

## Removal of heavy metals and organic chemicals in nature-based systems: a comprehensive review

### Élimination des métaux lourds et des produits chimiques organiques dans les systèmes basés sur la nature : un examen complet

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#### RÉSUMÉ

Les eaux pluviales constituent une ressource précieuse comme solution d'approvisionnement en eau. À ce jour, les différentes technologies de traitement appliquées au traitement des eaux pluviales donnent une eau de haute qualité pour la réutilisation. Néanmoins, leur capacité à éliminer les polluants récalcitrants, notamment les métaux lourds et les produits chimiques organiques, reste mal connue, ce qui gêne l'adoption de la collecte des eaux pluviales. Pour combler cette lacune, un examen exhaustif de la littérature mondiale a été réalisé afin de mieux comprendre la performance des systèmes de traitement des eaux pluviales. Les données documentaires recueillies dans 163 études sur les métaux lourds et 67 études sur les produits chimiques organiques axées sur cinq systèmes de solutions naturelles (par exemple biofiltres, aménagement de zones humides) et des technologies avancées (par exemple ozonation, oxydation chimique), démontrent que l'élimination des polluants est efficace. On a constaté que la conception des systèmes (par exemple la présence de plantes) et les conditions opérationnelles (par exemple taux d'infiltration) entraînent des répercussions importantes sur le traitement. Des recommandations sont présentées en fonction de différents niveaux de besoins pour la gestion des eaux pluviales.

#### ABSTRACT

Stormwater is a valuable resource as an alternative water supply. To date, various treatment technologies have been applied for stormwater treatment, providing high-quality water for reuse. Yet, there is still very limited knowledge about their ability in removing recalcitrant pollutants, especially for heavy metals and organic chemicals, which hinders the uptake of stormwater harvesting. To fill this gap, a comprehensive review of the global literature was conducted to provide a better understanding of the performance of stormwater treatment systems. Literature data was collected from 163 studies for heavy metals and 67 studies for organic chemicals involving five Nature-Based Solution (NBS) systems (e.g., biofilters, constructed wetlands) and advanced technologies (e.g., ozonation, chemical oxidation), showing effective removal of the pollutants. System design (e.g., plant presence) and operational conditions (e.g., infiltration rate) were found to have significant impacts on treatment. Recommendations have been proposed to satisfy the different levels of need in stormwater management.

#### KEYWORDS

Heavy metals, nature-based solutions, organic chemicals, stormwater harvesting, treatment performance.

## 1 INTRODUCTION

Stormwater as an alternative water resource to supplement water supply requires proper treatment prior to reuse. Nature-Based Solutions (NBS) have been used to treat stormwater and include various technologies such as biofilters, constructed wetlands, porous pavements, ponds and swales. These technologies play an important role in the whole stormwater treatment systems to reduce pollutants (Philp et al. 2008).

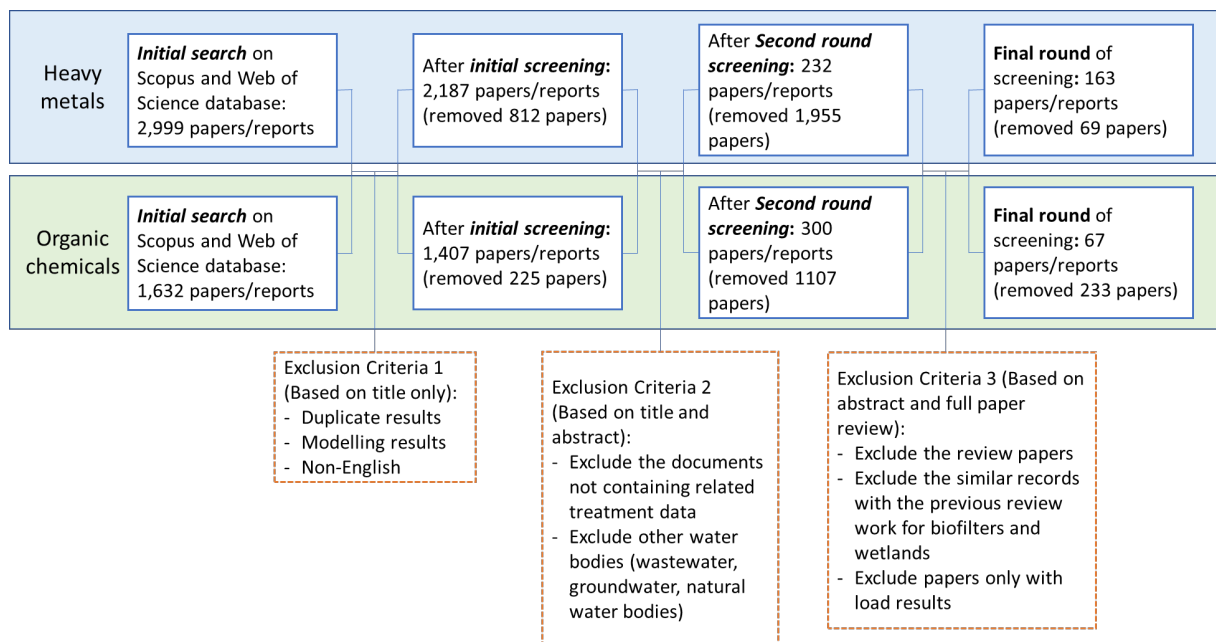
Currently, these NBS technologies have been tested in different trials (mainly for designs and operations) to improve their capacity in pollution mitigation (Ahammed 2017). However, the treatment performance of different systems has not been well reviewed in a systematic way to draw a thorough understanding of the system processes, especially for heavy metals and organic chemicals removal. This laid potential unreliability for large-scale applications in stormwater harvesting. Thus, a comprehensive review of the available literature is needed to establish a better knowledge of the performance of treatment technologies as well as the associated impacting parameters and provide proper recommendations for future treatment system implementation.

