Can geotextiles modify the transfer of heavy metals transported by stormwater in infiltration basins?

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Abstract Geotextiles are fibrous materials increasingly employed for the design of infiltration basins. However, their influence on the transfer of contaminants carried by stormwater has not been fully investigated. This study, based on column leaching experiments, aims at showing the effect of geotextiles on the transfer of three heavy metals (Zn, Pb and Cd) in a reactive soil (simulating an infiltration basin at laboratory scale). This effect depends on several factors, such as type of geotextile, hydric conditions (geotextile water content), hydraulic conditions (flow-rates) and the number of geotextiles installed. In all cases, geotextiles influence heavy metal retention by modifying flow and thus regulating contact between these metals and the reactive soil.

Keywords Geotextiles; heavy metals; flow; retention

Introduction Geotextiles are synthetic fibrous materials currently used in stormwater infiltration works such as infiltration trenches and ditches, infiltration basins and ponds. In these works, geotextiles are used to fulfil mechanical and hydraulic functions such as soil reinforcement, material separation, and water filtration. The influence of geotextiles on the transfer of contaminants transported by stormwater is seldom taken into account, yet some studies have shown that they can accumulate contaminants such as heavy metals in roads and in stormwater collection and infiltration systems (Legret et al., 1995; Hogland et al., 1987).

The “soil – geotextile” system resulting from the installation of geotextiles within the soil possesses specific characteristics that may differ greatly from those of the original soil. Firstly, geotextiles have specific mechanical, hydraulic and physico-chemical characteristics that differ from most soils (Ingold, 1994). Secondly, geotextiles and soil interact due to several mechanisms such as the migration of fine particles (Watson and John, 1999) and the development of microorganisms (Koerner and Koerner, 1992). These interactions can affect the original properties of the surrounding soil. Following this analysis, the infiltration of stormwater and the transfer of their associated contaminants can differ significantly in a soil amended with geotextiles.

The aim of this study was to describe and explain the influence of several geotextiles on the transfer of three heavy metals (Zn, Pb and Cd) within a reactive calcareous soil. These metals currently contaminate stormwater in urban environments (Valiron and Tabutchi, 1992), are toxic, and have different geochemical behaviors (Sigg et al., 1992). The soil originates from a calcareous fluvio–glacial deposit that fills several infiltration basins in Lyon (France). Leaching column experiments were conducted to simulate the transfer of the metals in the soil alone and the same soil amended with geotextiles. The soil was kept...
saturated to ensure constant hydraulic behavior. Several geotextiles were tested with several water contents. The influence of geotextiles was also tested vis-à-vis injection flow rates to complete previous studies for which just one flow rate was used (Lassabatere et al., 2004). This paper synthesizes all the results and focuses on technical improvements to be made in the use of geotextiles in infiltration basins.

Material and methods

Material

The soil corresponds to granulometric fraction <1 cm of the fluvio-glacial deposit that fills the “Django Reinhardt” infiltration basin in Lyon (France). The soil inherited the characteristics of the whole deposit, displaying heterogeneous and multimodal particle size distribution and a calcareous nature. Its high carbonate content (25%) results in a high pH (8.7) and a high reactivity relative to heavy metals (Plassard et al., 2000). Three geotextiles currently used in civil and environmental engineering and in infiltration basins in particular, have been tested: a needle-punched geotextile with long fibres (GNL), another with short fibres (GNS) and a thermosealed geotextile (GT) (Table 1). All are made of polypropylene. For the needle-punched geotextile, fibre cohesion is ensured by needle punching (penetration of needles). Cohesion of the thermosealed geotextile is ensured by compression and heating. The process (needlepunching or thermosealing) and fibre characteristics such as component and length affect the subsequent characteristics of geotextiles and their hydraulic behavior in particular. Before use, all the geotextiles were washed with sulfochromic acid to eliminate all production additives.

Leaching column experiments

Leaching columns were made of high-density polyethylene of 10 cm width and 30 cm long. The soil was introduced at 8% mass water content, which led to an average dry density of 1.81 g.cm$^{-3}$. The geotextiles were installed either dry or saturated depending upon the desired water content. In the second case, the geotextiles were saturated for more than 72 h to ensure complete saturation. Before being subjected to solute injections, columns were saturated using Mariotte bottles for 24 h. The total water volume ($V_0$) averaged 600–650 cm$^3$, and the soil saturation degree averaged 75%.

