Intensified Nature-based solutions for micropollutant removal from Combined Sewer Overflows: from laboratory experiments to pilot design

Solutions basées sur la nature optimisées pour l'élimination des micropolluants provenant des surverses des déversoirs d'orage : des essais en laboratoire au dimensionnement d'unité pilote

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RÉSUMÉ

Les surverses de déversoir d'orage (SDO) se produisent lorsque des précipitations intenses dépassent la capacité hydraulique des réseaux d'égouts unitaires et des ouvrages de rétention, entraînant le rejet d'eaux usées non traitées mélangées aux eaux pluviales dans la masse d'eau réceptrice. Outre les contaminants conventionnels, les SDO transportent un large éventail de micropolluants, venant des effluents domestiques et industriels (produits pharmaceutiques et des résidus de produits d'hygiène) et du ruissellement (pesticides et microplastiques). Dans cette étude, des solutions fondées sur la nature (SFN) ont été développées pour le traitement des SDO dans le bassin versant de la Sûre, une zone transfrontalière entre le Luxembourg et la Belgique (Wallonie). Des matériaux locaux ont été sélectionnés, puis caractérisés en fonction de leur aptitude à servir de substrats pour des systèmes de biorétention. Des essais en mésocosmes (eau synthétique, molécules actives ajoutées, température constante) ont été réalisés et ces systèmes ont atteint des rendements d'élimination supérieurs à 92 % pour 18 micropolluants ciblés. En outre, des biochars locaux ont été évalués en tant que substrat additionnel aux sables conventionnels afin d'améliorer les performances de la SFN. Les résultats de cette première phase sont présentés ci-dessous et ont été utilisés pour dimensionner des unités pilotes qui seront installées dans le bassin versant de la Sûre, tant du côté luxembourgeois que du côté belge.

ABSTRACT

Combined sewer overflows (CSOs) occur when the discharge in combined sewer systems exceeds the hydraulic capacity of the WWTP and storage volume in the system is reached. This results in the discharge of untreated wastewater/stormwater mixtures into receiving water bodies. In addition to conventional contaminants, CSOs convey a broad spectrum of micropollutants, from domestic and non-domestic sewage (e.g. pharmaceuticals, personal care product residues) and from surface runoff (e.g. pesticides, and microplastics). In this study, Nature-based solutions (NBS) were developed for the treatment of CSO discharges within the Sûre catchment, a cross-border area between Luxembourg, Germany and Belgium (Wallonie). Locally available materials were selected and subsequently characterized for their suitability as substrates in retention soil filters. Under controlled mesocosm conditions (i.e. synthetic water, spiked active ingredients, constant temperature), these systems achieved removal efficiencies exceeding 92% for 18 targeted micropollutants, in average. Furthermore, locally produced biochars were evaluated as potential admixture components to conventional sand substrates to enhance micropollutant removal from CSO discharges. The outcomes of this first phase have been used to design pilot plants that are installed in the Sûre catchment, both in Luxembourgish and Belgian sides. The presentation will also contain first results obtained from these pilots.

KEYWORDS

Combined sewer overflows, micropollutants, retention soil filter, nature-based solutions

1 INTRODUCTION

The implementation of recent water policies —most notably the revised Urban Wastewater Treatment Directive (UWWTD, 2024)—has heightened attention on the role of Combined Sewer Overflow (CSO) discharges in degrading surface water quality and has prompted proposals for more stringent control measures. CSOs, traditionally viewed as contributors of solids, organic matter, nutrients, and pathogens, are now recognized as major vectors of a wide spectrum of micropollutants. These include pharmaceuticals, household chemicals, personal care product residues, pesticides, microplastics, and industrial compounds. During heavy rainfall events, when hydraulic loads exceed WWTP capacity and the storage volume of the sewers, untreated or partially treated wastewater is released directly into receiving water bodies. Such episodic - but highly concentrated - discharges can severely impact aquatic ecosystems by altering oxygen dynamics, increasing microbial contamination, and introducing persistent organic pollutants and metals that accumulate in sediments and biota. Because these substances often occur in complex mixtures and may interact synergistically, their ecological and human-health implications are difficult to predict. Moreover, conventional mechanical-biological wastewater treatment processes —while indispensable — are not designed to fully remove many emerging contaminants. Effective management demands a catchment-wide perspective that accounts for all emission sources, including diffuse agricultural runoff, urban stormwater, small settlement discharges, and legacy contamination. Such an integrated approach is essential to inform regulatory frameworks and guide evidence-based policy and investment decisions.

