Model-based comparison of strategies for reduction of stormwater micropollutant emissions

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Comparaison des stratégies de réduction des émissions de micropolluants dans les eaux pluviales fondée sur un modèle

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RÉSUMÉ

Les stratégies pour réduire les émissions de micropolluants dans les systèmes d'eaux pluviales nécessitent la comparaison entre différents scénarios, incluant le contrôle des sources d'émission, le traitement au point de rejet ou leur combinaison. La modélisation dynamique intégrée est un outil important pour cette comparaison puisqu'elle permet de prendre en compte des données restreintes de campagnes de mesure et d'évaluer les performances des différentes stratégies en fonction des résultats des simulations. Cette étude présente l'exemple d'un modèle dynamique intégré, utilisé en combinaison avec des relevés de la qualité des eaux pluviales, pour évaluer 6 différentes stratégies d'amélioration de la qualité des eaux réceptrices en diminuant les flux de métaux lourds (cuivre, zinc) et de composés organiques (fluoranthène) vers les milieux naturels. Les sources de micropolluants ont été identifiées en utilisant des données SIG d'aménagement du territoire. En comparant les différentes stratégies de contrôle, le modèle a montré les bénéfices importants de la stratégie de contrôle des sources d'émission en termes de charges de micropolluants déversées dans l'environnement et des sédiments accumulés dans le bassin. Aucune des stratégies de contrôle de pollution simulées n'a réussi à respecter le critère de qualité de l'eau en termes de valeur limite d'émission. Cette étude met en évidence l'importante contribution que les modèles intégrés peuvent fournir à la gestion de la pollution des eaux pluviales.

ABSTRACT

Strategies for reduction of micropollutant (MP) emissions from stormwater systems require the comparison of different scenarios including source control, end-of-pipe treatment, or their combination. Dynamic integrated models can be important tools for this comparison, as they can integrate the limited data provided by monitoring campaigns and evaluate the performance of different strategies based on model simulation results. This study presents an example where an integrated dynamic model, in combination with stormwater quality measurements, was used to evaluate 6 different strategies to improve the recipient quality by reducing the fluxes of heavy metals (copper, zinc) and organic compounds (fluoranthene) to natural waters. MP sources were identified by using GIS land usage data. When comparing the different control strategies, the integrated model showed the greater benefits of the source-control strategy in terms of MP loads discharged in the environment and sediment accumulated in the pond. None of the simulated pollution control strategies managed to fulfil water quality criteria based on Emission Limit Values. This study highlights the great contribution that integrated models can provide to the management of stormwater pollution.

KEYWORDS

Integrated model, Micropollutants, Pollution control strategy, Stormwater quality model, Uncertainty analysis

1 INTRODUCTION

Management of stormwater pollution is increasingly seen as an important element in integrated strategies for reducing the emission of micropollutants (MP) into the natural aquatic environment. The growing awareness of the negative biological effects due to discharge of stormwater MP (e.g. Eriksson et al., 2007;Kayhanian et al., 2008;Wium-Andersen et al., 2011;Zhang et al., 2011) and the legal requirements demanding the reduction of discharge of these substances (e.g. the Water Framework Directive – WFD (EC,2000)) require extended monitoring campaigns, as well as development and implementation of strategies to control their discharge. The collection of representative samples during stormwater discharges is costly and difficult: these problems limit the development of extensive monitoring campaigns and thus reduce the support for the elaboration of pollution control strategies. Furthermore, MP are commonly found in low concentrations (in the range of ng/l-µg/l), which are difficult to measure.

An approach to overcome these limitations is based on the combination of the available sources of information about these pollutants. MP sources can be identified based on the characterization of the catchment, i.e. by analysing the area land usage commonly stored in GIS databases. Information about land usage can then be linked to potential MP sources (see Lützhøft et al., 2009 for further details).