## 2 METHODOLOGY

### 2.1 Data collection

#### 2.1.1 Systematic literature review

Data was collected mainly from open literature, through systematic search of two major databases: Scopus and Web of Science. Three rounds of screening were undertaken to shortlist relevant studies and exclude unrelated results from the database (detailed steps are shown in **Figure 1**). 163 publications for heavy metals and 67 publications for organic chemicals formed the final database for stormwater treatment performance assessment in this paper.



**Figure 1** Key steps and exclusion criteria of the systematic review of stormwater treatment performance data for heavy metals and organic chemicals.

#### 2.1.2 Overview of collected data

In this review, performance data were collected for heavy metals and organic chemicals. The detailed number of papers, pollutants and sites (designs) are summarized in **Table 1**. Biofilters are clearly the most common technology that was studied for their treatment performance in removing both heavy metals and organic chemicals. Constructed wetlands were also commonly tested, with more data reported for heavy metals (54 sites) than organic chemicals (15 sites). Porous pavements, ponds, and swales had comparably less data, especially for organic chemicals. As NBS often have variable performance in removing organic chemicals, there has also been relevant research for advanced

technologies, such as ozonation, photo-chemical oxidation, UV/H<sub>2</sub>O<sub>2</sub>.

**Table 1** Overview of data collected for different treatment technologies.

Technology	No. of papers	No. of pollutants	No. of sites (designs)
<b>Heavy metals</b>			
Biofilters	68	22	454
Constructed wetlands	44	20	54
Porous pavements	23	18	52
Stormwater ponds	21	19	47
Swales	7	5	23
<b>Sub-total</b>	<b>163</b>	<b>25</b>	<b>630</b>
<b>Organic chemicals</b>			
Biofilters	32	168	67
Constructed wetlands	10	43	15
Porous pavements	3	8	5
Stormwater Pond	4	11	5
Swales	8	41	19
Advanced technologies	10	19	10
<b>Sub-total</b>	<b>67</b>	<b>181</b>	<b>121</b>

## 2.2 Data analysis

A statistical analysis of the inflow, outflow concentrations and removal rates was undertaken. Outflow concentrations were compared with Australian Drinking Water Guideline (ADWG) values (referred to health values, except Al, Fe and Zn for aesthetic values) (NHMRC 2011) to assess heavy metal and organic chemicals of concern (both).

The impact of system design and operational parameters towards treatment performance was tested by *Kruskal Wallis Test* and Pearson and Spearman correlation analysis.