Water and solutes were injected upwards at a constant flow rate by a peristaltic pump. Initially, 1 $V_0$ of neutral solution was injected to reach steady state flow. This neutral solution was made of sodium nitrate (NaNO$_3$) at $10^{-2}$ mol.l$^{-1}$ dissolved in deionized water. Columns were then subjected to the injection in pulse mode of a tracer solution composed of potassium bromide (KBr) at $10^{-2}$ mol.l$^{-1}$ in deionized water: 0.56 $V_0$ width pulse followed by 5.5 $V_0$ of neutral solution. Bromide concentrations at the inlet and outlet were measured by ionic chromatography. The metals were then injected into the columns with 6.5 $V_0$ of metal solution (step mode) composed of zinc (Zn(NO$_3$)$_2$), lead (Pb(NO$_3$)$_2$), and cadmium (Cd(NO$_3$)$_2$) nitrate at $10^{-3}$ mol.l$^{-1}$ in deionized water. Its ionic strength was adjusted to $10^{-2}$ mol.l$^{-1}$ by adding sodium nitrate (NaNO$_3$). The heavy metal concentrations were measured at the inlet and the outlet with flame atomic adsorption spectroscopy (FAAS).

Table 1 Geotextile characteristics

<table>
<thead>
<tr>
<th>Fibre length</th>
<th>Thickness (mm)</th>
<th>Weight (g cm$^{-2}$)</th>
<th>Filtering opening size (µm)</th>
<th>Porosity (%)</th>
<th>Hydraulic conductivity (ms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNS</td>
<td>cm</td>
<td>5.0</td>
<td>620</td>
<td>55</td>
<td>86.5</td>
</tr>
<tr>
<td>GNL</td>
<td>m</td>
<td>5.8</td>
<td>720</td>
<td>50</td>
<td>86.5</td>
</tr>
<tr>
<td>GT</td>
<td>m</td>
<td>0.75</td>
<td>220</td>
<td>80</td>
<td>87.5</td>
</tr>
</tbody>
</table>
Solute elutions were characterized by their breakthrough curves, by plotting the relative concentrations at the outlet ([Solute]/[Solute]₀) against the relative eluted volume (V/V₀). Bromide mass balance and retardation factors were estimated by using the zero and the first order moments (Sardin et al., 1991). Bromide experimental elution was modeled with the MIM transport model. This model assumes that water is fractionated into a mobile fraction active in mass transport (fₘ), a stagnant immobile fraction (fᵢₘ) and an isolated fraction (fᵢₛ). The solutes are transported by convection and dispersion in mobile water and diffuse at the interface between the mobile and the immobile fractions with a first-order rate (van Genuchten and Wieranga, 1976). Fitting experimental data with MIM provided estimations of the fractions (fₘ, fᵢₘ, fᵢₛ) and the first-order solute exchange rate (α), which facilitates the characterization of flow homogeneity. The model was developed on MathCad Professional by LTHE (Grenoble). Metal elution was quantified by relative heavy metal concentrations at 6V₀ (C/C₀(6)). Heavy metal global retentions (Rₘₑ) were estimated as the percent of the total amount retained in the columns and were used to quantify the retention efficiency. They were estimated from the zero order moment of the heavy metal elution curves.

**Experimental schedule**

The leaching column experiments were performed in triplicate. The three geotextiles (GNS, GNL and GT) were tested with two different configurations: a simple configuration with a geotextile at the middle of the columns while the second used two geotextiles, one at the middle and the other at a quarter of the total length from the inlet. As described above, the geotextiles were installed either dry or wet. The control of water contents at the end of injections proved that the geotextiles placed dry presented far lower water contents. Two flow rates were tested (q = 7.3 × 10⁻² cm.min⁻¹ and Q = 19.2 × 10⁻² cm.min⁻¹) and had the same magnitude as the saturated hydraulic conductivity of the deposit. The experimental schedule is described in Table 2.