The results of the catchment characterization can subsequently be integrated with dynamic stormwater quality models, which include MP sources, stormwater transport through the drainage network, and stormwater treatment facilities. As discussed for combined systems by Rauch et al. (2005), by using these integrated models it is possible to study and understand the behaviour of complex stormwater systems and to assess different pollution control strategies. Given the inherent uncertainty in stormwater quality models (see the discussion in Bertrand-Krajewski (2007)), uncertainty analysis is an essential step for enabling the use of model results as support for decision making. In this study the Generalized Likelihood Uncertainty Estimation technique (GLUE - Beven and Binley, 1992) was used to estimate model uncertainty.

This study presents an application of these concepts applied to an industrial-residential catchment in Alberslund (Denmark). An integrated stormwater quality model, - combining MP source characterization with a dynamic runoff quality and a treatment model (see Vezzaro et al., 2012a) was firstly calibrated and subsequently used to evaluate different strategies for reduction of stormwater MP emissions (for selected MP: copper, zinc, and fluoranthene). The control strategies included both source control and extended treatment, and they were defined in collaboration with the local municipality. The results of this study shows how the proposed approach can be used to (i) quantify the MP loads across the catchment, and (ii) evaluate different strategies in order to find the most appropriate strategy to achieve the required water quality

2 MATERIAL AND METHODS

2.1 The Albertslund case study

The Hersted Industripark catchment is a 95 ha mixed industrial-residential catchment located in the Albertslund municipality (Denmark). Runoff is collected by a separate drainage network and open channels and treated in a retention pond (Basin K) before discharge to a stream (Figure 1). Several monitoring campaigns (Birch, 2012) have been carried out in the catchment in order to assess the present stormwater quality. Stormwater composite samples were collected at the pond inlet (using a flow-proportional sampler) and at the outlet (using a time-proportional sampler). Samples were analyzed for TSS, heavy metals (Cu and Zn were considered in this study) and organic substances (fluoranthene – CAS 206-44-0 – was considered in this study). TSS was analysed by filtering the sample through 1,5 mm WhatmanTM 934-AHTM glass microfiber filters and drying the filtrate remained on the filter at 1050C. Total and dissolved (0,45 µm filter) Cu and Zn were analysed using induced coupled plasma optical emission spectroscopy (ICP-OES). Fluoranthene was analysed using the Gas Chromatography Mass Selective Detector (GC-MSD) by Højvang Miljølaboratorium A/S.

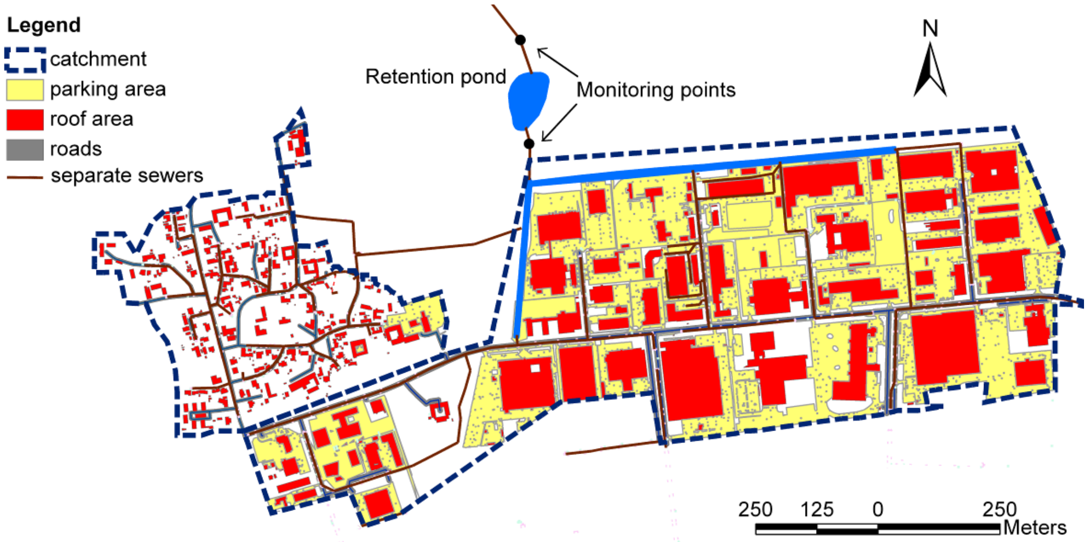

Figure 1. Characterization of the study area according to land usage (from Vezzaro et al. (2012a)).

