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Research article

Temporal variations in micropollutant inlet concentrations matter when planning the design and compliance assessment of stormwater control measures

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ABSTRACT

Stormwater Control Measures (SCMs) contribute to reducing micropollutant emissions from separate sewer systems. SCM planning and design are often performed by looking at the hydrological performance. Assessment of pollutant removal and the ability to comply with discharge concentration limits is often simplified due to a lack of data and limited monitoring resources. This study analyses the impact of using different time resolutions of input stormwater concentrations when assessing the compliance of SCMs against water quality standards. The behaviour of three indicator micropollutants (MP - Copper, Diuron, Benzo[a]pyrene) was assessed in four SCM archetypes, which were defined to represent typical SCM removal processes. High resolution MP data were extrapolated by using high resolution (2 min) measurements of TSS over a long period (343 events). The compliance assessment showed that high resolution input concentrations can result in a different level of compliance with water quality standards, especially when discharged concentrations are close to the limit values. This study underlines the importance of considering the high temporal variability of stormwater micropollutants when planning and designing SCMs to identify the most effective solutions for stormwater pollution management and to ensure a thorough consideration of all the environmental implications.

1. Introduction

Discharges of untreated urban runoff from separate stormwater systems represent a significant source of pollutants which can impair the quality of urban and peri-urban surface waters (Brudler et al., 2019a, 2019b; Masoner et al., 2019; Mutzner et al., 2022; Nickel et al., 2021; Spahr et al., 2020; Wicke et al., 2021). Stormwater pollutants stem from a variety of sources across urban areas and are affected by a wide range of transport and fate processes (Eriksson et al., 2007; Gasperi et al., 2014; Göbel et al., 2007; Müller et al., 2020; Mutzner et al., 2020). The outlet concentrations from an urban catchment thus show high spatial variability, which can be linked to land usage (e.g. Kang et al., 2021; Larm et al., 2022; Park et al., 2009). Further, the same catchment concentrations show high temporal variability, both during a discharge event (intra-event variability) and between events (inter-event variability) (Bertrand-Krajewski et al., 1998; Lee et al., 2002; Mutzner et al., 2022; Peter et al., 2020).

Stormwater Control Measures (SCM - Fletcher et al., 2015) are implemented to reduce flooding risks and the environmental impacts of discharges from separate sewers. Past work on SCM design considered both water quantity and quality aspects (e.g., Islam et al., 2021; Kaykhosravi et al., 2018; Zhang and Chui, 2018, U.S. EPA, 1999). However, the majority of the studies, as reviewed by Islam et al. (2021), focused on traditional pollutants (TSS, COD, N, P), with few examples (less than

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one-third) considering SCM removal of micropollutants (heavy metals, PAHs, e.g., (Jia et al., 2013; Jiang et al., 2019; Li et al., 2017). The pollutant removal of SCMs relies on various removal processes depending on the chosen system design (e.g., settling, adsorption, etc. - cf. Scholes et al. (2008)).

Several studies have shown that micropollutant concentrations in stormwater discharges can exceed water quality limit values (Eriksson et al., 2007; Masoner et al., 2019; Mutzner et al., 2020; Wicke et al., 2021). These are often applied as concentration limits for receiving water bodies based on effect studies to protect aquatic life and human health, and they are commonly referred to as Water Quality Standards (WQS). Overall, there is a lack of data on micropollutant concentration levels in urban runoff (Mutzner et al., 2022) and removal performance of SCMs (Spahr et al., 2020), limiting the SCM compliance assessment (if any) to traditional pollutants (e.g., TSS, BOD, P, N). Indeed, micropollutants from SCM discharges tend to be underregulated; thus, most countries have no clear design guidelines for their removal.

Considering the general lack of available data and the consequent weak requirements on micropollutant WQS in discharged stormwater, SCM design is often performed by using average concentration values (from, e.g. literature reviews or databases) that can be linked to different land usages (Göbel et al., 2007; Müller et al., 2020). While current tools allow to consider spatial variability (e.g. Kang et al., 2021; Larm et al., 2022; Park et al., 2009), the inherent temporal variability of stormwater discharges has been investigated by few studies (e.g. Furrer et al., 2023).

This study investigates how - in a design/planning phase - the temporal resolution of stormwater pollutant concentrations affects the estimated removal performance of different SCM designs and, thereby, their compliance with WQS when operating in actual field conditions. Specifically, the following research questions are addressed:

i. How do different SCMs perform under high temporal TSS and micropollutant concentration variations?
ii. How do concentration variations influence long-term (chronic) and short-term (acute) impact assessments?
iii. Does the dynamic behaviour need to be considered when designing SCM and assessing compliance with water quality standards?

Four SCM typologies, defined as “archetypes”, were simulated using a dynamic box model. Three indicator micropollutants (MPs) - selected according to their occurrence, different sources, and environmental fate - were investigated. As high time-resolution MP measurements are missing, the temporal variability of stormwater concentration was derived from a large data set of flow and total suspended solids (TSS) concentration measurements (343 events).

2. Material and methods

2.1. Indicator micropollutants

2.1.1. Indicator selection

Three indicator micropollutants (MPs) were selected in this study: Copper (Cu), Diuron, and Benzo-[a]pyrene (BaP). These MPs were chosen as i) their concentrations in stormwater are often reported above WQS (Brudler et al., 2019b; Mutzner et al., 2022; Spahr et al., 2020); ii) they represent three typical groups of concern: heavy metals, pesticides, and polycyclic aromatic hydrocarbons (PAHs); iii) they possess different inherent properties and thereby; iv) they are affected by different removal processes., This study uses the Environmental Quality Standards (EQS) defined by the European legislation (European Commission, 2013) as reference WQS. EQS are defined as Maximum Allowable Concentration (MAC-EQS) and Annual Average (AA-EQS). Corresponding values in the US regulation are the Criterion for Maximum Concentration (CMC) and the Criterion for Continuous Concentration (CCC).

