

Modelling the Physical Filtration of Particle-Bound Pollutants in Stormwater Biofilters

Modélisation de la filtration physique des polluants particuliers dans les ouvrages de biofiltration des eaux pluviales

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RÉSUMÉ

Les eaux pluviales urbaines provenant des routes contiennent des contaminants sous forme dissoute et particulaire, ce qui nécessite des stratégies de dépollution efficaces tenant compte du comportement des deux phases. De nombreux polluants possèdent des proportions particulaires importantes, dépassant 50 % et, dans certains cas, avoisinant l'association particulaire complète, ce qui souligne la nécessité de modéliser avec précision le transport et la rétention des particules. La taille des particules est essentielle à la performance de la filtration, car les particules plus grosses sont généralement éliminées près de la surface des biofiltres, tandis que les particules plus petites peuvent pénétrer plus profondément dans le média ou contourner complètement la filtration. L'objectif de cette étude est d'améliorer un modèle existant de transport et de traitement des micropolluants dans les ouvrages de bioretention (MPiRe), en y intégrant un processus de filtration physique dédié aux matières en suspension. Actuellement, MPiRe se compose d'un module hydrologique et d'un module de transport des polluants réactifs, mais traite uniquement les processus relatifs liés à la phase dissoute. Le module de filtration proposé simule l'élimination des particules en fonction de la profondeur, ce qui permet au modèle de capturer les mécanismes d'élimination des polluants liés aux particules qui font actuellement défaut dans le cadre de la modélisation.

ABSTRACT

Urban stormwater runoff from roadways contains contaminants in both dissolved and particulate forms, necessitating effective depollution strategies that account for the behavior of both phases. Many pollutants possess significant mass fractions bound to particulates, exceeding 50% and, in some cases, nearing complete particle association, underscoring the necessity of accurately modeling particulate transport and retention. Particle size is critical to filtration performance, as larger particles are typically removed near the surface of biofilters. In contrast, smaller particles may penetrate deeper into the media or bypass filtration altogether. The objective of this study is to enhance an existing model of micropollutant treatment in stormwater biofilters (MPiRe) by incorporating a physical filtration process for suspended solids. Currently, MPiRe consists of a hydrological module and a reactive pollutant transport module but addresses only dissolved-phase processes. The proposed filtration module simulates depth-dependent particle removal, enabling the model to capture particulate-bound pollutant removal mechanisms that are currently missing from the modeling framework.

KEYWORDS

Dissolved pollutants, Micropollutant, Particle filtration, Process modelling, Stormwater biofilter

1 INTRODUCTION

Urban stormwater and snowmelt are significant vectors for transporting pollutants in urban areas, including organic matter, nutrients, and trace metals, as well as emerging organic micropollutants such as Per- and polyfluoroalkyl substances (PFAS) and phthalates (Müller et al., 2020).

Contaminants can be present in both dissolved and particulate form in urban runoff (Tedoldi et al., 2018). Stormwater biofilters, as nature-based systems, can provide effective treatment of many of these pollutants. However, much of the stormwater literature often overlooks considering both phases and their key processes for removing pollutants (Lefevre et al., 2015). Gaining a deeper understanding of the processes within these systems is crucial for enhancing their design and representation in modelling techniques (Flanagan et al., 2019).

Contaminants carried in particulate form are removed by mechanical filtration within the filter media. When particles are predominantly larger than the pore sizes of the filter medium, they create a deposit on the surface. Conversely, when particles are generally smaller than the pore sizes, deposition takes place within the internal structure of the medium (Wakeman, 2007). Dissolved contaminants, however, bypass these physical mechanisms and are removed via chemical processes. Additionally, a fraction of contaminants bypasses the filter media without being retained.

The MPiRe (Micro-Pollutants in RaingardEns) model is a tool used to predict biofilters' performance in the removal of some key stormwater pollutants, by incorporating both a water flow module and a pollutant transport module (Randelovic et al., 2016). MPiRe currently simulates reactive transport processes (including advection, dispersion, volatilization, sorption, and biodegradation) relevant for the dissolved phase of micropollutants in a stormwater biofilter.

