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Wide-scope screening of micropollutants in stormwater ponds within Swedish urban catchments

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ABSTRACT

Stormwater refers to the resulting water from precipitation events. In urbanized areas, impervious surfaces result in an increased runoff and, consequently, mobilize pollutants occurring in urban environments to freshwater bodies. Stormwater ponds function as a treatment step of the water before it enters the recipient water body. However, their efficiency to remediate organic micropollutants remains largely unknown. Hence, there is a need to explore the ability of these man-made barriers to remediate organic micropollutants. In this work, we have investigated both influent and effluent water streams from two stormwater ponds during distinct hydrological events to assess their contribution to pollution transport by means of wide-scope screening of organic micropollutants.

Several chemicals have been detected. The observed differences in the chemical profile in samples from different ponds highlighted that the activities in the catchment area heavily impacted the composition of the stormwater. Unexpectedly, the chemical profiles of the stormwater during dry and rainy periods were found to be comparable. Additionally, increased contamination was detected in effluent stormwater, indicating poor treatment and the potential redissolution of previously retained chemicals, highlighting the need for better treatment and remediation strategies in man-made stormwater ponds to ensure sustainability of recipient water bodies.

1. Introduction

Stormwater refers to the resulting water from precipitation events, such as rainfall or snowmelt. In urbanized areas, a big part of the land is covered by impervious materials due to the construction of paved streets, parking spaces, and buildings, thus preventing soil absorption of stormwater (Hvitved-Jacobsen et al., 2010; Ishimatsu et al., 2017). This results in an increased runoff and, consequently, stormwater can mobilize pollutants occurring in urban surfaces to receiving water bodies (Beryani et al., 2024; Flanagan et al., 2021; Masoner et al., 2019; Zhang et al., 2024). Such micropollutants occurring in stormwater can originate from diverse sources, including roads, building roofs and facades, vehicles (like vulcanization accelerators, antifreeze fluids, and coatings), pesticides use, industrial activities, and several human activities (Launay et al., 2016; Zhang et al., 2024). Hence, stormwater is a diffuse source of pollutants to the aqueous environment (Müller et al., 2023; Tuomela et al., 2019) and its treatment before discharge to recipient water bodies is key for a sustainable management of freshwater.

Stormwater ponds function as a treatment step for the urban and rural run-off water before it enters the recipient water body. The efficiency of the pond to treat and remediate organic micropollutants largely depends on sedimentation, i.e. retention of particles and particle associated (highly hydrophobic) pollutants in the pond, although treatment to some extent also occurs though natural degradation of organic pollutants, plant uptake and volatilization (Liu et al., 2019; Viklander et al., 2019). Traditionally, stormwater quality investigations have focused on well-known and legacy organic micropollutants, such as metals, nutrients, organic matter or polyaromatic hydrocarbons (PAHs), which show large affinity for particles and sediments (Viklander et al., 2019; Wicke et al., 2021). However, there is a need to better understand the ability of man-made barriers such as stormwater ponds to treat and remediate persistent, hydrophilic organic micropollutants such as pharmaceuticals or vehicle related contaminants (Masoner et al., 2019; Schwarzenbach et al., 2006), e.g. by performing comprehensive wide-scope high-resolution mass spectrometry (HRMS) screening studies.

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With a higher affinity for the aqueous phase, it can be expected that large amounts of organic micropollutants are discharged to recipient water bodies where they can cause harm and contaminate water sources (Luthy et al., 2019; Saifur and Gardner, 2021). Additionally, limited research has been conducted on identifying organic micropollutants at both the inlet and outlet streams from stormwater ponds during dry and rainy events.