Cu (Copper) is released by a great variety of sources across the urban environment, including building materials (roofing, paints, wood preservatives, algaecides) and traffic (brake pads) (Müller et al., 2020). Although Cu is not listed in the EU legislation as a priority pollutant, it can have high toxicity to the natural environment in its dissolved phase (Comber et al., 2008, U.S. EPA, 2007), and it is one of the major contributors to the overall toxicity from separate stormwater (Brudler et al., 2019a, 2019b). Therefore, EQS for copper is often defined at the national level. For example, the water quality legislation in Denmark (Miljøministeret, 2023) defines a MAC-EQS of 2 μg/l and an AA-EQS of 1 μg/l for the dissolved fraction. In comparison, the US-EPA (US. EPA, 2023) sets a CMC of 4.8 μg/l and a CCC of 3.1 μg/l for saltwater (total concentration). The dominant removal mechanisms to reduce Cu levels are adsorption to particles and subsequent sedimentation or filtration, cation exchange and adsorption for DOC-complexed forms of the filtered or dissolved phase (Søberg et al., 2019).

Diuron or 3-(3,4-dichlorophenyl)-1,1-dimethylurea (InChIKey XMTQQYYKAHVGBJ-UHFFFAOYSA-N), is a persistent herbicide with acute toxicity that is classified as “known/likely” human carcinogen (Chen and Young, 2008). The primary sources of diuron in stormwater runoff are building materials, as it is used in paints and renders (Burkhardt et al., 2011; Spahr et al., 2020; Wicke et al., 2021). US regulations do not consider Diuron, but it is listed as a priority pollutant in the EU Directive on EQS (European Commission, 2013) with AA-EQS of 0.2 μg/l and MAC-EQS of 1.8 μg/l (total concentration). Diuron is often found in stormwater runoff and its transformation processes (Bollmann et al., 2014; Gasperi et al., 2014). Diuron is hydrophilic, with a low tendency to bind to particles. Therefore, it is predominantly present in the dissolved fraction (Spahr et al., 2020), with a low removal potential through sedimentation processes, as shown by the results of Sebastian et al. (2015, 2014), for example.

BaP (Benzo-[a]pyrene, InChIKey FMMWHPNWAFZXNH-UHFFFAOYSA-N) is a PAH with primary sources from traffic (incomplete combustion of fossil fuels, oil spills) and diagenetic transformations of plant material (Bowman et al., 2002). BaP is considered to be among the most critical stormwater contaminants affecting humans concerning drinking water (Makepeace et al., 1995). US regulations do not consider BaP, but it is listed as a priority pollutant in the EU legislation with AA-EQS of $1.7 \cdot 10^{-4}$ μg/l and MAC-EQS of 0.027–0.27 μg/l (total concentration), depending on the type of water body (European Commission, 2013/39/EU). The lower limit of 0.027 μg/l will be applied in this study. BaP is highly hydrophobic and, therefore, expected to sorb readily onto particles, which makes sedimentation filtration and adsorption its primary removal mechanism (Bowman et al., 2002).

2.1.2. Input TSS data

The study utilises one of the most extensive high-resolution data sets available in the literature on stormwater pollution, i.e. the measurements from the industrial catchment of Chassieu (France) described in Métadier and Bertrand-Krajewski (2012). The catchment has an impervious area of 133 ha and is drained by a separate sewer system. Continuous rain, flow, and turbidity measurements (converted to total suspended solids - TSS) were collected with a 2-min time step from 2004 to 2011 (Métadier and Bertrand-Krajewski, 2011, 2012; Sun et al., 2015). These continuous data were subdivided into storm events, defined by i) having a discharge >4 l/s (to separate from the dry-weather flow of industrial cooling water), ii) a minimum duration of 4 h in between rainfalls, and iii) a rise in the discharge less than 2 h after the rainfall has started. From these data, 343 events were selected for this study as they had none or only a few missing data points (<10 min continuous gap in the data series) (Jensen et al., 2022).

2.1.3. Generating time series of MP concentrations

High time-resolution MP data are generally limited (e.g. Furrer et al., 2023), and most available measurements are reported as Event Mean Concentrations (EMC). High-resolution TSS data are, on the other hand, more abundant and provide information about inter- and intra-event variability. As TSS is a significant vector for several stormwater pollutants with a potential for sorption (e.g., PAHs), this study assumes that the TSS variability can be used as a proxy to describe MP variability. According to this assumption, the EMC for the two pollutants follow the same lognormal distribution and have same intra-event variability, i.e., they show similar behaviour during a discharge event (e.g., flushes taking place during the same part of the event). However, other micropollutants (e.g., diuron) have a lower tendency to sorb, and their variability might differ from the one shown by TSS. Therefore, specific care has been taken when interpreting results for these MP, especially when extrapolating intra-event variability from TSS.

Based on the above assumption, the TSS measurements from Chassieu are used to introduce and create high-resolution MP data. The MP times series are created by the following steps (Fig. 1):

- Step A: a lognormal distribution is fit to the 343 TSS EMCs from Chassieu, following the previous analysis from (Métadier and Bertrand-Krajewski, 2012; Mourad et al., 2005), resulting in a probability density function (PDF) and corresponding cumulative density function (CDF).
- Step B: an “original” PDF (and corresponding CDF) is generated for each MP by using the lognormal distribution parameters estimated by (Mutzner et al., 2022) and listed in Table 1.
- Step C: the score of each of the 343 events in the TSS CDF (from Step A) is found and translated into the corresponding value in the MP “original” CDF, obtaining an MP EMC value for each event (representing inter-event variability).

The high-resolution (2-min) MP concentration data (to represent intra-event variability) are then generated by running these steps for each event:

- Step D: normalizing the high-resolution TSS data by using the corresponding TSS EMC value.
- Step E: rescaling the normalized values by the estimated MP EMC (from Step C), obtaining 2-min MP concentration values.