The data was treated using normalized principal component analysis (PCA). Let us consider a matrix M, containing all data, with n rows (individuals) and p columns (variables). The rows correspond to the leaching column replications (QS, QGNLd, QGNLw, etc.) and the columns correspond to variables (fᵢₘ, fₘ, α, C/C₀(6), Rₘₑ). To avoid redundancy of information (fᵢₘ + fₘ + fᵢₛ = 100%), only mobile and immobile fractions are considered for PCA analysis. Each individual is considered as a vector of space Rⁿ whose coordinates are its scores relative to the p variables. Each variable is considered as a vector of space Rᵖ whose coordinates are its values scored by all the individuals. PCA determines the principal components that maximize the inertia of the orthogonal projections onto them. These

<table>
<thead>
<tr>
<th>Column</th>
<th>Flow rate (cm.min⁻¹)</th>
<th>Geotextile</th>
<th>Hydric state</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q S</td>
<td></td>
<td>None</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Q GNL w</td>
<td>19.2 × 10⁻²</td>
<td>GNL</td>
<td>wet</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>Q GNL d</td>
<td></td>
<td>GNL</td>
<td>dry</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>Q GNS d</td>
<td></td>
<td>GNS</td>
<td>dry</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>q S</td>
<td></td>
<td>None</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>q GNL w</td>
<td></td>
<td>GNL</td>
<td>wet</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>q GNL d</td>
<td></td>
<td>GNL</td>
<td>dry</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>q 2 GNL d</td>
<td>7.3 × 10⁻²</td>
<td>2 GNL</td>
<td>dry</td>
<td>geo. at L/2 and at L/4</td>
</tr>
<tr>
<td>q GNS d</td>
<td></td>
<td>GNS</td>
<td>dry</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>q 2 GNS d</td>
<td></td>
<td>2 GNS</td>
<td>dry</td>
<td>geo. at L/2 and at L/4</td>
</tr>
<tr>
<td>q GT d</td>
<td></td>
<td>GT</td>
<td>dry</td>
<td>geo. at L/2</td>
</tr>
<tr>
<td>q 2 GT d</td>
<td></td>
<td>2 GT</td>
<td>dry</td>
<td>geo. at L/2 and at L/4</td>
</tr>
</tbody>
</table>
components form an orthonormal basis of the space and correspond to the eigenvectors of matrices $M^T M$ or $T M M$, depending on whether individuals or variables are considered. The quality of the projection is quantified by the ratio of the “explained inertia” over the total inertia. This ratio is measured as the ratio of the principal component eigenvalues over the sum of all the eigenvalues (i.e. the trace of matrix $M^T M$). The principal component analysis lists the eigenvalues (by decreasing order), the corresponding eigenvectors (principal components) and provides the maps of the projection of variables and individuals onto the principal components (Dagnelie, 1984). The maps of the projection of variables can be interpreted in terms of correlation between variables. If two variables are close or opposite to each other, their correlation is significant. If two variables are orthogonal, they can be considered as independent. In the case of individuals, if two of them are close to each other, they can be considered as similar. Otherwise, they are considered as significantly different. Variable and individual maps facilitate the interpretation of all these data by highlighting the correlations between variables and the resemblance between individuals.

Results

Firstly, the results show that geotextiles had an effect on both flow and heavy metal retention while, secondly, that the experimental procedure was capable of quantifying these effects. Leaching columns ($q_S$ and $q_{GT}$) are presented below in order to illustrate this.

In all cases, experimental bromide elution was well modeled and the fractions ($f_m$, $f_{im}$ and $f_{is}$) and the solute exchange rate ($\alpha$) could be estimated efficiently (Figure 1(a)). For column $q_S$, elution is characterized by an asymmetrical shape with substantial tailing (Figure 1(a)). This reveals that the flow is heterogeneous (Sardin et al., 1991). The MIM model confirmed this heterogeneity by providing considerable immobile and isolated fractions at the expense of the mobile fraction (50.7%). For columns $q_{GT}$, bromide elution was more symmetrical (Figure 1(a)). This reveals a more homogeneous flow. The MIM model provided a higher mobile fraction (around 80%) at the expense of lower immobile and isolated fractions. Thus bromide elution analysis and modelling proved accurate and pertinent in quantifying the effect of geotextiles on flow.