## 3 RESULTS

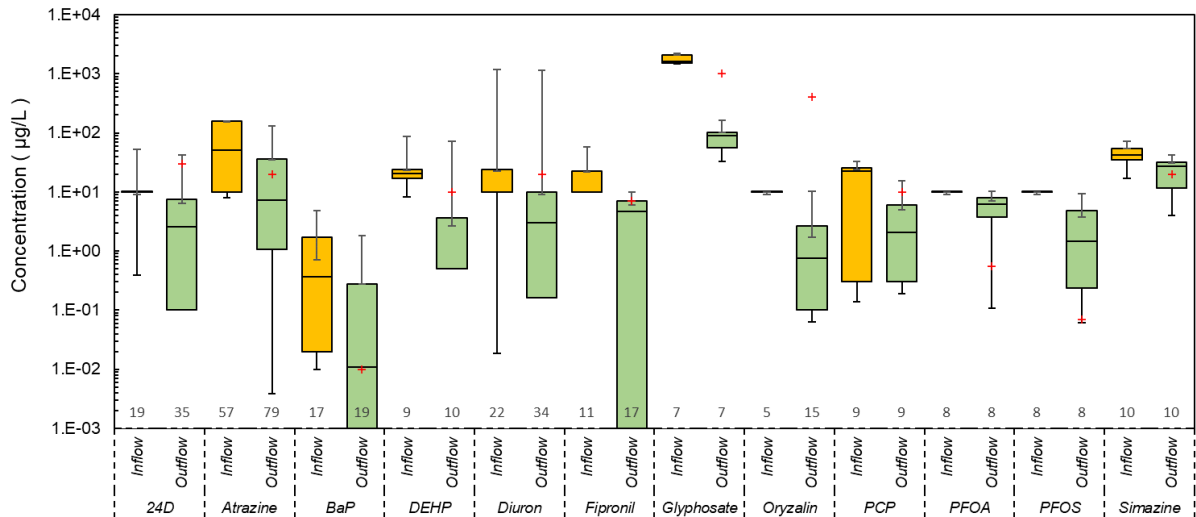
### 3.1 Overview

Overall, biofilters can effectively remove both metals and organic chemicals (**Figure 2**), with the majority of outflow concentrations remaining below ADWG values. Constructed wetlands also works well in treating metals and organic chemicals with over 50% median removal rates for most chemicals. By comparison, porous pavements, ponds and swales demonstrate poorer treatment performance with large variation. For example, Ni is observed to have net leaching in porous pavement treatment. Advanced technologies present excellent removal ability for organic chemicals with over 80% removal rates which possess the potential as the post-treatment method after NBS systems to provide higher quality water for reuse.

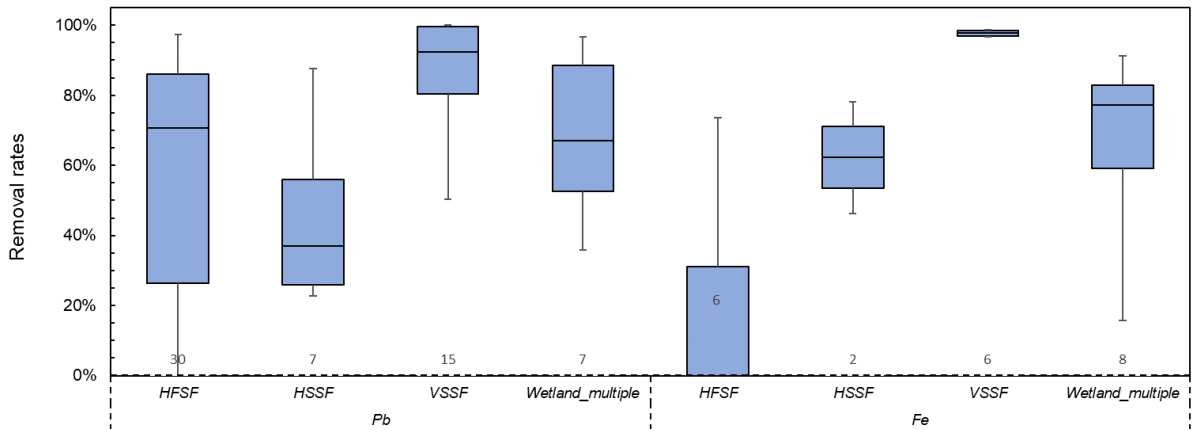
### 3.2 System design and operational parameters impact

Plant presence, submerged zone presence and media type were found to have significant impact in biofilter treatment performance for both metals and organic chemicals ( $p < 0.05$ , *Kruskal Wallis Test* & Pearson correlation). There is clear removal improvement observed for plant and submerged zone presence. However, media type presents different impacts towards metals and organic chemicals treatment. For example, traditional media of soil and sand displays good performance for metals, while particulate amendments (e.g., biochar) play an important role for organic chemicals removal process. Therefore, plant and submerged zone involvement is recommended for biofilters with improved performance. On the other hand, the choice of media type needs to consider the target pollutants in the local areas.

Vertical flow constructed wetland shows the positive impacts in metals removal clearly as stated in **Figure 3** (Pb and Fe as examples) compared with other wetland designs. It is attributed to the vertical infiltration through wetland media which helps the adsorption process for pollutants reduction. Hence, vertical flow design is preferred for wetland application with better pollutants removal.



**Figure 2** Boxplot of inflow and outflow concentrations of organic chemicals in stormwater biofilters. Red plus symbols stand for ADWG values - PFOS used "PFOS+PFHxS" values in ADWG. Numbers next to the x-axis stand for the number of data points used for each boxplot



**Figure 3** Removal of Pb and Fe in different constructed wetland designs. Number next to the x-axis stands for the number of data points used for each boxplot (HFSF- horizontal free surface flow wetlands; HSSF- horizontal subsurface flow wetlands; VSSF- vertical subsurface flow wetlands; wetland multiple - wetlands in series)

## 4 CONCLUSION

This review summarizes the significant design and operational parameters towards the performance of stormwater treatment technologies, such as plant and submerged zone presence for biofilters, flow patterns design for constructed wetlands. Based on the assessment of these parameters, the specific recommendations have been proposed in terms of each treatment system to improve their pollutants reduction ability for the process operations. Fortunately, these recommendations have the potential to be adopted as the technical guidance for the future systems implementation.

## LIST OF REFERENCES

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