In this work, we conducted a wide-scope screening of relatively hydrophilic anthropogenic micropollutants and used HRMS to investigate both influent and effluent water streams from two stormwater ponds impacted by, among others, heavy traffic and residential and industrial areas in the Uppsala and Stockholm regions in Sweden. Additionally, to study the impact of hydrological events in the mobilization of organic micropollutants of anthropogenic origin, the current investigation included samples from both rain events and periods with no precipitation in the catchment area. Eventually, outlet streams of both selected ponds discharge to Lake Mälaren (Sweden), which serves as source water for drinking water production for approximately 2 million people. It is therefore of utmost importance to investigate potential chemical hazards in stormwater ponds in the catchment area in order to be able to address and ensure the quality of the source water.

2. Materials and methods

2.1. The Tibble and Gottsunda ponds

In this study, outdoor stormwater ponds were evaluated and chosen based on various criteria. The focus was on comparing dry and rainy periods, prioritizing man-made barriers with a continuous flow of stormwater. Furthermore, the potential impact of pond outlets on large, significant water bodies played a crucial role in selecting the sampling sites. As a result, two stormwater ponds in the Stockholm-Uppsala region of Sweden were examined.

The Tibble pond, located in the Upplands-Bro municipality of Sweden, has been in operation for nearly 65 years, with particle sedimentation as the primary designed stormwater treatment process. With a catchment area of approximately 649 ha, a surface area of 5700 m^2, and an average depth of 1.5 m, the pond predominantly serves residential areas, woodlands, and meadows (97 %), with only 3 % encompassing industrial zones, motorways, and parking areas (Andersson et al., 2012). Additionally, it is noteworthy that a rail track from the national rail track networks runs over the Tibble pond. The pond occasionally receives untreated wastewater redirected from a nearby sewage pump station, although such incidents are rare and have not been reported since January 2021 (personal communication, Lennart Eriksson, Upplands-Bro municipality). As our sampling took place 2022–2023, no such incident occurred during our sampling campaigns. The effluent from Tibble pond flows into a small natural wetland before discharging into Görväln Bay in Lake Mälaren, which is Sweden's primary water source, providing drinking water to nearly 2 million people (Röjning and Ångman, 2022).

In contrast, the Gottsunda pond in Uppsala municipality, Sweden, is a newly constructed stormwater pond with a catchment area of approximately 104 ha, a surface area of 5860 m^2, and an average depth of 1–1.2 m. The pond includes multiple pre-sedimentation basins and a large lagoon, which has also been converted into a stormwater park for educational purposes (Näslund et al., 2023; Uppsala Kommun, 2023). While Tibble pond is influenced by nearby industrial areas and motorways, Gottsunda pond is located within residential and green spaces, suggesting a different pollution profile for the two ponds. The effluent from Gottsunda pond flows into the River Hågaån, eventually reaching Lake Mälaren through Lake Ekoln, further impacting the region's primary drinking water source.

2.2. Sample collection

Samples collection took place both during periods with no hydrological events (from now on, dry samples) and during hydrological events (from now on, rain samples). With that, we aimed at investigating the potential differences in chemical composition of stormwater depending on distinct hydrological conditions. Water samples were collected both at the inlet (influent stream) and outlet (effluent stream) of the ponds to investigate the potential impact of the pond retention time, such as potential remediation of micropollutants through sedimentation, volatilization and biotransformation processes. For the simplicity of the text, samples are coded according to T (Tibble), G (Gottsunda), I (influent), E (effluent), D (dry conditions) and R (rain conditions) (e.g. TID refers to Tibble Influent in Dry conditions.

The base flow (approx., 300 m^3 h^{-1} for Tibble and 9 m^3 h^{-1} for Gottsunda, Fig. S1) during dry periods was found to be relatively constant when measured during sample collection. During these periods, time-integrated composite samples were collected for a period of 72 h (total sample volume: 10 L). TID and TED samples were collected in September 2022 and GID and GED in August 2023. As hydrological events induce a large change in the influent and effluent flow rates and, consequently, time-integrated sampling would not be representative (Ort et al., 2010). Hence, flow-triggered volume-proportional composite sampling was chosen for the high flow events. After a significant increase in the influent flow, sample collection was automatically triggered by the autosampler. Subsequently, for Tibble pond, 40 mL of stormwater was collected every 100 m^3 entered/exited the pond, covering approximately 36 h of rain event. For Gottsunda pond, 40 mL of stormwater was collected every 40 m^3 entered/exited the pond, covering approximately 11 days of consecutive rain events. TIR and TER sample collection occurred in March 2023 while GIR and GER in September 2023. Detailed flow profiles as well as aliquot collection event are shown in Fig. S1.