2.1.4. Resampling the high-resolution time series

The high-resolution MP time series are resampled at lower resolution to represent different sampling approaches: i) 10- and ii) 60-min flow-proportional averages, simulating pooled samples from, e.g., an autosampler; iii) site mean concentrations (SMCs), calculated as the mean of all the EMCs (i.e. the average pollution level discharged from the catchment). All of the resulting time series are presented in 2-min resolution in the results section; however, the 10-min and 60-min time series repeat the same concentration values over 10 and 60 min, respectively. The EMC time series repeats the same concentration value over the entire event, and the SMC time series repeats the same concentration value across all events.

2.2. SCM archetypes

2.2.1. Archetypes definitions

Four SCM archetypes are defined to include approaches that are often used in stormwater pollution management: First Flush Tank (FFT - based on the first flush assumption), Filter (FIL - based on filtration/adsorption), Low-Flow Diversion (LFD - based on the assumption of

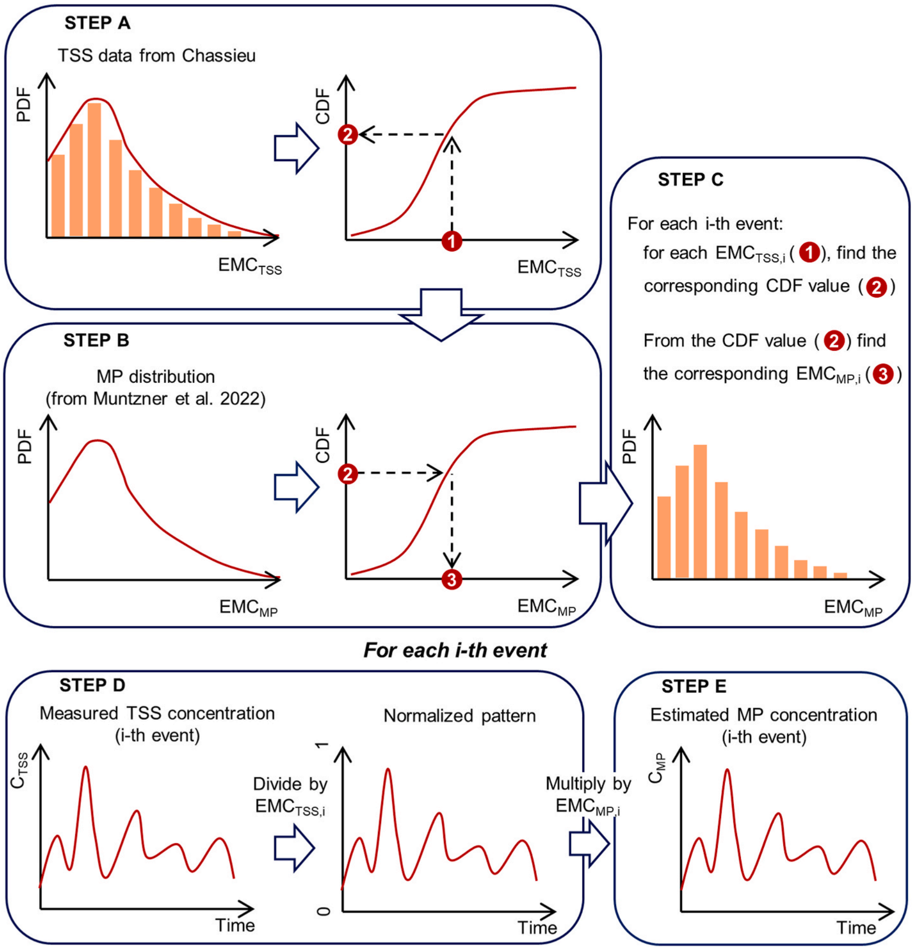

Fig. 1. The steps adopted to obtain MP data (EMC and high-resolution data) from available data (high-resolution TSS data and MP distribution of EMC values).

dilution), and Wet Detention Pond (WDP - based mainly on sedimentation). These four archetypes are designed with flow or volume (or both) as inflow constraints. Typically, SCMs are equipped with bypass or overflow structures to cope with flow exceeding the design capacity. For simplicity, the SCM archetypes in this study are assumed to have bypass structures that divert stormwater directly to the receiving water body without any treatment. The flows discharged to the river are thus a combination of treated and untreated stormwater (FIL, WDP) or untreated stormwater (LFD, FFT), as exemplified in Fig. 2.

- *First Flush Tank (FTT).* The FFT is a storage tank that intercepts the first volume of an event. According to the first-flush assumption, this volume should contain the most significant fraction of the event pollutant load. The stored volume is later sent to a combined system for further treatment. Once the storage is filled, the remaining flow is discharged to the receiving water body without treatment. Thus, FFT discharges only when design capacity is exceeded.
- *Filter (FIL).* The filter archetype represents a category of SCMs that remove pollutants through filtration and adsorption processes (e.g., biofilters). The FIL is conceptualised as a unit with a horizontal flow and a hydraulic capacity limited by the filter media's conductivity. When the inlet flow exceeds the flow capacity, the excess flow is diverted to the bypass. The FIL discharges to the receiving water body at each event.
- *Low Flow Diversion (LFD).* The LFD is an experimental SCM first tested in a separate catchment in the Copenhagen Harbour, and it is essentially a separate sewer overflow. The LFD is built based on the assumption that when the runoff flow exceeds a predefined threshold, the dilution of stormwater pollutants will ensure that the excess flow can be discharged to the water body without environmental risks. The flow below the threshold is sent to a combined system for further treatment. LFD thus discharges diluted stormwater only when design capacity is exceeded.
- *Wet Detention Pond (WDP).* The WDP archetype represents a category of SCMs with a storage volume where sedimentation is the primary pollutant removal process. The pond has a constant outflow (representing a boundary condition often applied in stormwater discharge regulation), so storage depends on the water balance between the inlet and outlet flow. When the available storage capacity is exceeded, the exceeding flow of untreated stormwater is diverted to the bypass. The WDP thus discharges to the receiving water body at each event.