The goal of this study is to improve the outputs of the MPiRe by comparing the base model to an improved version that incorporates an additional physical filtration process.

2 METHODS

The developed model will be tested using the existing field data set (Flanagan et al., 2019). It will focus on a select group of pollutants measured in both dissolved and particulate phases, including trace metals (Zn, Cu), phthalates (Di(2-ethylhexyl)ftalat, DEHP; dinonylphthalate, DBP), alkylphenols (para-nonylphenol NP; 4-tert-octylphenol, OP; Bisphenol-A, BPA), and polycyclic aromatic hydrocarbons (pyrene, Pyr; fluoranthene, Fluo; and phenanthrene, Phen).

Partitioning data from the field data set will determine the proportion of pollutants entering the biofilter in dissolved and particulate phases, quantifying the contribution of particle-bound transport for each contaminant based on their particulate fraction.

$$\frac{C_p}{C_p + C_d}, (1)$$

Where C_p is the particulate pollutant concentration and C_d is the dissolved pollutant concentration.

While the transport of the dissolved phase will be based on the current pollutant transport module in MPiRe, a new module will be used to represent the transport of particles and their physical filtration. The relative importance of the principal filtration mechanisms (cake versus depth filtration, see Figure 1) will be determined by comparing the particle size distribution measured for runoff and drained water from the study site, as well as the pore size distribution estimated for the biofilter's filter media. In addition, the model will represent exchanges between the dissolved and solid phases due to sorption or desorption. By incorporating this dual-phase representation, the enhanced model will represent both chemical removal processes and physical removal

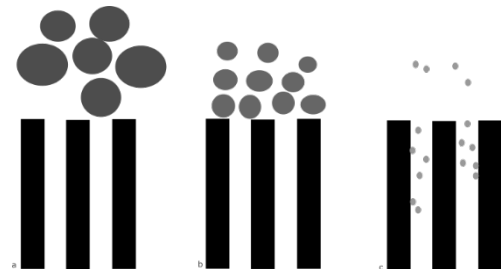


Figure 1: Illustrates the principles of blocking (a) and bridging (b) mechanisms involved in cake filtration. Additionally, it depicts depth filtration (c), where particles accumulate within the filter media.

processes, which collectively influence the fate of pollutants in stormwater biofilters. To evaluate MPIRe’s accuracy, confidence intervals of the predictions will be compared with measured outlet concentrations for different pollutant fractions.

3 RESULTS AND DISCUSSION

Numerous contaminants display significant particulate-bound mass fractions, frequently surpassing 50% and, in certain instances, nearing 100%. This behavior is especially evident among hydrophobic organic compounds like DEHP, OP, Phenanthrene, Fluoranthene, and Pyrene, as well as metals such as Zn and Cu. The boxplots in Figure 2 clearly illustrate this trend. For most hydrophobic contaminants, particulate fractions cluster well above 0.5, with several events approaching 1.0, indicating near-complete association with particles. Metals like Zn and Cu also show elevated particulate fractions, though with more variation between events. Conversely, polar compounds like BPA display consistently low particulate fractions across both RR and BFS, mostly remaining in dissolved form due to their higher water solubility and weaker interactions with suspended solids.