All samples were collected and stored in pre-rinsed HDPE bottles and transported to the laboratory within 3 days from sampling. Upon reception at the laboratory, the samples were kept at −20 °C until analysis.

2.3. Sample treatment

Samples were extracted by means of a multilayer solid-phase extraction (SPE) procedure to capture a wide range of relatively hydrophilic chemicals. Method was applied according to Gago-Ferrero et al. (Gago-Ferrero et al., 2015). Briefly, 500 mL of unfiltered stormwater were pH adjusted to 6–7 with formic acid and ammonia before extraction with an in-house prepared multilayer SPE cartridge containing, in the lower layer, a mixture of a non-polar copolymer (Isolute ENV+, 150 mg), a weak cation exchange (Sepra ZT-WCX, 100 mg), and a weak anion exchange (Sepra ZT-WAX, 100 mg) sorbent and, in the upper layer, a reversed-phase polymeric sorbent (Sepra ZT, 200 mg). SPE cartridges conditioning consisted of 6 mL MeOH followed by 6 mL Milli-Q water. The loading of the samples was performed with vacuum and a drop rate of approximately 1 drop per second. After loading, the cartridges were dried under vacuum for 20 min. After that, samples were eluted, without vacuum, with 4 mL MeOH/ ethyl acetate (v/v 50:50) containing 2 % ammonia. Thereafter, the cartridges were dried for approximately 1 min under vacuum and then eluted with 2 mL MeOH/ ethyl acetate (v/v 50:50) containing 1.7 % formic acid. Extracts were then evaporated under a gentle nitrogen stream to a volume of 100 μL and reconstituted with 400 μL MQ-water to a final volume of 500 μL (preconcentration factor, x1000). Sample extracts were store at −20 °C until analysis.

2.4. Chemical analysis

Sample analysis was performed using a UHPLC-HRMS system. The chromatographic separation was performed with a Vanquish Horizon UHPLC system and was coupled to a Quadrupole- Orbitrap mass spectrometer (Q Exactive Focus), both from Thermo Fisher Scientific (Bremen, Germany).

The chromatographic separation was carried out in reverse phase with a Cortecs UPLC C18 column (2.1 × 100 mm, 2.7 μm) from Waters Corporation (Milford, USA) with a guard column (2.1 × 5 mm, 2.7 μm) containing the same material in a Vanquish Horizon UHPLC unit (Thermo Fisher Scientific, Bremen, Germany). The column was kept at 40 °C. For positive mode, the mobile phase consisted of Milli-Q water with 0.1 % formic acid and MeOH with 0.1 % formic acid. For negative mode, Milli-Q water with 5 mM ammonium acetate and MeOH with 5 mM ammonium acetate were used. Chromatographic gradient started at 10 % organic phase for 1 min, and increased to 90 % by 15 min, where it was kept constant for 2 min. Then, back to the initial condition within 0.1 min and kept at that for 1.9 min, before the next run. The total run time was 20 min. The flow rate was kept constant at 0.3 mL min^{-1} and the injection volume was set to 10 μL.

The chromatographic eluate was connected to a Q Exactive Focus HRMS instrument (Thermo Fisher Scientific, Bremen, Germany) equipped with a Heated Electrospray Ionization source, operating in both positive and negative ionization modes. The Orbitrap was run in both positive and negative polarity modes, with a full scan acquisition in the range *m/z* 100–1000. MS2 data was acquired via data-dependent acquisition (DDA) in discovery mode (with a loop count set of n = 3) and stepped collision energies of 10 and 30 eV and a dynamic exclusion of 3.0 s. The ion source settings were as follows: sheath gas flow rate 35 a.u., auxiliary gas flow rate 10 a.u., sweep gas flow rate 0 a.u., spray voltage 3 kV (for both positive and negative), capillary temperature 350 °C, S-lens RF level 55 a.u., and auxiliary gas heater temperature 350 °C.