2.2.2. *Archetypes model*

The SCMs' performance is estimated using a dynamic mass balance model based on the schematic water flows outlined in Fig. 2. The concentration discharged to the water body is defined as the flow-weighted average of the outlet and bypass flows from the archetype, and it is determined at a 2-min time step (corresponding to the resolution of the available input data).

The volume and hydraulic capacity of the four SCM archetypes are sized to fulfil the same objective, i.e. the capture of 50% of the runoff generated from the Chassieu catchment. A maximum discharge flow of 0.5 l/s/ha is set for the flow-constrained SCM (WDP). This limit represents a constraint often used in Denmark to protect downstream river bodies from excessive flows (Jensen et al., 2020), and with this as a boundary condition, the pond volume is selected to ensure that the 50% capture rate can be achieved.

Pollutant removal in the SCM archetypes is estimated by using constant removal rates. The LFD and the FFT intercept a fixed runoff flow and volume, respectively, which is subsequently sent for treatment at the WWTP. The removal efficiency for the intercepted runoff is thus assumed to be 100%. The FIL and the WDP removal efficiencies consider the MP fractionation between dissolved and particulate phases, with different removal processes affecting each phase. (e.g. the MP particulate fraction is removed by settling/filtration with this process affected by the TSS present in the SCM, while the dissolved fraction is removed by adsorption in FIL - see more details in the SI). Wide intervals of pollutant removal in SCMs are reported in the literature (Langeveld et al., 2012). The average removal rates used in this study (Table 2) were estimated based on a combination of inherent properties and literature values, as explained in detail in the SI.

2.3. *Approach for assessing results*

The evaluation of the effects of SCM discharges can be relevant at

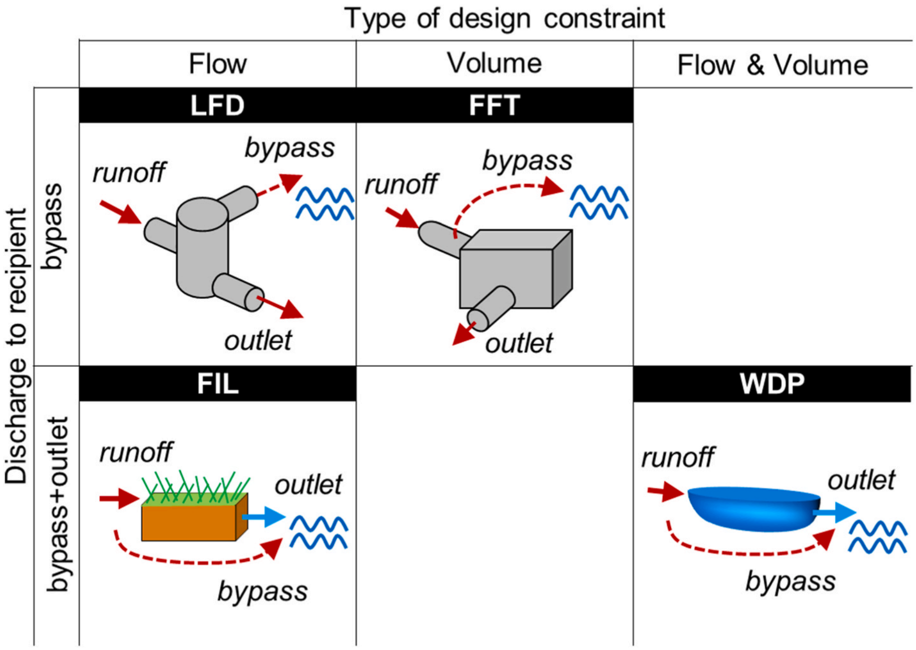

Fig. 2. Schematization of the conceptual models for the four SCM archetypes (LFD: Low Flow Diversion, FIL: Filter, FFT: First Flush Tank, WDP: Wet Detention Pond). Solid arrows indicate flows at each event, and dashed arrows indicate flows only when design capacity is exceeded. Brown arrows: untreated stormwater, blue arrows: treated stormwater.

Table 1
Characteristics of investigated MPs: measured values (reported as parameters of lognormal distributions from Mutzner et al. (2022), and used EQS values (European Commission, 2013; Miljøministeret, 2023). All values are in µg/l.

IMP	10% percentile	Median	90% percentile	MAC-EQS	AA-EQS
Cu	5.3E+00	5.9E+01	2.6E+02	2	1
Diuron	2.3E-03	1.9E-02	3.0E-01	1.8	0.2
BaP	2.9E-03	4.8E-02	7.9E-01	0.027–0.27	1.7 10^{-4}

Table 2
Removal efficiencies applied in the archetypes model for the intercepted runoff fraction.

Pollutant	FIL	FFT	LFD	WDP
TSS	75%	100%	100%	75%
Cu	55%	100%	100%	60%
Diuron	75%	100%	100%	0%
BaP	85%	100%	100%	45%

several different temporal resolutions. The overall SCM performance in reducing pollutant loads is calculated as the Capture Ratio, i.e. the fraction of pollutant mass intercepted/treated by the SCM. The MP concentration discharged from the archetype SCM to the receiving water body (flow-weighted average of the SCM outlet and bypass), obtained with different MP input resolutions (2 min, 10 min, 60 min, EMC, SMC – see section 2.1.4), are evaluated at three different output aggregation levels:

- Long-term evaluation: the mean discharged values across all events in the data series (outlet and bypass SMC) are used to assess chronic effects by comparing them to AA-EQS.
- Short-term evaluation: the mean discharged values for each event in the data series (outlet and bypass EMC) are used to assess for acute effects by comparing them to MAC-EQS.
- Instantaneous evaluation: each 2-min time step of all events in the data series accounts for acute effects by comparing them to MAC-EQS.

Compliance against the EQS is calculated as the Required Dilution Factor (RDF), i.e. the ratio between the calculated concentration and the EQS. The RDF indicates the dilution needed to ensure compliance with the EQS, i.e. if there is an insufficient dilution, the SCM discharge poses a threat to the downstream water environment.