The Interreg Greater Region–funded QualiSûre project aims to respond to this multifaceted challenge by developing a comprehensive master plan for preserving and improving the water quality of the Upper Sûre Lake. With a storage capacity of 60 million m³, the Upper Sûre Lake not only supplies a hydroelectric power plant but also functions as Luxembourg's most important drinking water reservoir. It currently provides 43% of the country's annual water demand and supplies 79 of its 102 municipalities. These functions underline the strategic importance of maintaining both the quality of the lake's water and the reliability of its overall ecosystem services. The reservoir's catchment extends over 428 km², two-thirds of which is located in Wallonia, Belgium. Today, 40 wastewater treatment plants (WWTPs) and 60 rainwater systems discharge into the Sûre River, including 6 WWTPs located in Wallonia. Consequently, pollutant loads originate from both sides of the border, making it clear that substantial improvements in water quality can only be achieved through coordinated, cross-border action.

In line with the strategic priorities of the Greater Region, Nature-based Solutions (NBS) (particularly Retention Soil Filters, RSF) have been selected to address point-source pollution, especially at critical emission hotspots within the Sûre catchment. These solutions are conceived to blend seamlessly into the existing landscape while enhancing local biodiversity. Preference is given to the use of locally sourced materials—such as sand-based substrates—or materials derived from circular economy processes, including biochar produced from cellulose or plant-based waste residues. This not only strengthens the environmental sustainability of the interventions but also reduces transport-related emissions and costs.

2 MATERIALS AND METHODS

The methodological framework used in this project consists of the following fundamental steps:

1. **Substrate preselection and characterization**

Nine sands originating from the Greater Region (four from Luxembourg L-Brouch-corr, L-Brouch-rem, L-Folchette-beton, L-Bech-Moselle; four from Germany D-Rhine, D-Lava, D-Saar, D-Liapor; one from Belgium B-Hoslet) were selected taking into account i) geographic location and geological configuration, ii) quarries databases and iii) provided supplier datasheets. These materials were then characterized via granulometry analysis, chemical composition (i.e. proximate analysis, alkaline saturation, BET etc.) and bioavailability (i.e. Ion/cation exchange capacity and elemental composition) before being selected for further laboratory testing. As NBS design demonstrated to enhance performance towards pollutant degradation when intensified with the addition of admixtures (Brouwir et al, 2025, Salmeron et al., 2024, Venditti et al. 2024), the possibility to use locally produced biochar was explored. Ponceret-C, Terre-C and TCharBon-C biochars locally pyrolyzed in Wallonia were tested with conventional kinetic studies and their adsorption evaluated in comparison to two biochars widely applied in previous studies: Emisûre-AC purely produced from plant residues and WOW-AC produced from recovered cellulose from toilet paper, both activated biologically by fermentation.

2. Mesocosm test under controlled conditions (lab scale)

Six Soil Filters (Figure 1) (SF1: Rhine sand, 20 % CaCO3, 15% granular activated carbon (GAC); SF2: Rhine sand, 20 % CaCO3, 15% biochar from plant residues activated biologically (Emisûre-AC); SF3: Mosel sand, 20 % CaCO3, 15% AC; SF4: Mosel sand, 20 % CaCO3; SF5: Lavasand; SF6: Expanded sand, 15% Emisûre-AC) were designed based on the results of the preselection. The substrates were planted with *Phragmites australis* and *Iris pseudacorus* - common macrophytes used in NBS, also applied in prior projects such as Interreg Greater Region funded EmiSûre and CoMinGreat (Brouwir et al, 2025, Salmeron et al., 2024, Venditti et al. 2024, Venditti et al. 2021).

The configurations were tested at mesocosm laboratory scale (25 L volume with an initial Hydraulic Loading Rate (HRL) of 30 L/m2 day) with synthetic wastewater (Chemical Oxygen Demand=70 mg/L, Total Nitrogen=10 mg/L, Total Phosphorous= 3 to 6 mg/L, Ammonium Nitrogen=6 mg/L) spiked with 5 µg/L of 18 micropollutants, which were selected to be considered as reference parameters for untreated wastewater and CSO (i.e. ibuprofen and paracetamol), surface and street run off (i.e. 1,3-Diphenylguanidine (DPG), Hexamethoxymethyl-Melamine (HMMM), PPD-Quinone), and diffuse pollution from agriculture (i.e. Metolachlor).

Figure 1: Mesocosms installation at University of Luxembourg

3. Identification of pollution hot spots

Possible locations for the pilot plant were jointly selected with the Luxembourgish and Belgian water authorities and WWTP operators, based on monitored overflow activities, available infrastructure, and overall relevance for the sensitivity of receiving water bodies. Seven locations were initially identified and later reduced to four by considering infrastructural criteria such as: i) accessibility of the facilities, ii) availability of power supply and iii) availability of Wi-Fi, etc.