Data were processed via commercially available software Compound Discoverer™3.3 (Thermo Scientific™) and visualized using GraphPad Prism 10.4.1.

2.5. Quality control and quality assurance

Procedural blanks and quality control (QC) samples were extracted alongside stormwater samples. QC samples consisted of spiked Milli-Q water with a reference standard mix at different concentration levels: QC high (100 ng L^{-1}), QC medium (50 ng L^{-1}) and QC low (10 ng L^{-1}) in Milli-Q water. These concentration levels were selected based on environmental relevant concentrations reported in literature for organic micropollutants (Gasperi et al., 2014; Peter et al., 2024).

The set of native reference standards used for QC purposes contained 232 CECs. The complete list of CECs included in the QC spiking mix can be found in Table S1 in Supporting Information. The list of spiking chemicals consisted mainly of industrial chemicals, pesticides, pharmaceuticals as well as personal care products and stimulants. The selection of chemicals was based on previously reported occurrence in urban stormwater samples. QC samples were assessed for the qualitative recovery of the spiked chemicals to ensure the correct performance of the extraction methodology. Additionally, procedural blanks, QC as well as stormwater samples were spiked with a set of isotopically labelled internal standards (ILIS) at 50 ng L^{-1}. The complete list of 21 ILIS can be found in Table S2 in Supporting Information.

2.6. Suspect screening strategy

A comprehensive list of chemicals potentially present in Swedish stormwater systems was created based on previously reported detections in urban aqueous environments. OMPs in stormwater ponds can originate from both street and surface runoffs as well as wastewater improperly collected into the sewer systems. Hence, the suspect list created contains organic micropollutants associated with surface runoff (such as vehicle-related compounds and pesticides) and wastewater (like industrial chemical, pharmaceuticals, and personal care products). Overall, the final suspect list contains 328 OMPs, divided into six categories: industrial chemicals, vehicle related, PFAS, pesticides, pharmaceuticals, and personal care products/other. The complete list of chemicals as well as the corresponding source of information can be found in Table S3 in Supporting Information. It is worth noting that, although several other pollutants could be detected in stormwater samples, such as polycyclic aromatic hydrocarbons or metals, the suspect list was curated for the chemical families detectable under the current analytical methodology. Compound identification confidence is reported according to Schymanski et al. (2014).

3. Results and discussion

3.1. Quality control and assurance

The overall method performance was evaluated via the assessment of the qualitative recovery of native reference standards. From the 232 standards spiked, 91 % recovered at the QC high (100 ng L^{-1}); 90 % at QC medium (50 ng L^{-1}) and 82 % at QC low (10 ng L^{-1}). The elevated number of detections of spiked chemicals in the QC samples highlighted the versatility of the extraction methodology as well as its appropriateness for the current study on environmental contaminants in stormwater. Additionally, a mix of 21 isotopically labelled standards (ILIS) was spiked in all samples before extraction, including procedural blanks and QC as well. While 95 % of the spiked ILIS were recovered in the procedural blanks (only one could not be detected), their recovery rate in real stormwater samples ranged between 71 % and 86 %. Although there is a clear impact of the matrix composition in the extraction of the ILIS, their recovery rates were considered satisfactory and, thus, supported the confidence on the detection of OMP in stormwater samples.

3.2. Occurrence of organic micropollutants in stormwater ponds

In total, 64 chemicals were detected in the dissolved phase of the stormwater samples analyzed, covering several groups of chemicals (pesticides, pharmaceuticals, vehicle related, etc.). Fig. 1 depicts the occurrence of the pollutants in the different samples. Differences in the occurrence of OMP were observed between stormwater from the Tibble and Gottsunda ponds. On average, 47 OMPs were detected across four samples from Tibble, whereas only 31 OMPs were identified in Gottsunda, highlighting spatial variability in OMP contamination across the studied sites.

