

Evaluating Performance of Zeolite Amendments for Enhancing Heavy Metal Retention in Infiltration Swales

Évaluation des performances des amendements à base de zéolite pour améliorer la rétention des métaux lourds dans les rigoles d'infiltration

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RÉSUMÉ

Les zones urbaines sont confrontées à des défis croissants liés aux phénomènes météorologiques extrêmes, ce qui nécessite le développement de solutions d'infrastructures vertes multifonctionnelles. Les rigoles d'infiltration sont largement utilisées pour gérer les eaux pluviales, mais leur performance à long terme est compromise par l'accumulation de métaux lourds, en particulier le cuivre provenant des eaux de ruissellement des toits. Cette étude évalue le potentiel des amendements à base de zéolite pour améliorer la rétention des métaux lourds et la conservation des sols dans les rigoles d'infiltration. Un dispositif expérimental semi-technique comprenant 18 rigoles végétalisées a été mis en place, comparant trois configurations : sol normal, mélange sol-zéolite et couche superficielle de zéolite, associées à différentes communautés végétales. Les eaux pluviales provenant d'un toit en cuivre seront appliquées sur une période d'un an, avec une analyse de l'efficacité de l'élimination du cuivre, de la contamination du sol et du potentiel de régénération de la couche de zéolite. Des tests complémentaires en laboratoire seront utilisés pour évaluer la cinétique et la capacité d'adsorption. Les résultats visent à déterminer la rétention des polluants, la durabilité et les avantages en termes de biodiversité, afin de soutenir des stratégies durables de gestion des eaux pluviales en milieu urbain.

ABSTRACT

Urban areas are facing increasing challenges from extreme weather events, necessitating the development of multifunctional green infrastructure solutions. Infiltration swales are widely used to manage stormwater, but their long-term performance is compromised by the accumulation of heavy metals, in particular copper leached from roof surfaces. This study evaluates the potential of zeolite amendments to enhance heavy metal retention and soil conservation in infiltration swales. A semi-technical experimental setup with 18 vegetated troughs was established, comparing three configurations: regular soil, soil-zeolite mix, and a zeolite surface layer, combined with either a designed plant community or a standard lawn seeding. Stormwater from a copper roof will be applied over a one-year period, with analyses of copper removal efficiency, soil contamination, and the regeneration potential of the zeolite layer. Complementary laboratory tests will be used to assess adsorption kinetics and capacity. The findings aim to determine pollutant retention, durability, and biodiversity benefits, supporting sustainable stormwater management strategies in urban environments.

KEYWORDS

Zeolite, infiltration swales, copper, stormwater treatment, urban green infrastructure

1 INTRODUCTION

Heavy rain events, prolonged drought periods, and days with extreme heat are all challenges cities face today (Kind et al., 2019; Rosenzweig et al., 2018). In the future, some of these may become even more acute in certain cities as climate change progresses. These problems are affecting the people in cities either directly or indirectly, e.g., extreme heat can directly lead to dehydration or heatstroke, or indirectly, for example, to kidney diseases (World Health Organization, 2021).

To reduce the impact of these weather events, green elements in the city are particularly recommended, known as urban green infrastructure (UGI), sometimes also called blue-green infrastructure (Kind et al., 2019; World Health Organization, 2021). One example of these UGI is swales with engineered soil to promote infiltration and purify water, called infiltration swales (DWA-A 138-1, 2024). These elements can also store water, hence mitigating risks from heavy rain events, and contribute to evapotranspiration through their vegetation.

However, these elements require a significant amount of space and are therefore not easily implementable, especially in dense cities. Due to fierce competition for space, infiltration swales should not only be used as technical structures for water management but also serve as multifunctional areas that, for example, enhance biodiversity in cities. Examples of applications include infiltration of stormwater runoff from roads or roof surfaces (DWA-A 138-1, 2024).

Due to different types of water contamination, a distinction must be made between these two sources. Both contain organic pollutants, such as biocides, and inorganic contaminants, including heavy metals. However, street runoff, for example, has a significantly higher share of particulate contaminants, whereas pollutants from roof surfaces are predominantly dissolved (Charters et al., 2025; Kayhanian et al., 2012). The pollutants are often present in ecotoxic concentrations that significantly exceed legal limits (LeFevre et al., 2015). Infiltration swales must therefore be highly effective at removing contaminants so that the infiltrating water does not pose a risk to groundwater. Regarding heavy metals, infiltration swales face the problem of accumulation, which can lead to migration of heavy metals in deeper soil and result in a risk to groundwater (Rommel et al., 2019). Additionally, heavy metals are non-degradable; therefore, the soil in infiltration swales becomes highly contaminated.

To mitigate these challenges, a wide variety of additives are being investigated, in particular to increase the retention of pollutants in soils (Westholm, 2023). Zeolite, for example, is a promising material. It is a group of aluminosilicates that have a porous structure and a high ion exchange capacity. It is already being used successfully in technical filters for stormwater runoff from roof surfaces (Milovanović et al., 2022). Laboratory tests and tests on a technical scale for swales also showed promising results (Wilfong et al., 2021). However, these tests were not extensive and covered only a few rain events. The aspect of biodiversity in relation to amendments has also not been examined in detail.