Considering heavy metal elution, lead was never eluted, whereas zinc and cadmium were eluted at a molar ratio of 1:1. The geotextiles did not disturb this pattern as illustrated by

![Figure 1](image_url)

**Figure 1** (a) Bromide experimental elution (points) and the MIM model (lines) (b) heavy metal elution for columns of soil ($q_S$) and of soil amended with the geotextile GT dry ($q_{GTd}$) at flow rate $q$. 

Downloaded from https://iwaponline.com/wst/article-pdf/51/2/29/434835/29.pdf
columns $qS$ and $qGT$ (Figure 1(b)). Geotextile GT decreased the elution of zinc and cadmium similarly, without breaking their association. The relative concentrations were decreased from 14.1% to 0.8% for zinc and from 14.6% to 0.9% for cadmium. Global retention was increased from 95.6% to 99.95% for zinc and from 95.96% to 99.94% for cadmium. Consequently, cadmium can be considered as a good indicator of heavy metal elution. Thus we present only results relative to cadmium.

To avoid a lengthy description of the whole dataset, the PCA results are presented directly. According to the eigenvalues (Table 3), the two first principal components explain nearly 95% of the inertia, which is quite good (Dagnelie, 1984). Thus, the projection of the variables and the individuals on the factorial plane defined by these components conserves most of the information (Figures 2 and 3).

The projection of variables on the factorial plane shows several correlations (Figure 2). The first component (axis $F_1$) is positively correlated with global retention and negatively correlated with elution. This axis represents the global efficiency of retention in columns. The second axis is explained by the opposition between the exchange coefficient – the positive coordinate on axis $F_2$ – and the immobile fraction – the negative coordinate on axis $F_2$. This results from the fact that for certain leaching columns, modifications of flow homogeneity affected the value of the exchange coefficient more, whereas for others, it affected the value of the immobile fraction more. Nevertheless, this axis explained the inertia far less efficiently than axis $F_1$ and thus could be considered as not very pertinent or meaningful. The main result illustrated in Figure 2 is that the variables relative to flow

![Figure 2](https://iwaponline.com/wst/article-pdf/51/2/29/434835/29.pdf)

**Figure 2** Projection of variables on the two-component subspace (correlation circle)
homogeneity (mobile and immobile fractions) are closely correlated with axis $F_1$. This means that the degree of flow homogeneity and retention efficiency are positively correlated. In other words, significant mobile fractions correspond to significant retention and low elutions. This results from the fact that homogeneous flow ensures better contact between heavy metals and reactive soil. When flow pathways run through all the soil, heavy metals can easily reach all its reactive particles and thus be retained. On the contrary, the fractionation of water, with significant immobile and isolated fractions, decreases the heavy metals/soil contact and thus their retention (Lassabatere et al., 2004).

The projection of individuals (leaching columns) on the factorial plane is illustrated in Figure 3. Individuals of each series are linked to a common centre of gravity thus form a star. This figure scatters the columns tested at high flow rate $Q$ on the one hand, and the columns tested at low flow rate $q$ on the other. This scattering may result from the effect of flow rate on retention efficiency. The change in flow rates triggers a change in solute mean residence times and thus in contact times between the heavy metals and the reactive soil. Consequently, global retention efficiency is then modified.

At high flow rate $Q$, the columns of soil ($QS$) cannot be distinguished from the columns amended with geotextiles ($QGNLd$, $QGNSd$ and $QGNLw$). All the stars overlap and, none of them can be really distinguished from the others, proving that the geotextiles have no significant influence on flow and heavy metal retention. On the contrary, at lower flow rate $q$, the stars can be distinguished from the others, so that we can assume that geotextiles

![Figure 3 Projection of individuals (leaching columns) on the two-component subspace](https://iwaponline.com/wst/article-pdf/51/2/29/434835/29.pdf)
significantly affect flow and heavy metal retention. The stars can be gathered into subgroups along a straight line \( (D) \) (Figure 3). From the bottom left side to the top right side: subgroup (1) of the soil columns \( (qS) \), subgroup (2) of the soil columns amended with the dry needlepunched short fibre geotextile placed dry \( (qGNSd) \) and with the needlepunched long-fibre geotextile placed wet \( (qGNLw) \), subgroup (3) of the soil columns amended with the needlepunched long-fibre geotextile placed dry \( (qGNLd) \) and, lastly, subgroup (4) of the soil columns amended with the thermosealed geotextile \( (qGTd) \) and two geotextiles placed dry \( (q2GNLd, q2GNSd \text{ and } q2GTd) \). The subgroups at the bottom on the left correspond to a heterogeneous flow and a low retention. On the contrary, on the top right side, the subgroups correspond to a homogeneous flow and optimal retention. The position of the subgroups in relation to soil columns \( (qS) \) on straight line \( (D) \) quantifies the degree of flow homogenization and improved heavy metal retention due to the geotextiles.