It is also worth noting that 20 OMP were detected in all samples from both ponds, including influent-effluent and dry-rain. Among these ubiquitous chemicals, the vast majority corresponded to vehicle related contaminants including compounds such as benzotriazoles, hexylamines, methoxylmethyl melamine derivatives as well as phosphates. This is in line with previous studies where vehicle related chemicals where commonly detected in stormwater samples (Kang et al., 2024; Santana-Viera et al., 2025). Additionally, 5 extra chemicals were found in all Gottsunda samples while not ubiquitous in Tibble (e.g. tributylamine, PFOS and 2,6-dichlorobenzamid), while additional 14 OMP were also ubiquitous in Tibble samples while not in Gottsunda (mainly pharmaceuticals). These differences in chemical composition among the ponds align with the distinct characteristics of the catchment areas and the historical inputs. As shown in Fig. 2, the number of PFAS as well as industrial chemicals detected in Tibble and Gottsunda ponds were quite similar. However, there were large differences in the abundance of vehicle related, pharmaceuticals and personal care products. The first type of contaminants could be explained due to the higher impact of motorways and industrial areas in the Tibble pond catchment area, as well as to the fact that a rail track from the national rail track networks runs over the Tibble pond. While traffic pollution is often associated with road vehicles, trains are also potential sources of plastic additives, flame retardants, lubricants, etc. Thus, the regular railing of train

