

Évaluation de la remobilisation de contaminants dans des sols urbains soumis à l'infiltration des eaux pluviales : proposition d'un cadre méthodologique

Evaluating contaminant remobilization from urban soils during stormwater infiltration: a methodological framework

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RÉSUMÉ

En milieu urbain, les projets de gestion des eaux pluviales sont fréquemment confrontés à des sites où le sol présente un fond anthropique élevé (remblais, friches industrielles). L'absence de méthodologie pour évaluer la remobilisation potentielle des contaminants provenant de ces horizons représente un frein pour l'infiltration des eaux pluviales. L'approche proposée combine (1) une démarche de modélisation hydrodynamique de la zone non-saturée, pour estimer la lame d'eau atteignant l'horizon contaminé, et (2) des essais de percolation en colonne, pour évaluer la dynamique de remobilisation de divers contaminants. Les résultats de modélisation suggèrent que les processus capillaires et l'évapotranspiration peuvent contribuer à une réduction significative des flux d'exfiltration dans les systèmes de gestion « à la source ». Sur le plan expérimental, cinq sols ont été caractérisés, représentant un gradient de contamination tout en excluant des cas de pollution concentrée. Les métaux, métalloïdes et hydrocarbures présentaient généralement des concentrations décroissantes en sortie de colonne, avec des niveaux de contamination en phase dissoute du même ordre de grandeur que les concentrations dissoutes observées dans les eaux de ruissellement urbaines. Bien que les concentrations se stabilisent autour d'une valeur modérée, ce « régime permanent » représente une contribution significative au flux massique total exporté de la colonne. Sur l'un des sols étudiés, les percolats présentaient un pH très basique, ce qui souligne une autre forme d'impact à laquelle il convient de demeurer vigilant.

ABSTRACT

In urban areas, stormwater management projects are increasingly faced with constrained sites where the soil displays high anthropogenic backgrounds (backfills, brownfield sites). A methodology is needed to assess the potential remobilization of contaminants from such soil horizons, and thereby the suitability of implementing stormwater infiltration. The present approach combines (1) hydrodynamic modelling in the vadose zone to estimate the water depth reaching the contaminated horizon, and (2) leaching column experiments to assess the concentration dynamics for various contaminants. Modelling results suggest that capillary processes and evapotranspiration may contribute to mitigate exfiltration fluxes by up to 60% in "decentralized" systems. The experimental method was applied to five soils representing a gradient of contamination but excluding cases of severe pollution. Metals, metalloids and hydrocarbons typically exhibited decreasing concentrations at the column outlet, with dissolved-phase contamination levels of the same order of magnitude as the dissolved concentrations found in urban runoff. Flow interruption had a low to moderate impact on contaminant remobilization. The "steady-state" phase nevertheless represented a significant contribution to the total mass load exported from the column. Monitoring of effluent pH also revealed highly alkaline pH for one soil, thus pointing out a potential additional impact of stormwater infiltration that should be looked upon.

MOTS CLÉS / KEYWORDS

Essais de percolation, HAP, Infiltration, Métaux, Sols urbains / Column leaching experiments, Infiltration, Metals, PAHs, Urban soils.

1 INTRODUCTION

In urban areas, stormwater management through infiltration is becoming increasingly popular. However, this shift has also raised new concerns regarding the potential transfer of contaminants towards groundwater. While research efforts have been dedicated to the fate of runoff contaminants in infiltration-based systems, the potential remobilization of contaminants from urban soils with high anthropogenic backgrounds (e.g. backfills or brownfield sites) below infiltration devices has been comparatively overlooked. This represents a crucial issue in a context where urban projects tend to shift towards the rehabilitation of existing (and often constrained) areas. Consequently, a methodological framework is needed to provide insight into the potential impacts of stormwater infiltration under such conditions (e.g. US-EPA, 2013).