2.2 Integrated stormwater quality model

The integrated model (Vezzaro et al., 2012a) is composed of three parts, representing the various elements of a stormwater drainage system: MP sources, drainage network, and treatment facilities. The inputs to the integrated quality model are the rainfall intensities and the MP release rates, which are estimated according to the information provided by the catchment characterization, while runoff and total MP concentrations are provided as model outputs.

To estimate the MP sources, the catchment is characterized into three different areas (Figure 1): roofs (with a 5% of metal roofs – value defined according to typical values observed in similar catchments), roads, and other impervious areas (e.g. parking lots). This classification can be performed by using cartographic information on land usage (stored in GIS databases) that is commonly available at the municipality level. For each land usage it is possible to find MP release data in the existing literature (e.g. Lützhøft et al., 2009).

The drainage network is modelled by using a dynamic runoff quality model: the catchment outflow is calculated with a non-linear reservoir approach, while stormwater quality is estimated by using an accumulation-washoff model.

Stormwater treatment is modelled by applying the Stormwater Treatment Unit model for MicroPollutants (STUMP - Vezzaro et al., 2010), a conceptual dynamic model which simulates the fate of various MP (subdivided into particulate and dissolved phase) in different treatment systems. MP fate processes (mostly affecting the MP dissolved phase) are simulated by using the pollutant inherent properties, with an approach inspired by multimedia fate and transport models known from chemical risks assessment, which reduces the need for expensive MP monitoring campaigns.

The integrated model was applied in this study to estimate the fluxes of TSS, heavy metals (Cu and Zn) and fluoranthene over a 10-year period (1994-2004, defined according to the available rainfall data) and elaborate statistics regarding pollution loads deriving from stormwater discharge in the catchment.

2.3 Analysis of model performance

A detailed analysis of the model performance and the uncertainty of the simulated MP concentration is presented in Vezzaro et al. (2011). The GLUE approach was used to estimate the model prediction bounds based on the approach initially proposed by Blasone et al. ((2008) and further schematized in Vezzaro et al. (2012b) and Breinholt et al. (2012). According to this approach, model prediction bounds are generated by using the parameter sets (defined as "behavioural" in the GLUE terminology) which ensure coverage of a fraction γ of the observation. This fraction γ is defined according to the estimated measurement and model uncertainty.

The quality of the estimated prediction bounds can be evaluated by using the Average Relative Interval Length (ARIL), which was introduced by Jin et al. (2010) as:

$$ARIL = \frac{1}{N_{obs}} \sum_{j=1}^{N_{obs}} \frac{Limit_{upper,j} - Limit_{lower,j}}{Z_T(t_j)} \qquad (1)$$

where N_{obs} is the number of available observations; $Limit_{upper,j}$ and $Limit_{lower,j}$ are the upper and lower prediction bounds at the time t_j, and $Z_T(t_j)$ is *j-th* the measured value. The ARIL thus expressesa measure of the magnitude of uncertainty bounds when compared to measurements (i.e. with ARIL=1 uncertainty bounds have the same magnitude of the measurement). Table 1 summarizes the main results of the uncertainty analysis. The low coverage of some observed values (flows and pond outlet concentrations) were mainly due to input uncertainty (time displacement in rainfall input) and model structural uncertainty (insufficient description of the hydraulic conditions in the pond). Nevertheless, these uncertainties were not judged as detrimental for the model application (for further details the reader is directed to Vezzaro et al. (2011;2012a)).