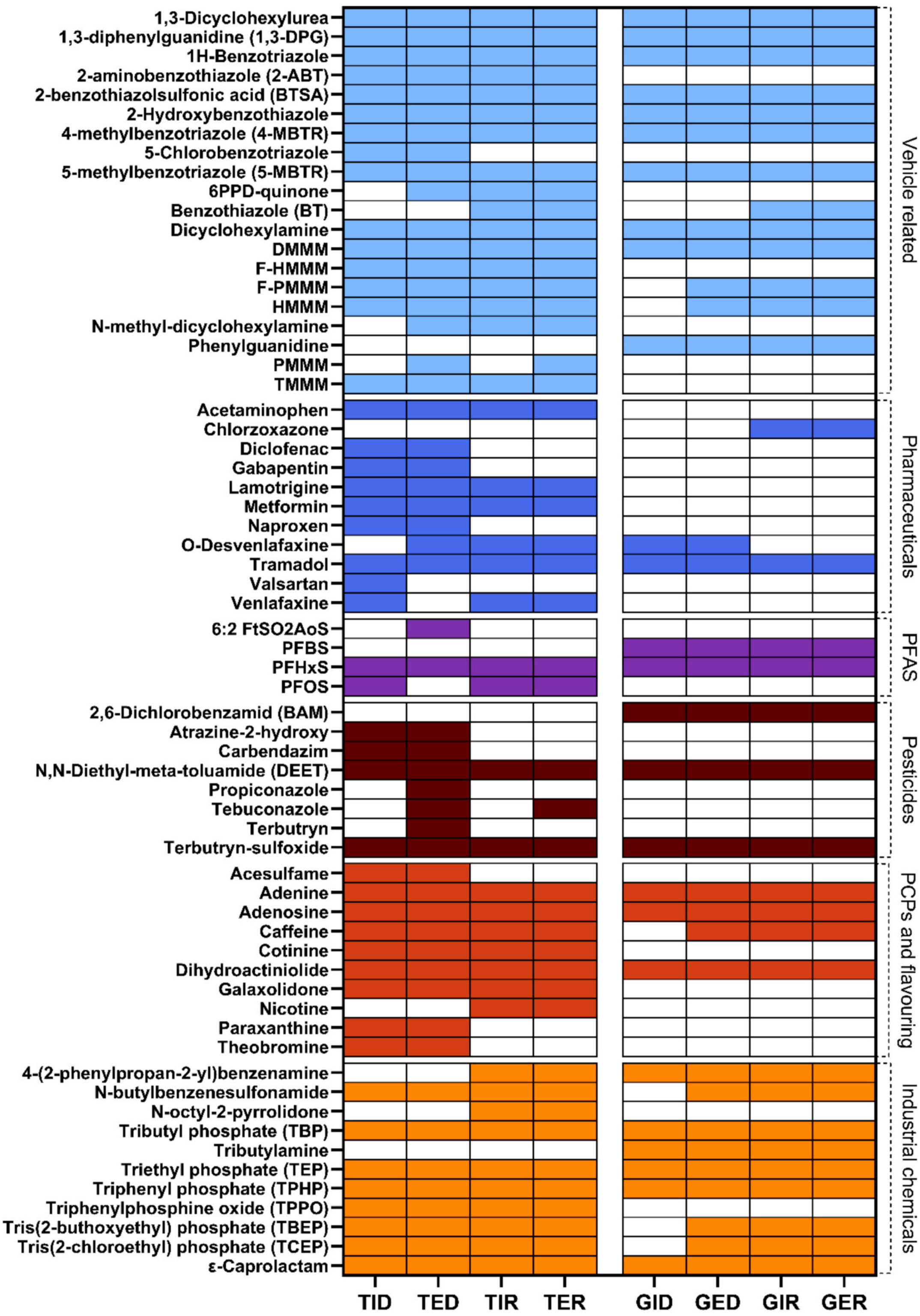

Fig. 1. Detections (shadowed cells; blank cells indicating ‘not detected’) of organic micropollutants in stormwater samples. TID: Tibble influent dry; TED Tibble effluent dry; TIR: Tibble influent rain; TER: Tibble effluent rain; GID: Gottsunda influent dry; GED; Gottsunda effluent dry; GIR: Gottsunda influent rain; GER: Gottsunda effluent rain.

convoys over the pond could have contributed to the pollution of the area. Several studies have identified organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) as well as heavy metals in soils at the vicinity of railways as a results of train traffic (Stojic et al., 2017; Vaiškūnaitė and Jasiūnienė, 2020; Wiłkomirski et al., 2011). Thus, it is not unreasonable to derive a potential source of pollution of vehicle related chemicals into stormwater from train traffic.

Notably, a higher prevalence of pharmaceuticals and personal care products was detected in the Tibble pond compared to the Gottsunda pond (Fig. 2), further emphasizing spatial variations in contaminant profiles between the two sites. The presence of stimulant chemicals in

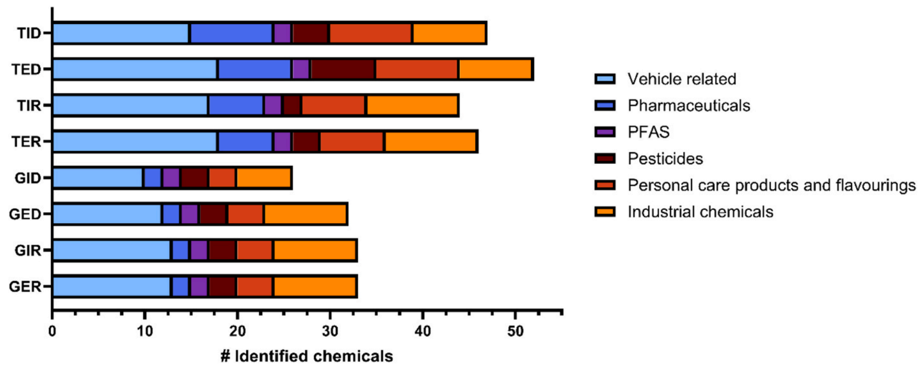

Fig. 2. Distribution of identified chemicals in stormwater samples per family expressed on a number of chemicals basis. TID: Tibble influent dry; TED Tibble effluent dry; TIR: Tibble influent rain; TER: Tibble effluent rain; GID: Gottsunda influent dry; GED; Gottsunda effluent dry; GIR: Gottsunda influent rain; GER: Gottsunda effluent rain.

