey shading) and the early and late outflow phases (1 and 2) of infiltration basin A, B and C. The different symbols indicate experimental run 1, 2 and 3. Asterisks (*) indicate concentrations below the reporting limit.

For Zn, concentration reductions occurred primarily for the total concentration, with the lowest concentrations typically observed at the second outflow sample (A2, B2, C2), reflecting progressive pollutant removal. This behaviour is consistent with particle-associated Zn removal through filtration and sedimentation. In contrast, Cu showed an increase in both total and dissolved concentrations in the infiltrated water relative to the inflow, with the highest values generally occurring in the later outflow samples suggesting mobilisation of Cu from soil. This aligns with Flanagan et al. (2019), who observed that road sediment and contaminated soil can leach Cu under infiltration conditions. Regarding the behaviour of the organic micropollutants, BPA and PAH16 were reported only in the run 3 inflow and were either below reporting limits or present at very low concentrations in the outflow, indicating removal within the systems. This is consistent with the strong sorption properties of hydrophobic compounds, which are known to be well retained the unsaturated zone (Tedoldi et al., 2016). In contrast, the organotin compound MBT showed higher concentrations in the outflow than in the inflow, indicating a potential internal source within the infiltration basins. Similarly, MOT was detected in the outflow of run 1 only, which may also indicate leaching. Its absence in subsequent runs suggests that any leachable fraction in concentrations above reporting limit may have been flushed out earlier. However, DBT was reported in the inflow of run 1 but was found at low levels or below reporting limits in the outflow, indicating effective treatment in the system. Overall, the presence of certain organotin compounds in the outflow likely reflects leaching from the soil or construction materials (e.g., geomembrane, drainage pipes) rather than contributions from the stormwater itself. This will be further investigated.

4 CONCLUSION

The pilot-scale infiltration basins allowed controlled investigation of pollutant behaviour during stormwater infiltration under field conditions. While several contaminants, such as Zn, BPA and PAH16, were effectively removed during the infiltration process, others including Cu and organotin compounds showed mobilisation, indicating that infiltration systems can function as both sinks and sources of pollutants. This highlights the need to consider both pollutant retention processes in the soil and leaching from material when evaluating groundwater risks associated with stormwater infiltration. Further work will investigate the contribution of soil concentrations and construction materials to leaching, as well as additional contaminants such as PFAS that were not included in the present analysis.

LIST OF REFERENCES

Arora, M., Fletcher, T.D., Burns, M.J., Western, A. W., Yong, C. F., Poelsma, P. J., James, R. B., 2023. The influence of stormwater infiltration on downslope groundwater chemistry. Environ Geochem Health 45, 8489–8501. https://doi.org/10.1007/s10653-023-01732-3

Fardel, A., Peyneau, P.-E., Béchet, B., Lakel, A., Rodriguez, F., 2020. Performance of two contrasting pilot swale designs for treating zinc, polycyclic aromatic hydrocarbons and glyphosate from stormwater runoff. Sci. Total Environ. 743, 140503. https://doi.org/10.1016/j.scitotenv.2020.140503

Flanagan, K., Branchu, P., Boudahmane, L., Caupos, E., Demare, D., Deshayes, S., Dubois, P., Meffray, L., Partibane, C., Saad, M., Gromaire, M. C., 2019.Retention and transport processes of particulate and dissolved micropollutants in stormwater biofilters treating road runoff, Sci. Total Environ. 656, 1178-1190, https://doi.org/10.1016/j.scitotenv.2018.11.304.

Müller, A., Österlund, H., Marsalek, J., Viklander, M., 2020. The pollution conveyed by urban runoff: A review of sources. Sci. Total Environ 709, 136125. https://doi.org/10.1016/j.scitotenv.2019.136125.

Pinasseau, L., Wiest, L., Volatier, L., Mermillod-Blondin, F., Vulliet, E., 2020. Emerging polar pollutants in groundwater: potential impact of urban stormwater infiltration practices. Environ. Pollut. 266, 115387 https://doi.org/10.1016/j. envpol.2020.115387

Tedoldi, D., Chebbo, G., Pierlot, D., Kovacs, Y., Gromaire, M.-C., 2016. Impact of runoff infiltration on contaminant accumulation and transport in the soil/filter media of Sustainable Urban Drainage Systems: a literature review. Sci. Total Environ. 569e570, 904-926. https://doi.org/10.1016/j.scitotenv.2016.04.215

Tirpak, R.A., Afrooz, A.N., Winston, R.J., Valenca, R., Schiff, K., Mohanty, S.K., 2021. Conventional and amended bioretention soil media for targeted pollutant treatment: a critical review to guide the state of the practice. Water Res. 189, 116648. https://doi.org/10.1016/j.watres.2020.116648

Zubair, A., Hussain, A., Farooq, M.A., Abbasi, H. N., 2010. Impact of storm water on groundwater quality below retention/detention basins. Environ Monit Assess 162, 427–437. https://doi.org/10.1007/s10661-009-0807-y