As the TSS data set used as a proxy spans several years, it would have been interesting to look at different annual averages for the MPs. However, there is no continuous data for an entire year, as many events are excluded from the data set. Therefore, the "long-term evaluation" results are compared against the EU annual average criterion (AA-EQS) to assess chronic effects. In an actual compliance assessment, EU AA-EQS should be evaluated on yearly data, as annual variation must be expected.

3. Results and discussion

3.1. Dimensioning of SCM archetypes

The SCM design constraints described in section 2.2.2 resulted in the dimensions listed in Table 3. The design criteria influence the TSS mass captured by each SCM archetype (Fig. 3). Indeed, a higher flow capacity or storage volume leads to a larger amount of the TSS mass captured in the archetype.

The two SCMs based on intercepting the polluted flow (FFT and LFD) achieve an increasing capture ratio for increasing dimensions (see Fig. S2), reaching a 100% capture ratio (i.e. indicating that the SCMs capture all the discharges). The capture ratio for the FIL and WDP is a combination of the removal efficiency (75% for the FIL and WDP - Table 2) and the bypassed flows, where the bypass is reduced for increasing dimensions of the SCM.

There are minor differences between the TSS capture ratio calculated with different temporal input resolutions (below 5% at the design size – see Table 3). Using SMC and EMC as input leads to a lower removal than higher resolutions in the input data. An exception is FFT, where using a SMC can result in an underestimation of almost 10% of the captured TSS mass. This is explained by the presence of flushes (i.e. periods with higher concentrations than the EMC) in the data, which can occur when the SCM capacity is exceeded, i.e. when bypass takes place. This suggests that the FFT can intercept these flushes, i.e., the flow discharged when the FFT capacity is exceeded represents a minor fraction of the event load.

Based on the assumption of a similar variability between TSS and the MPs, similar results are expected for the investigated substances. This underlines the importance of considering the intra-event variability when assessing SCM removal performance. This is relevant for FFT and LFD, which are specifically designed based on the assumption of dynamic behaviour of the pollution level (i.e. first flush assumption and dilution, respectively).

Fig. 4 depicts the mean concentration in the discharge to the recipient (bypass plus outlet) across all 343 events. Generally, the SCM archetypes based on a treatment process and with a bypass (FIL and WDP) achieve lower discharge concentrations of MPs than the SCMs based on intercepting the most polluted fraction of stormwater (FFT and LFD). Two exceptions are, however, diuron in the WDP (as no removal occurs) and BaP in the FIL. It should be noted that the FIL and WDP discharge at each event (i.e. the values shown in Fig. 4 are the mean of 343 events), while FFT and LFD have a reduced number of discharges (98 and 243 discharged events, respectively). This should be considered when assessing the impacts on the downstream water body.

The comparison of different input resolutions shows a decrease in discharged concentration for more aggregated values (from the original 2-min resolution to SMC) for most MPs (see SI). The different SCM archetypes show different behaviour, with a decrease in the estimated outlet concentration for FIL and LFD (about 4–8% and 9–14%, respectively) when changing from 2-min high-resolution data to the EMC. The differences for WDP are negligible (below 1%). This behaviour underlines the importance of considering intra-event variations in pollutant levels, e.g., pollutant flushes that can occur during bypass of the SCM. Using the SMC can increase the estimated outlet concentration by up to 80%, depending on the removal efficiency (in the case of BaP in

Table 3
Design constraints for the SCMs archetypes to reach a 50% runoff capture rate, and estimated TSS capture ratios with different time resolutions.

Archetype SCM	Design criterion		TSS capture ratio [%]				
	Flow constraint (m^3/s)	Volume constraint (m^3)	2 min	10 min	60 min	EMC	SMC
FIL	0.165	–	35.0	35.1	36.0	38.7	38.4
FFT	–	3600	58.4	58.4	57.7	52. 3	49.6
LFD	0.165	–	45.5	45.6	46.7	50.3	49.9
WDP	0.0925	700	38.2	38.3	38.4	38.4	37.2

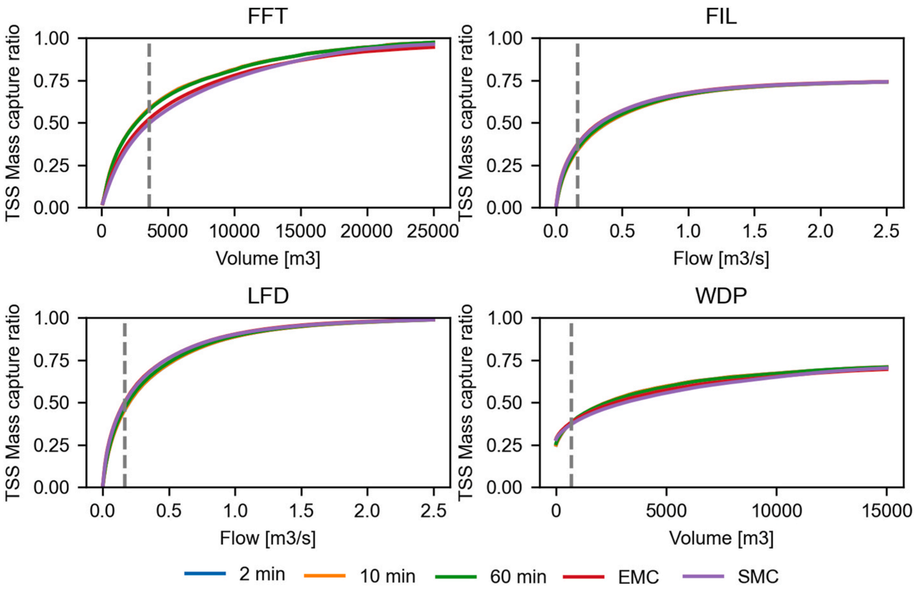

Fig. 3. TSS capture ratios as a function of design constraint for the four SCM archetypes. The dashed grey vertical line indicates the SCM design criterion based on a 50% runoff capture rate (Table 3).