Table 1. Summary of the performance of the integrated stormwater quality model (from Vezzaro et al. (2011;2012a)).

Model output	Fraction of observation covered by model uncertainty bounds	ARIL
Hydrological outputs		
Catchment outflow	40%	1.21
Pond outflow	40%	0.565
Stormwater quality – catchment outflow concentrations		
Cu	67%	2.24
Zn	80%	2.20
Fluoranthene	75%	2.91
Stormwater quality – pond outflow concentrations		
Cu	52%	0.421
Zn	42%	0.464
Fluoranthene	67%	0.160

2.4 Comparison of pollution control strategies

Six different scenarios (see Table 2) were identified in collaboration with Albertslund municipality as potential options for reducing the MP loads discharged in the aquatic environment downstream Basin K. These included a combination of different source control options and extended end-of-pipe treatment options. The integrated model was run to simulate the existing situation (baseline scenario) and to compare with the 6 potential scenarios.

A random sample from the behavioural parameter sets identified by GLUE was employed to simulate the MP fluxes in the catchment over a 10-year period (1994-2004). A total of 1000 simulations were used to calculate statistical results describing the pollution related to stormwater discharge in the catchment.

The outputs that were considered include the average yearly loads entering to and discharged from the retention pond, as well as an evaluation of the potential risk for the downstream aquatic environment based on the exceedance of Emission Limit Values (ELV).

2.4.1 Source control options

- Scenario A: conversion of 50% of the industrial area to residential. The composition of the new residential area (roofs, roads and other impervious areas) was obtained by analyzing the land usage data of a contiguous residential neighbourhood of similar characteristics. This scenario is subdivided into two scenarios: Scenario A1: where zinc gutters are allowed; and Scenario A2: where zinc gutters and metal roofs are not authorized in buildings.

- Scenario B: local treatment by infiltration of runoff from roads and parking areas into local facilities such as swale trenches (wadi). The discharge from these facilities is then conveyed to Basin K. When runoff flow exceeds the threshold on 1.5 l/s/ha, water is accumulated in the trench and released afterwards. For simplicity in the simulations, the various trenches placed across the catchment were lumped into a single unit for each different land usage (roads, roofs, and other impervious). A fixed MP removal rate was assumed in the local treatment unit by using a conservative value of 60% for metals (this low value was assumed by combining the findings presented in Hatt et al. (2009) and Fassman (2012)) and 80% for fluoranthene (DiBlasi et al., 2009).

- Scenario C: disconnection of roof surfaces and local infiltration of roof runoff into groundwater. This scenario is subdivided into two scenarios: Scenario C1 considers only disconnection and infiltration of the roof in the industrial area, while Scenario C2 considers all the roof surfaces in the catchment.

2.4.2 End of pipe treatment options

- *Scenario D*: increase of the pond depth. In *Scenario D1* the depth is increased from 0.8 m to 1.2 m, while in *Scenario D2* the depth is increased to 1.7 m.
- *Scenario E*: subdivision of the pond into three serial basins of equal volume. The total volume of the pond is not changed, while the depth of the first basin is increased by 0.5 m to increase settling.
- *Scenario F*: this scenario considers the effects of sediment resuspension caused by the fish population in the pond. These species are usually introduced by citizens for recreational purposes (fishing), unaware of the potential negative effect on the performance of the treatment unit. Sediment resuspension was calculated by assuming a total biomass of approximately 100 kg carp in the pond and by using a resuspension rate of 23 g/m^2 (Breukelaar et al., 1994).