Contaminant transfer from urban soils to groundwater would result from the combination of two elements: (1) infiltrated water reaching the contaminated horizon, and (2) remobilization of contaminants upon contact with water. On the one hand, capillary processes in the upper horizon of infiltration-based facilities contribute to a reduction in the volume between inflow and exfiltration, particularly in “decentralized” systems (Flanagan et al., 2019; Hanley et al., 2024). On the other hand, various methodological approaches and scales can be used to assess contaminant mobility in a soil, ranging from lab-scale batch tests to *in situ* studies. For example, the decision flowchart proposed by US-EPA (2013) relies on the “Synthetic Precipitation Leaching Procedure” (US-EPA method 1312), which consists of a batch test in slightly acidified de-ionized water. However, the lack of representativeness of batch tests, widely discussed in scientific and technical literature (RECORD, 2018), often makes column leaching tests a pragmatic compromise to simulate water flow in soil while maintaining controlled and repeatable conditions (Seidl et al., 2022; Skjennum et al., 2023). Hence, the method proposed in the present work builds upon the combination of (1) hydrodynamic modelling in the vadose zone, to simulate water fluxes reaching a certain depth under different configurations, and (2) column leaching tests to evaluate contaminant remobilization as a function of the cumulative water depth.

2 MATERIALS AND METHODS

2.1 Hydrodynamic modelling in the vadose zone

This modelling approach aimed to estimate exfiltration fluxes from a generic infiltration facility implemented above a contaminated soil horizon. This genericity enabled the exploration of various designs and their expected consequences on water fluxes. The facility was described using the following features (Figure 1): catchment-to-infiltration area ratio, depth of the surface storage zone, soil type, and soil thickness above the contaminated horizon. Inflow runoff was calculated based on 10-year precipitation data measured in three French cities with different climates (Lyon, Paris, Nantes). Evapotranspiration records were also applied as an upper boundary condition. Free drainage was prescribed at the bottom of the system. A one-dimensional representation of the system and the processes was adopted. The governing flow equations, *viz.* Richards’ equation combined with the van Genuchten-Mualem relationships for the retention and permeability curves, were solved with the HYDRUS-1D software package.

2.2 Experimental characterization of the soils’ leaching behaviour

2.2.1 Studied soils

Five soils from the *Greater Lyon* metropolitan area were selected for this study, representing a gradient of contamination but excluding cases of severe pollution. In four of the five soils, at least one of the following substances exceeded the 90th percentile of concentrations measured in major French urban areas, as reported in the “BDSolU” urban soil analysis database (<https://www.bdsolu.fr/fr>): As, Cr, Cu, Ni, Zn, and Σ 16 PAHs.

2.2.2 Experimental setup and contaminant analyses

Each soil was sieved to <1 cm, then packed into glass columns (30 cm in height, 10 cm in diameter). The compaction procedure was adapted from ISO 21268-3 with a mass drop height increased to 40 cm, in order to reach a bulk density close to 1 g/cm³. Unsaturated downward percolation was achieved by supplying water from the top at a rate of 40 mm/h ($\approx 10^{-5}$ m/s). After a cumulative water depth of at least 2000 mm, the flow was interrupted for 3 days, then resumed for a second infiltration phase. Aliquots were taken from the column outlet at selected times, filtered at 0.45 μ m, then analysed for several trace metals (Cd, Cr, Cu, Ni, Pb, Zn), metalloids (As, Sb), as well as total hydrocarbons and PAHs when these contaminants had been quantified in the soil. Experiments were carried out in triplicates, except for one soil for which the sample quantity was limited.

2.3 Coupling modelling and experimental results

Concentration data from the column leaching tests were converted into cumulative mass loads of contaminants (in mg/m^2) that would be released by a soil horizon of equivalent thickness and bulk density, as a function of the cumulative water depth. Analytical uncertainties and left-censored data were accounted for to construct “envelopes” representing the range of possible contaminant fluxes for each column. Finally, these experimental results were coupled with modelling outputs, considering that exfiltration fluxes from the infiltration facility correspond to the cumulative water depth reaching the contaminated soil horizon (Figure 1).