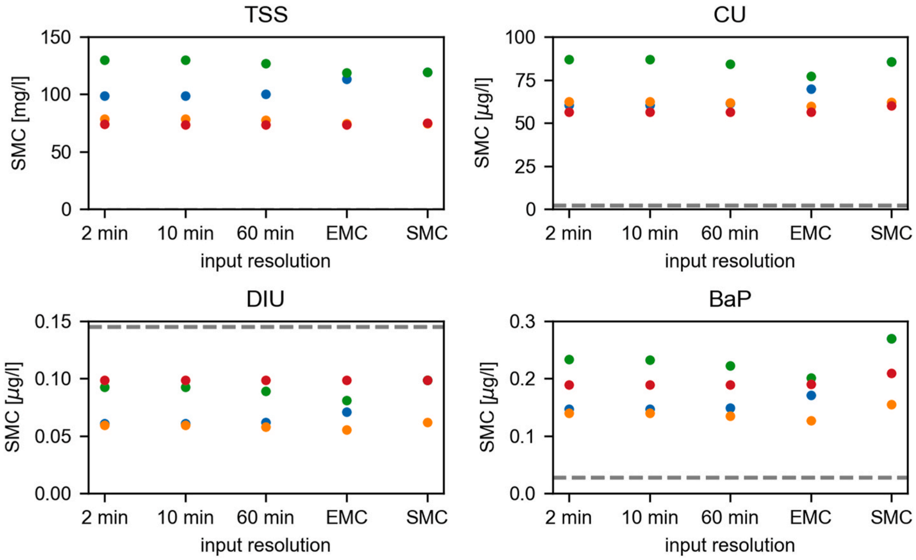

Fig. 4. Site Mean Concentrations (outlet and bypass) discharged to the recipient over the considered period (343 discharge events) for different input resolutions. The dashed horizontal lines show the AA-EQS for each MP.

the FFT). This shows how disregarding the inter-event variability might lead to incorrect estimation of the SCM ability to reduce stormwater pollution. For example, FFT intercepts an important part of the discharged pollutants (partially supporting the first flush assumption) in this data set. Therefore, using low-resolution data (such as EMC) can significantly overestimate the discharged pollutants. This should be considered when designing SCMs to avoid under- or oversizing.

Comparison with chronic threshold AA-EQS. Fig. 4 shows that Cu and BaP discharged concentrations exceed the chronic limit (AA-EQS) for all input resolutions. Therefore, Cu and BaP might pose a risk to the aquatic environment if dilution in the recipient is insufficient. On the other hand, diuron is always significantly below the threshold. Hence, in our case, an aggregated input concentration (such as SMC) reasonably estimates the chronic chemical risk caused by SCM discharges (expressed by AA-EQS exceedance). This would be different for datasets with a more pronounced pattern in the pollutant dynamics. For example, for data with higher concentrations during the first volume runoff (e.g. a more evident first flush pattern) or low flow rates, likely to be intercepted by the SCM, using SMC becomes more of a conservative estimate and vice versa. It is important to note that the recipient's background concentration should be considered in a "real" performance evaluation. This is relevant if there are other sources of pollutants or – in the case of Cu – if the pollutant is a naturally occurring element.

3.2. *Short-term evaluation on event-basis and acute effects*

Fig. 5 compares the discharged concentrations to the recipient for each event against the threshold for acute toxicity (expressed as MAC-EQS), shown as the required dilution factor (RDF), i.e. the dilution factor needed to ensure compliance with the AA-EQS. The white colour in the figure indicates that no discharge to the recipient occurred for that event. In this comparison, using the SMC as input resolution results in