Table 2. Summary of simulated pollution control scenarios

Pollution control scenario	
Source control	
A1	Conversion to residential area (with zinc gutters)
A2	Conversion to residential area (without zinc gutters)
B	Swale-trenches (wadi)
C1	Infiltration of roofwater (only from industrial areas)
C2	Infiltration of roofwater (from the entire catchment)
End-of-pipe treatment	
D1	Increase of the pond water level from 0.8 m to 1.2 m
D2	Increase of the pond water level from 0.8 m to 1.7 m
E	Subdivision of the pond
F	Introduction of wildlife

3 RESULTS AND DISCUSSION

3.1 Pollution control scenario comparison

3.1.1 Pollutant loads discharged to aquatic environment

Figure 2 shows the simulated yearly pollutant loads for the simulated scenarios. While the catchment submodel provided only total concentrations, the STUMP submodel allowed the estimation of the fate of the different MP fraction, with the particulate Cu and Zn fraction removed by settling and the fluoranthene mainly removed by degradation processes (acting on the dissolved phase). The high uncertainty affecting the catchment quality submodel resulted in wide prediction bounds (expressed by the bars in Figure 2), which hampered a clear and unambiguous comparison of the simulated pollution control strategies.

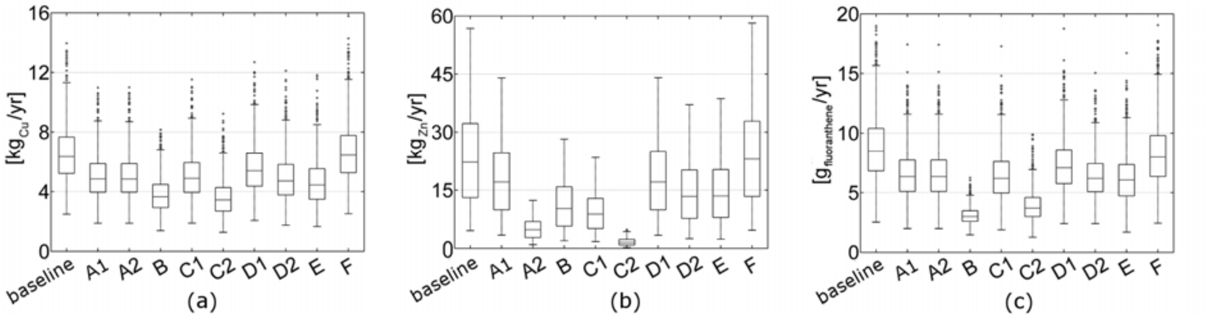

Figure 2. Comparison of simulated yearly loads for different scenarios for Cu (a), Zn (b) and fluoranthene (c).

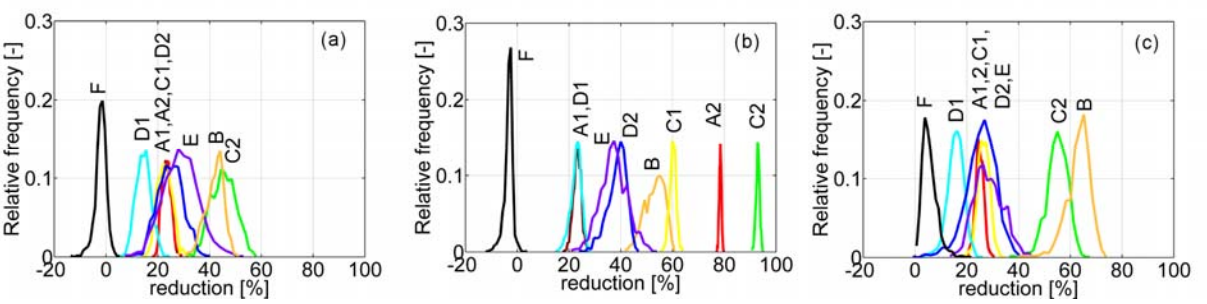

Figure 3. Percentage variation of estimated MP loads compared to the baseline scenario at the pond outlet for Cu (a), Zn (b), and fluoranthene (c).