environmental samples, such as caffeine or sweeteners as acesulfame, are indicators of wastewater contamination (Buerge et al., 2009, 2006, 2003). While caffeine is frequently detected in environmental aquatic matrices due to its high pseudo-persistence and mobility, the presence of acesulfame as well as pharmaceuticals such as acetaminophen, diclofenac, lamotrigine or venlafaxine in the Tibble pond are clear indications of household wastewater impact. Wastewater can reach stormwater ponds by, e.g. leakages in the sewage infrastructure (Sidhu et al., 2013) or combined sewer overflows (Launay et al., 2016), or even by households accidentally connected to the stormwater rather than the wastewater network, and would explain the detection of these OMP in Tibble pond. Historically, Tibble pond has been sporadically affected by wastewater inflows during heavy rain events when the flow of influent of wastewater to the wastewater treatment plant was unbearable for the infrastructure or during power failure at a nearby sewage pumping station (personal communication, Lennart Eriksson, Upplands-Bro municipality). However, during the sampling period there was no inflow of wastewater to Tibble pond, being the last overflow of wastewater into Tibble 21 months before stormwater samples were collected for this study. In any case, the potential contribution of household wastewater to stormwater through accidental sewer connections, sewer malfunctioning or even infiltration of contaminated groundwater could not be discarded. Presence of human metabolites or pharmaceuticals in stormwater has been widely described in the literature (Kang et al., 2024; Labad et al., 2025; Santana-Viera et al., 2025).

In general, Gottsunda pond showed a less complex chemical profile with mainly vehicle related and industrial chemicals with very limited occurrence of pharmaceuticals and personal care products. Although sporadic wastewater inflows as well as some spills on the street that eventually are flushed to the pond cannot be discarded, the results suggest that the wastewater impact in Gottsunda pond may be minor.

3.3. Are stormwater treatment systems safe chemical filters for organic micropollutants?

Overall, the pollution profiles identified in both Tibble and Gottsunda ponds are complex, highlighting the need for improved stormwater treatment, especially in urban locations.

Stormwater ponds have traditionally been designed to prevent flooding after hydrological events; however, they have also been intended as a barrier to hold chemical and biological pollution before discharge to recipient water bodies (Flanagan et al., 2021; Sébastian et al., 2014). Hence, the evaluation of the effectiveness of such constructions to remove or remediate the presence of OMPs is essential.

For Tibble and Gottsunda stormwater ponds, however, a high number of OMPs were detected in the effluent stream versus the influent stream (Fig. 3), except for the samples collected in rainy events in Gottsunda, where the number of chemicals remained constant. This

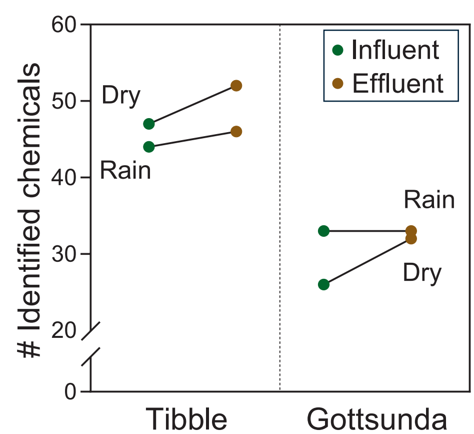

Fig. 3. Change in the number of detected chemicals in influent and effluent samples at both Tibble and Gottsunda in dry and rain periods as an indication of pond treatment for remediating organic micropollutants.

clearly indicates that the ponds effluents contain hazardous anthropogenic chemical mixtures of potential concern for the recipient water bodies and associated drinking water consumers.