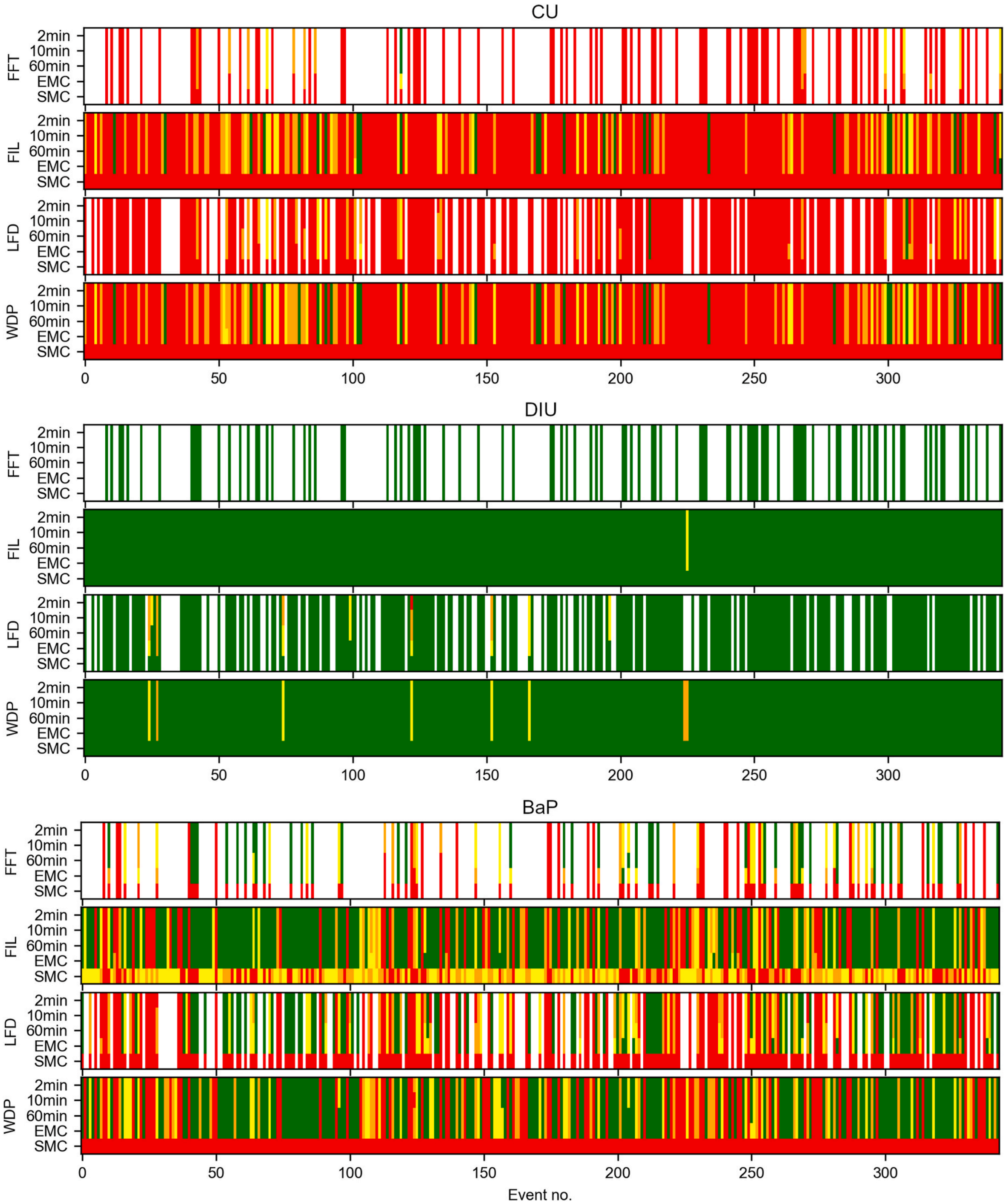

Fig. 5. Heat map of the Required Dilution Factor (RDF – calculated against MAC-EQS) for all events and input resolutions. The modelled 343 events are displayed on the x-axis, and the input resolution of the concentration to the archetypes is on the y-axis. The color of each event depends on the RDF: Green RDF below 1 (no EQS exceedance), yellow RDF between 1 and 2, orange RDF between 2 and 5, red: RDF above >5. The white colour indicates that no discharge took place for that event. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

low variability (see violin plot in Fig. S3 in the SI). Indeed, the archetype's inlet concentration is constant, and thus, the changes in outlet concentration originate only from the mixing of bypass and outlet.

Diuron is a good example of a pollutant, generally compliant with the threshold value (as shown by the predominantly green colour, i.e. RDF below 1, with 97–100% of discharges below the limit), while Cu is generally non-compliant. Indeed, as the predominantly red colour shows, 66–85% of discharged events have RDF above 5. BaP swings both ways, ranging between compliance (RDF<1 – between 35% and 67% of discharges) and high risk (RDF>5, between 16% and 37% of discharges) depending on the chosen time resolution. When the capacity of the FFT is exceeded (in about 29% of the analysed events), the bypassed water poses a serious risk to the environment, as about 85% of events have an RDF above 5 for Cu. However, potential background concentrations in the recipient have not been considered.

Fig. 5 exemplifies how the SMC is unsuitable for assessing compliance with short-term (acute) limits (as the MAC-EQS). While diuron always complied with the chronic EQS (Section 3.3), the comparison against the short-term limit showed events with noncompliance (8–9 events depending on the SCM, corresponding to about 3.2% of the discharge, although 1.6% had an RDF below 2). These exceedances would be missed if the SMC is used as an input. Conversely, using the SMC as input leads to overestimating the risk BaP poses. Indeed, using a high-resolution input shows how several events (around 42%–67% depending on the SCM archetype) comply with the MAC-EQS, while all events exceeded the threshold when SMC was used as input.

In the case where the SMC > EQS (as for Cu and BaP), the SMC overestimates the number of times the threshold value is exceeded (up to 8% and 42–67% fewer exceedances for Cu and BaP, respectively). Vice versa, in the case where SMC < EQS (as for diuron), the SMC underestimates the number of times the threshold value is exceeded (about 2% fewer exceedances). Thus, if the archetypes were designed using the SMC, they would be over-dimensioned in most events, while noncompliance in extreme events would be neglected. This underlines how regulators should clearly define the temporal resolution of the input data used for compliance assessment to avoid unwanted adverse effects on the receiving water body.

3.3. *Instantaneous evaluation at 2 min resolution*

Fig. 6 shows the number of time steps (sum over all the discharge events) when the estimated outlet concentration exceeded the MAC-EQS. The estimated non-compliance periods (i.e. above MAC-EQS) tend to increase for more aggregated values. Only a minimal difference can be seen when switching from 2-min to EMC. SMC tends to provide more conservative estimates, overestimating the non-compliance period compared to the 2-min resolution. This suggests that considering inter-event variability is more relevant than intra-event variability. Thereby, these results are less affected by the assumed link between TSS and MP behaviour, also for micropollutants with a low tendency to sorb.

Cu exceeds the MAC-EQS most of the time, confirming the patterns observed for the average outlet concentration (section 3.4), while DIU is almost always below the threshold. BaP shows an interesting behaviour, with the SMC significantly overestimating non-compliance.

Suppose a conservative approach is adopted, where a single timestep above the MAC-EQS is sufficient to classify the whole event as non-compliant (corresponding to the "one out, all out" principle adopted by, e.g. the EU legislation). In that case, the influence of the input resolution becomes more evident (see SI for more detail). In countries where SCMs are required to comply with WQS, it is thus important that the input resolution matches the one defined by the considered WQS. However, current WQS definitions lack a unique definition of how samples should be taken, i.e., if limits refer to instantaneous concentrations (grab samples) or event-based samples. In comparison, different maximum concentrations for different exposure periods for dissolved oxygen and unionised ammonia have been defined in, e.g. English and Welsh regulations (Crabtree et al., 2012). Although such a detailed level cannot be reached for micropollutants due to a large number of pollutants, logistical limitations in sample collection and high analysis costs, environmental regulations could better define the timeframe for compliance evaluation. This would then allow the selection of the appropriate input resolution and monitoring strategy.