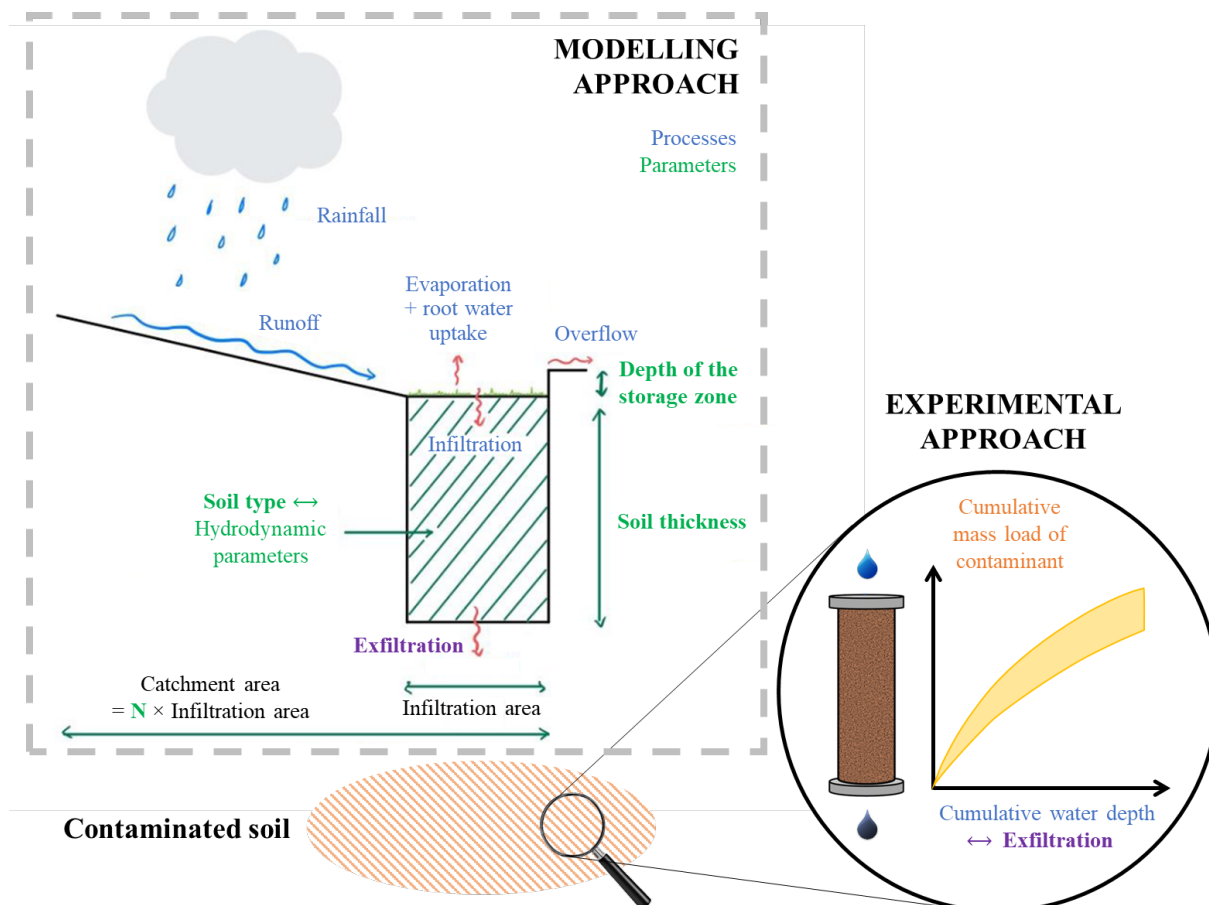


Figure 1 – Schematic representation of the overall methodology combining modelling and experimental approaches.

3 RESULTS & PERSPECTIVES

Due to the space constraints, only the experimental part will be presented in this abstract.

The column leaching tests yielded consistent results between replicates: for most samples, except for the first sample collected after flow was initiated or resumed, differences among triplicates were smaller than the analytical uncertainties. Across the five characterized soils, dissolved-phase concentrations of metals and metalloids ranged as follows: Cd ($<1 \mu\text{g}/\text{L}$) < Cr, Ni, Sb (a few $\mu\text{g}/\text{L}$) < As, Cu (a few tens of $\mu\text{g}/\text{L}$) < Zn (up to $150 \mu\text{g}/\text{L}$). Overall, these concentrations were of the same order of magnitude as those reported for dissolved fractions in urban runoff (Masoner et al., 2019). Pb generally displayed very low levels, except for one soil that leached dissolved Pb concentrations exceeding $100 \mu\text{g}/\text{L}$, even though its total Pb content was comparable to that of the other sites.

For most elements (As being a notable exception), concentrations exhibited a typically decreasing trend with increasing infiltrated water depth, before stabilizing around a value that generally remained above the analytical limits of quantification (Figure 2). Flow interruption was found to have a low to moderate impact on the concentrations, and stabilization was reached more rapidly during the second infiltration phase. This “steady-state” stage in the leaching dynamics nonetheless represented a significant contribution to the total mass flux exported from the column, amounting to a few milligrams up to several tens of milligrams per square meter for

a cumulative water depth equivalent to three times the annual rainfall in Lyon, i.e. ≈ 2500 mm (Figure 2). These findings confirm that the initial peak concentration should not be the only concern when assessing the risks of remobilization toward the aquifer.