Remarkably, samples collected in periods with no rain and, thus, with very limited potential to flush off building surfaces, streets, etc. showed similar number of OMPs identified or even higher than samples collected in rainy periods. This could be due to rainfall precipitation diluting the concentration of OMPs in the stormwater and that such dilution could hinder their detection. Additionally, potential infiltration of wastewater through sewer network cracks or accidental household connections could be impacting the composition of stormwater. On top of this, sewer usually contain sediment and biofilm layers, which could potentially act as temporary reservoirs for OMPs, which are redissolved during dry periods. In any case, the fact that dry samples are heavily polluted, especially in the outflows, raises concern towards the sustainability of these stormwater management and treatment strategies.

The continuous discharge of OMPs from stormwater ponds into recipient water bodies such as Lake Mälaren poses a risk to aquatic ecosystems, water quality, and the safety of drinking water supplies (Malnes et al., 2023,2022). Furthermore, the presence of OMPs at considerable distances from their emission sources shows their high mobility and ability for long-range transport via diffuse sources. The persistence of these compounds, coupled with their resistance to natural degradation processes, raises concerns about the potential for stable or even increasing concentrations over time, thereby exacerbating risks to aquatic environments (Figuière et al., 2022; Malnes et al., 2023). This scenario is particularly important for water bodies used for drinking water production, such as Lake Mälaren.

The presence of persistent OMPs, including endocrine-disrupting chemicals, presents substantial ecotoxicological risks by facilitating bioaccumulation and inducing reproductive toxicity in aquatic organisms, thus threatening biodiversity and ecosystem stability (Figuière et al., 2022; Malnes et al., 2023).

Although particulate fraction of the sample or sediment analyses were not conducted in this study, previous literature has reported the desorption of OMPs from sediments (Drummond et al., 2023; Hajj-Mohamad et al., 2017), suggesting that these compartments may act as long-term reservoirs of contaminants and contribute to legacy pollution. This phenomenon highlights the limitations of current stormwater management practices and emphasizes the urgent need for advanced treatment technologies, stricter regulatory frameworks, and continuous environmental monitoring. Addressing these challenges is important to safeguard the ecological integrity of Lake Mälaren and ensure the sustainability of its drinking water resources.

4. Conclusions

Stormwater samples in both rain and dry periods have been collected and analyzed from both the inlet and outlet flows in stormwater ponds in Sweden. Their analysis revealed the presence of several organic micropollutants, with vehicle related contaminants dominating the chemical profile in all samples. Land use and anthropogenic activities within the pond catchment area have been found to influence the chemical composition of stormwater pollution. This was evidenced by the higher prevalence of pharmaceuticals, personal care products, and vehicle-related chemicals detected in stormwater samples from the more traditional pond compared to the more modern pond with less historical impacts. Although the comparison cannot be fully conclusive because of many differing factors, it serves as an example of how variation can arise and what factors that seem to be impactful. Additionally, the chemical profiles of the stormwater during dry and rainy periods were found to be comparable, indicating the continuous supply of chemical pollution into recipient water bodies even if there is no precipitation. Additionally, an increased number of chemicals was often detected in the effluent streams versus the influent highlighting the need for better treatment and remediation strategies in man-made stormwater treatment systems to ensure sustainability of recipient water bodies.

Environmental implications

Discharging stormwater polluted with organic micropollutants, such as pharmaceuticals, pesticides, and vehicle-related contaminants, poses significant environmental risks to the recipient water bodies. In this study, we have evaluated the presence of such type of contaminants in stormwater impacting Lake Mälaren in Sweden, the major source of water for drinking water production. We have identified several pollutants and complex chemical profiles in stormwater pond effluent, highlighting the need for better treatment for stormwater. Additionally, we have identified that traditional stormwater ponds are yielding more complex chemical pollution profile in the effluent streams than influent stormwater. This highlights the need for better treatment for stormwater.

CRediT authorship contribution statement

Alberto Celma: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Victoria Eriksson:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Oksana Golovko:** Writing – review & editing, Funding acquisition, Conceptualization. **Karin Wiberg:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109691.

Data availability

Data will be made available on request.

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