This example demonstrates how differences in input resolution may yield considerably different conclusions, emphasising the need for establishing clear guidelines to accompany EQS values, both in estimating compliance before constructing an SCM and how to conduct inspections afterwards.

4. Conclusion

The high inter- and intra-event variability of stormwater pollutant levels is well-acknowledged in literature, and this should be included in planning SCMs, as this variability can affect their design (type and scale) and the assessment of their impact on the receiving water bodies. This study shows that the chosen input data resolution can either reveal or mask the effects of inter-event concentration variations when assessing the performance of different SCMs in protecting the downstream water environment from stormwater pollutants.

Performance of different SCMs under high temporal variability. This study shows that solutions with only bypass (LFD, FFT) and no outlet will significantly reduce pollution within their design capacity, as they reduce the number of discharge events. However, when their capacity is exceeded, and in catchments or for pollutants not showing a first flush behaviour, these SCMs depend more on dilution to reduce their impact on the receiving water body. Therefore, looking beyond the design storm is paramount when evaluating the effects of these design solutions. Regarding flow-constrained archetypes vs volume-constrained, differences will depend on flush patterns in the data set, i.e., whether there are pollutant flushes (i.e. periods with higher

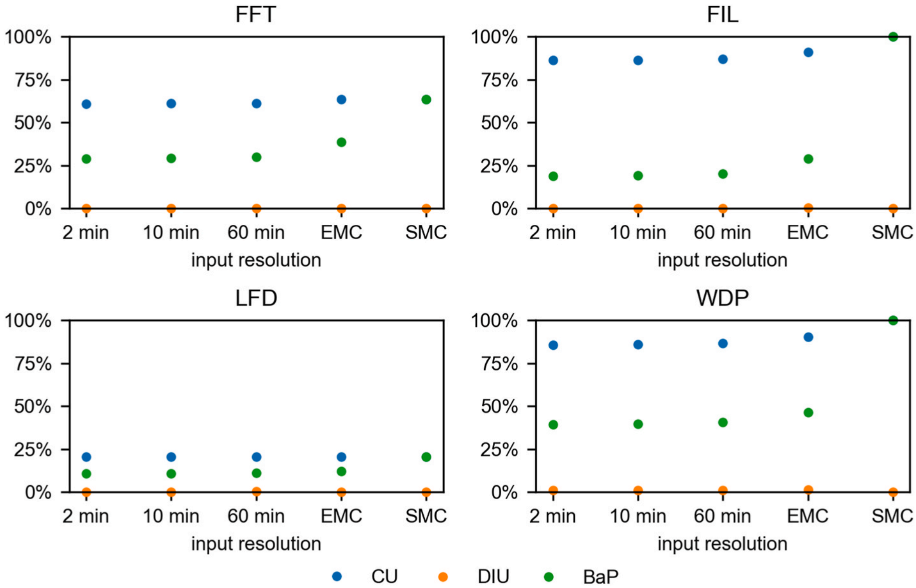

Fig. 6. Fraction of 2-min time steps when the outlet concentration to the recipient exceeds the MP threshold (MAC-EQS) for each SCM archetype. The x-axis shows the different resolutions for input concentrations.

concentrations) and if the SCM intercepts them or if they occur during bypass (i.e. when the design capacity is exceeded). A better pollution reduction is thus achieved for SCM that do not depend on strong assumptions on pollutant behaviour (such as the first flush or dilution hypotheses). The effects of flow-vs. volume-constrained designs were overshadowed by the difference in removal efficiencies of the archetypes (e.g., the difference between diuron removal in WDP vs. filter). The importance of removal efficiencies exemplifies how important it is to acquire accurate information on the pollutant profiles in runoff (types and levels, including concentration variation) so that the SCM design can optimally target pollutants close to threshold values. Intercepting flushes will only be relevant if the SCM has a low removal efficiency for the intercepted pollutant.

Long-term (chronic) and short-term (acute) impact assessment. Input resolution influences the compliance assessment (SCM design) for discharge concentration limits. However, negligible differences were noted for discharged pollutant loads. For the discharged concentrations, the importance of the input resolution increased when the mean inlet concentration had values close to the water quality standard. Indeed, minor differences in the SCM removal performance can significantly change the overall impact assessment, primarily when strict criteria (e.g. “one out, all out” criterion) are employed. The lack of specific information in existing regulations and SCM guidelines creates a loophole where average values (such as SMC) are widely used in the planning phase. This neglects the inter- and intra-event variability of stormwater pollutants, leading to a focus on chronic standards. However, this does not guarantee that SCM prevents acute effects.

Including dynamic behaviour in compliance assessment. Input resolutions should match the resolution of the compliance criteria (e.g., using EMC to make short-term evaluations at the event level). In some cases, additional insight was gained by a higher resolution input. Water quality standards for micropollutants should be extended with more detailed temporal definitions, especially for acute effects, to ensure better congruence between input resolution and aggregation levels. For example, by specifying the duration needed to collect a sample for assessment against MAC-EQS (grab sample/instantaneous, time-weighted average, event concentration, etc.). This may be recipient specific, but defining the necessary knowledge on influent pollution levels is needed.

Suggestions for further research include work to achieve (1) better descriptions of runoff pollution levels, e.g., by including a range of micropollutants, understanding their concentration temporal variations, also in relation with TSS and other traditional water quality parameters, which are relatively more straightforward to measure and thus would ensure broader applicability of the proposed approach; (2) a better understanding of SCM properties and performance, incl. estimation of uncertainties related to SCM performance; and (3) a better understanding of effects of different pollutant concentrations, e.g., the exposure time that should be used when assessing impacts on the downstream ecosystem, leading to regulations that include exceedance frequency into the compliance assessment.

CRediT authorship contribution statement

Ditte Marie Reinholdt Jensen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lena Mutzner:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Yuansong Wei:** Writing – review & editing, Conceptualization. **Peter Steen Mikkelsen:** Writing – review & editing, Investigation, Conceptualization. **Luca Vezzaro:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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Data availability

Used data are collected from freely available repositories

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Appendix A. Supplementary data

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