Additionally, a possibly overlooked effect that was observed for one soil corresponds to a highly alkaline leachate (pH between 8.5 and 10 throughout the experiment), which may adversely impact groundwater ecosystems. This aspect should be addressed as well when assessing the suitability of a given site for stormwater infiltration, especially as it is relatively independent of the presence of soil contamination.

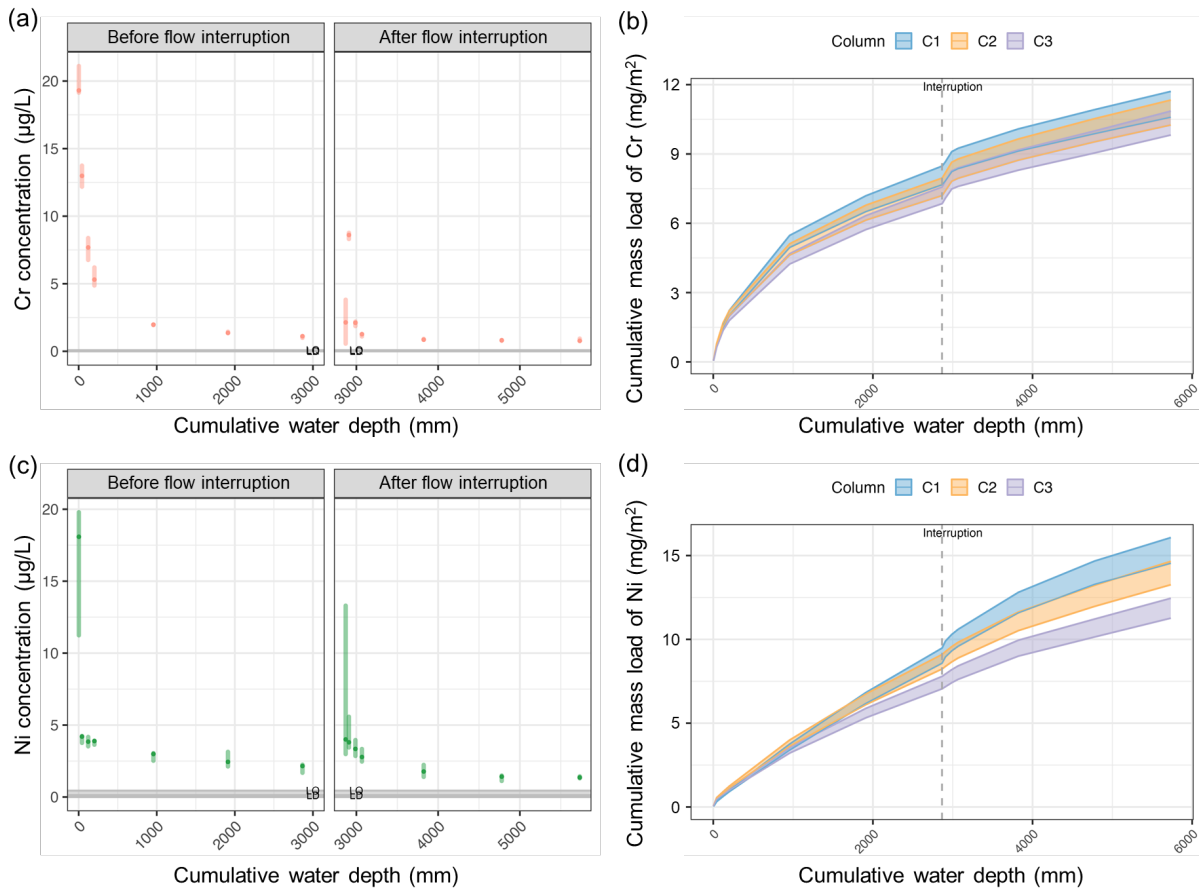


Figure 2 – Experimental results for chromium (a, b) and nickel (c, d) leached from one soil: dissolved concentrations at the column outlet (a, c) and cumulative mass loads (b, d) plotted as a function of the cumulative water depth. Vertical lines in panels (a) and (c) indicate variability between triplicates (min-max range).

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