The projection of individuals highlights the significant effect of geotextiles on flow and heavy metals retention. It also highlights that their effect depends on several factors. Firstly, the flow rate must be sufficiently low. If the flow is too strong, the effect of the geotextiles appears negligible. Secondly, the water content of the geotextiles must be sufficiently low. For instance, the needlepunched long fiber geotextile has no effect on flow or heavy metal retention, when placed wet \( (qGNLw – \text{ subgroup } 2 – \text{ Figure 3}) \). On the contrary, the same geotextile placed dry \( (qGNLd – \text{ subgroup } 3) \) significantly homogenized flow and decreased heavy metal retention. The type of geotextile also plays an important role. Under the same installation conditions (i.e. dry), the effects were far more significant for the thermosealed geotextile \( (qGTd – \text{ subgroup } 4) \) than for the two other geotextiles \( (qGNSd \text{ and } qGNLd – \text{ subgroups } 2 \text{ and } 3) \). Lastly, all the columns amended with two geotextiles (subgroup 4) ensured a quasi-homogeneous flow with almost-total heavy metal retention. Adding the second geotextile led to a very efficient retention system.

**Conclusion**

This study proved that the introduction of geotextiles in a reactive soil affected the transfer of certain heavy metals. Geotextiles had no direct effect such as chemical retention or filtration of particles and associated metals (Lassabatere, 2002). They modified heavy metal retention only by regulating flow and thus the contact between the heavy metals and the reactive soil. Their effect was optimized for certain hydric conditions (low water content in the geotextiles), type of geotextile (thermosealed) and configuration (two geotextiles in the columns).

These conclusions confirm previous studies (Lassabatere et al., 2004) and bring into relief new information: flow rate must be low enough to favor the positive effect of geotextiles. These studies show that geotextiles can be used in infiltration basins but that this use should be optimized by design and operational parameters. For the site used in this study, mention can be made of the following technical recommendations. Geotextile water content should be kept low enough to ensure a positive effect on flow and heavy metal retention, but also high enough to let water pass through it in order to prevent any capillary effect jeopardizing efficient operation (Morris et al., 1999). Concerning design, great care must be taken when choosing geotextiles, though it appeared that thermosealed geotextiles were the most efficient. Geotextile wettability, i.e. its capacity to saturate via capillarity, should be low enough to prevent any easy and systematic saturation (Dierickx, 1996). Geotextiles that are sold with additives to increase their wettability should be washed prior to their installation in infiltration basins.

Concerning the operational phase, inlet flow rates and water levels in the basins should be controlled to avoid excessive water pressure on the geotextile, preventing their total saturation. However, great care should be taken to ensure that the geotextile has sufficient water content to prevent any excessive capillary effect unfavorable to good infiltration basin...
operation. Water content could be monitored by using air injection wells, such as those developed for tensiometric barriers (Morris et al., 1999; Thomson et al., 1996). Nonetheless, this advice is specific for this particular case. Further research is needed to investigate other factors, such as geotextile clogging with local accumulation of fine reactive particles and the development of microorganisms, which can interact directly or indirectly with heavy metals (Nealson and Stahl, 1998). Each case should be carefully investigated using laboratory experiment to take into account the type of contaminants involved, the nature of the soils and the prevailing hydric and hydraulic conditions.

Acknowledgement
The authors thank all the organizations that sponsored this study and in particular the Rhône Alpes Region, “Les Entretiens Jacques Cartier”, the French Ministry of Education and Research, and the French Ministry of Foreign Affairs. The authors also thank Michel Bisping (Laval University, Quebec), Martine Ghidini-Fatus and Marc Danjean (LSE, ENTPE, France). The English was corrected by Keith Hodson.

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