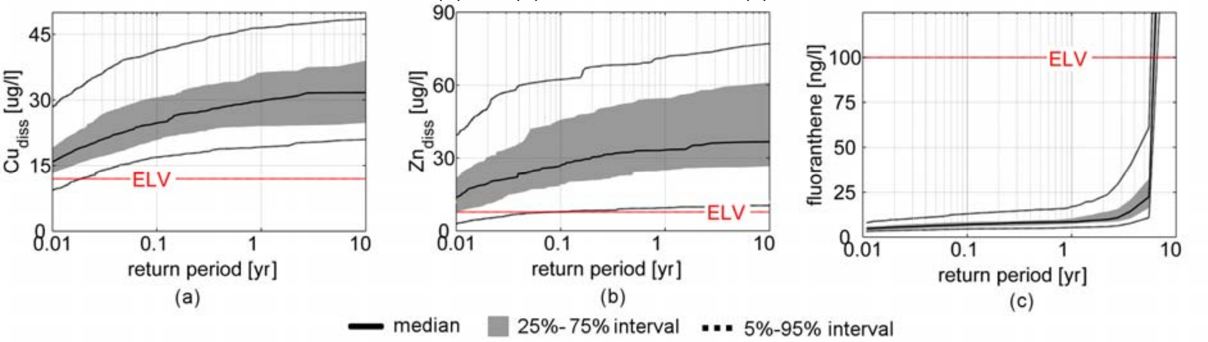

Figure 4. Return period of simulated outlet event mean concentrations (EMC) against ELV for dissolved Cu (a - ELV 12 µg/l), zinc (b – ELV 7.8 µg/l) and fluoranthene (c - the ELV of 0.1 µg/l).

Nevertheless, it was possible to draw some general conclusions regarding the different scenarios.

Source control options are generally providing a greater reduction in MP loads discharged at the pond outlet than end-of-pipe treatment options (Figure 3). However, these results vary depending on the substance and on the scenario. The implementation of swale trenches (B) and the disconnection of all the roofs in the catchment (C2) provided the greater load reduction for all the three simulated substances. Fluoranthene and copper show similar patterns, with scenario B and C2 obtaining higher reduction than all the other scenarios. The load reductions obtained for scenario B was 10-20% lower than the simulated removal rates in the trenches (60% for Cu and Zn, 80% for fluoranthene). This is caused by the resuspension of polluted sediments in the pond, where the reduction in inlet loads to the pond is compensated by the resuspension of polluted sediments.

Metallic roofs and zinc gutters are the major source of Zn in the catchment, as the greater reduction in Zn loads are obtained for the scenarios dealing with these sources (in order of efficiency: C2,A2 and C1). All the remaining scenarios (source-control and end-of-pipe treatment) obtain similar performance, as shown by the overlapping bounds in the estimated reduction (Figure 3). Therefore, the prioritization of the possible pollution control strategy cannot be based only on the expected reduction in pollutant loads, but should include additional criteria (discussed in the next paragraphs). The presence of fish in the pond (scenario F) is expected to increase the heavy metal loads by a maximum of 10%, while no significant effect is expected for fluoranthene.

3.1.2 . Compliance with Emission Limit Values

The ability of STUMP to simulate dissolved MP allowed the evaluation of the system performance with respect to the ELV for heavy metals, which are commonly targeting the dissolved form. Figure 4, for example, illustrates the simulated return period of event mean concentrations at the pond outlet for the baseline scenario. From this chart is possible to evaluate the frequency of exceedance of ELV for the simulated MP over the 10-year simulation period. Figure 4 shows that ELV for both dissolved Cu and Zn are exceeded by more than 90% of the simulation during the entire simulated period. Conversely, the ELV for fluoranthene was exceeded only during a single event (i.e. the ELV can be assumed to be fulfilled). From these results, dissolved Cu and Zn are expected to pose a risk to the downstream environment. However, this is a conservative assessment, as dilution in the receiving waters is not considered in this study.