Therefore, we decided to investigate zeolite further. We not only focus on improved removal but also on soil conservation. We want to answer the following questions with our investigations:

1. How much does zeolite, as an additive in the vegetated soil zone, reduce the concentration of copper in stormwater from copper roofs during treatment, and does the type of application (mixing or layering) have a significant influence?
2. To what extent can zeolite, as a layer on top of infiltration swales, protect the underlying vegetated soil zone from pollutants, and can this layer be regenerated for multiple uses?
3. Does using a designed plant community in vegetated soil zones enhance the retention of copper during stormwater treatment?

2 METHODS

Based on the positive results in laboratory tests in the literature regarding the retention of copper using zeolite (Wilfong et al., 2021) a semi-technical test setup was chosen, accompanied by laboratory tests.

2.1 Semi-Technical Experiments

At the end of August 2025, 18 pilot-scale infiltration swales with a surface area of approximately 1 m² each and varying soil structures were installed. At the bottom, all swales have a 20 cm thick layer of gravel to achieve sufficient dewatering of the soil above. Additionally, a 30 cm thick layer of either regular soil or a soil mix is applied. Above the soil layers, there is an additional 30 cm of freeboard that can be dammed up during heavy rainfall events. The regular soil is a mixture of topsoil for planting purposes and sand, meeting the soil requirements outlined in the German technical guideline DWA-A 138-1 (2024) for infiltration swales. The soil mix consists of regular soil and clinoptilolite, a mineral from the zeolite group, in a 6:1 volume ratio. On some of the troughs filled with regular soil, an additional 5 cm layer of zeolite was put on top. This extra layer was applied after 2 months of plant growth. The 2 months were chosen to ensure sufficient plant growth. The layer is visible in Figure 1 as a white surface.

The swales were planted either with standard lawn or with a designed plant community. Each combination of plants and different soil structures was produced in triplicate and is listed in Table 1.

Table 1 Experimental design: semi-technical experiments according to soil layers and plants

	REGULAR SOIL	REGULAR SOIL + ZEOLITE MIX	REGULAR SOIL + ZEOLITE LAYER
STANDARD LAWN	3x	3x	3x
PLANT COMMUNITY	3x	3x	3x

The swales will receive stormwater runoff from a nearby copper roof, which showed 1.46 mg/l copper in a random sample. Every swale is connected to a 5 m² roof area, resulting in a connection ratio of 5:1. The water is first collected, sampled, and then distributed to the troughs, all of which utilise gravity exclusively. Distribution across the troughs is planned to use a point source, as existing infiltration basins for roof runoff often also have individual entry points. It is also intended to determine the inflow volume by flow measurements.

Similarly, the water below the troughs is collected and analysed. In addition to dissolved and particulate-bound copper, electrical conductivity, pH value, and DOC will be examined to gain insights into possible retention mechanisms. At the start of the trials, the water quantities below the troughs are not collected. However, this should be retrofitted during the experiment to enable a more accurate assessment of the water balance of the troughs.

Irrigation of the swales with stormwater begins in December 2025 and runs for a total of one year. Subsequently, various soil layers will be analysed to determine the copper content in different soil layers and the amount of copper that has accumulated. Additionally, the zeolite should be scraped off the surface and rinsed to determine if it can be regenerated and reused in infiltration swales.



Figure 1 Experimental setup two weeks after application of the zeolite layer

2.2 Accompanying Experiments

In addition to the outdoor experiments, several smaller laboratory investigations have been conducted to further enhance the understanding of zeolites' capabilities for removing heavy metals with a standardized tests to determine basic parameters such as the cation exchange capacity. Additionally, equilibrium and kinetic tests have been conducted to determine the maximum removal capacity of the zeolite and the time required for it to

adsorb heavy metals from the water.

Additionally, column experiments have been conducted using a 5 cm zeolite layer; for comparison, a 30 cm zeolite layer will also be used. This is to better understand whether possible observations from the outside troughs can be attributed to the zeolite layer or must be explained otherwise.

3 OUTLOOK

In summary, the experiments are designed to determine whether zeolite can enhance infiltration swales in terms of durability, removal efficiency, and biodiversity. We hypothesize that the zeolite layer will significantly improve the removal efficiency and conserve the soil below it. Furthermore, we hypothesize that the soil-zeolite mix will have a considerably higher removal efficiency than the regular soil.

The pilot-scale experiments are already installed, and monitoring will start in December 2025; therefore, the first results will be available at the conference in June and will be presented there.

4 FUNDING AND NOTES

The project is kindly funded by the German Research Foundation (DFG) as part of the Research Training Group “Urban Green Infrastructure – Training Next Generation Professionals for Integrated Urban Planning Research” (GRK 2679).

AI was used for linguistic improvement in the creation of this text and for the translation of the abstract and title into French. Specifically, the programs Grammarly, DeepL, and Microsoft 365 Copilot were used.

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