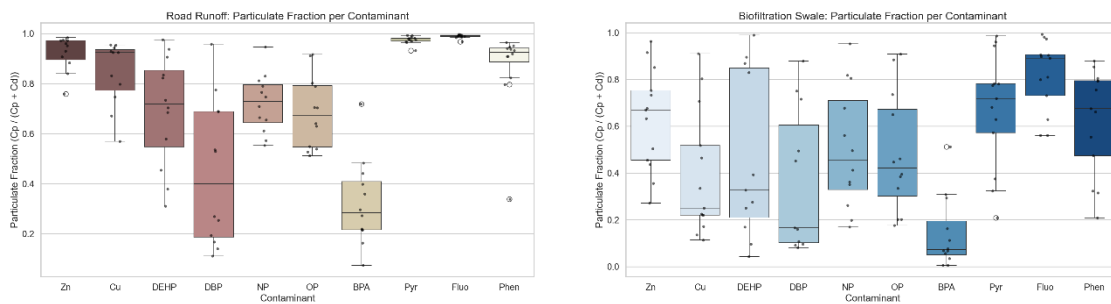


Figure 2. The distribution of particulate fractions across sampling events is illustrated for a) samples collected from untreated Road Runoff (RR) and b) those from the outlet drain of the Biofiltration Swale (BFS) for each contaminant, red points represent mean values. Hydrophobic contaminants such as DEHP, OP, and Phenanthrene, Fluoranthene, Pyrene, along with metals like Zn and Cu, consistently demonstrate a higher association with particulates. In contrast, more polar compounds, including BPA, primarily remain in their dissolved form, as indicated by the experimental data from RD 212, a highway situated in an industrial zone of Compans.

The broad range of pollutants in particulate form in both RR and BFS indicates that the current dissolved-only model in MPIRe is insufficient for accurately capturing the retention of hydrophobic organics and metals, which are primarily associated with particles at this site.

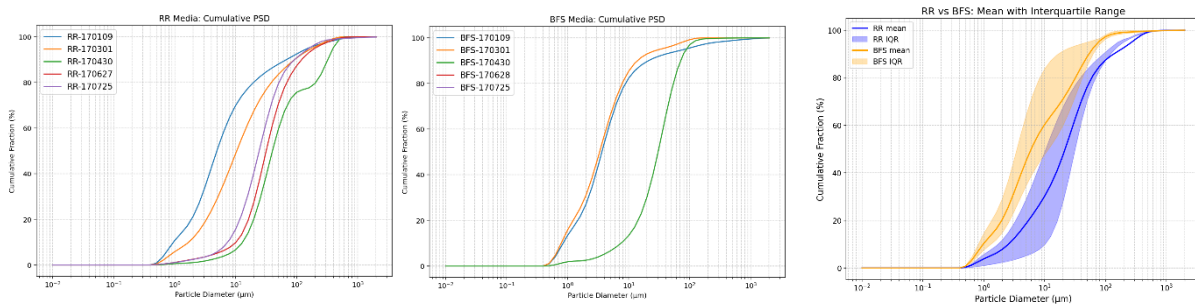


Figure 3: (a) Cumulative particle size distributions (CPSD) for different events from untreated Road Runoff samples (RR) and (b) Biofiltration Swale (BFS) outlet drain samples, and (c) their mean CPSD comparison with the shaded area between the two curves representing the interquartile range (IQR). BFS samples contain consistently finer particles (left-shifted curve), while RR exhibits coarser particle sizes and a broader distribution (right-shifted curve).

Because physical filtration is strongly governed by particle size and pore structure, cumulative particle size distributions (CPSD) will be used to characterise filtration efficiency. Untreated road runoff (RR) exhibits a coarser particle size distribution, indicating the presence of larger particles that are readily removed through

surface straining. The outlet drain of the Biofiltration Swale (BFS) shows a finer distribution, reflecting the preferential retention of coarse and medium particles within the biofilter (Figure 3), indicating a deeper penetration of fine particles. Although these smaller particles make up a relatively small part of the inlet suspended solids, their transport is critical in accurately representing outlet concentrations.

The CPSD profile highlights the importance of integrating particle size into the filtration model representation. Particle-size-dependent filtration is anticipated to enhance the accuracy of predictions regarding the removal of particulate-bound pollutants.

By considering how particle size affects depth-dependent trapping, the improved model should more accurately replicate the retention of pollutants associated with particles, as well as account for the variability observed in outlet particulate fractions from event to event. This comparison will determine whether enhanced predictions of particle-bound pollutant removal can effectively represent the system's behaviour, thereby making the model more suitable for accurately depicting both the dissolved and particulate fractions.

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