4. Pilot test

Potential pilot plant locations for CSO treatment were identified and designed according to Table 1. The pilots are currently being constructed and expected to be monitored during 2026.

Table 1: Selected pilot locations and design specifications

	Surre (L)	**Martelange (L)**	**Vaux-sur-Sure (B)**	**Tintage (B)**
Substrate	Lavasand	Mosel sand	Mosel sand	Mosel sand
Admixture	No	GAC layer	TCharBon-C layer	TCharBon-C layer
Macrophytes	Phragmites australis Iris pseudacorus	Phragmites australis Iris pseudacorus	Phragmites australis Iris pseudacorus	Phragmites australis Iris pseudacorus
Configuration	Vertical flow	Vertical flow	Vertical flow	Horizontal flow

3 RESULTS AND OUTLOOK

Preliminary results from mesocosm scale show more than 92 % elimination for the 18 compounds – in average -

under controlled conditions. When looking at the effect of adding a biochar to intensify the performances (Figure 2), the soil filter results to be more effective in the removal of micropollutants from wastewater with high stability and thus low variation. This enhancement is particularly evident when looking at the removal of metolachlor and carbamazepine.

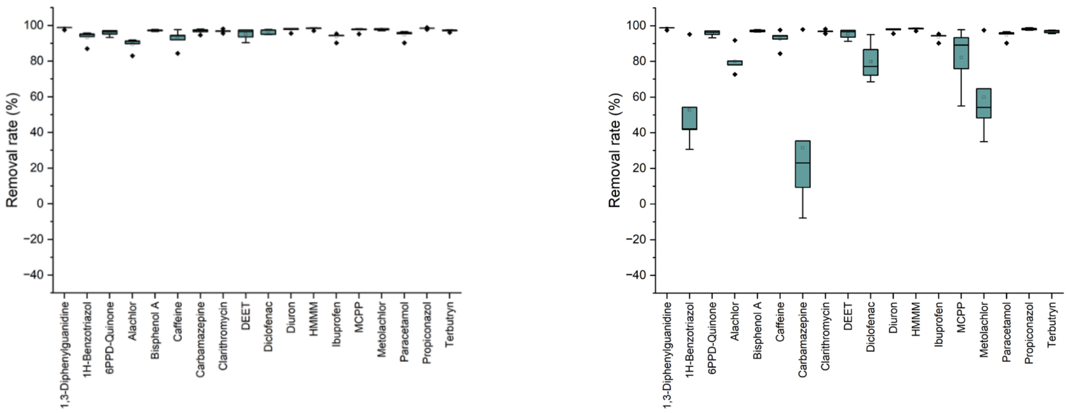

Figure 2: Removal of 18 compounds when SF3 is intensified (left) compared to the absence of admixture, SF4 (right)

Adsorption jar test studies showed higher performance of TCharBon-C, Terre-C and Ponceret-C with similarities to conventional GAC (Figure 4, diclofenac kinetics as example). For this reason and its commercial availability, TCharBon-C was selected to be applied as local admixture in the retention soil filter pilots operated in Wallonia.

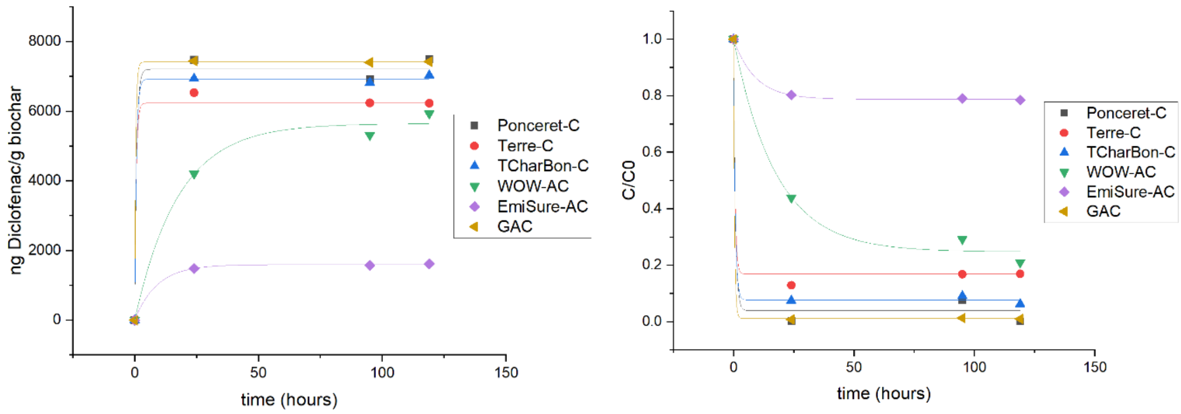

Figure 4: Kinetics of biochars towards the removal of diclofenac

The conference contribution will also cover first results of the pilot plants.

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