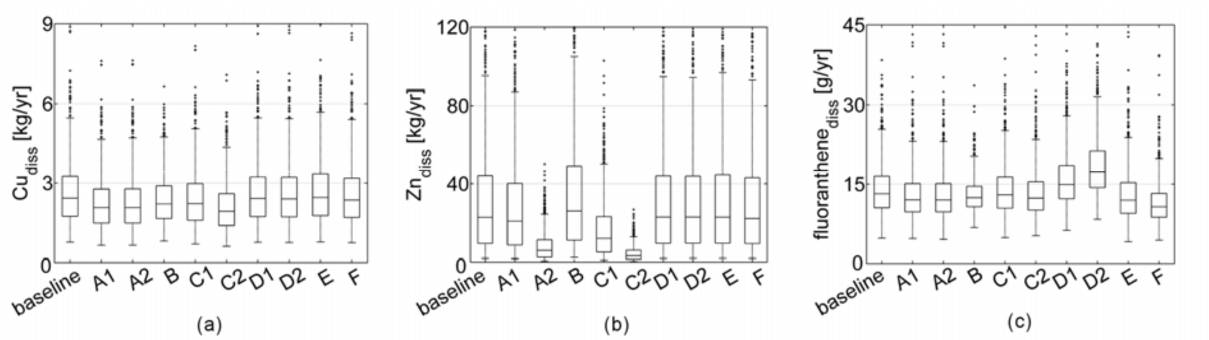

Figure 5. Comparison of simulated yearly dissolved loads for different scenarios for Cu (a), Zn (b) and fluoranthene (c).

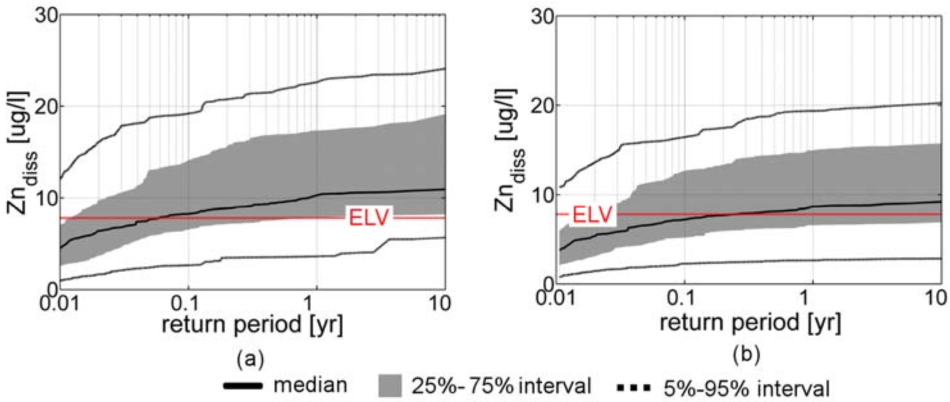

Figure 6. Return period of simulated outlet event mean concentrations (EMC) against ELV for dissolved Zn (ELV 12 µg/l) for scenario A2 (a) and C2 (b).

None of the simulated scenarios succeeded in significantly reducing the frequency of ELV exceedance (some examples are shown in Figure 6). The major pollutant removal process in the detention pond is settling, i.e. the dissolved phase is not affected by an improved treatment capacity. Also, sorption/desorption processes affect the two phases, resulting in a lower decrease of the dissolved fraction compared to the particulate fraction. The benefits due to the reduction of total MP entering the pond was compensate by the decrease in the amount of MP sorbing to particles and susbsequently removed through settling. This can be seen in Figure 5 (showing the results for Zn), where a significant decrease in the load of dissolved pollutants can be seen only for the source-control scenarios which are ensuring the better performance also for the total pollutants (scenario A2 and C2). However, these reductions were not sufficient to decrease EMCs below the water quality criterion: for example, the ELV for dissolved Zn is exceeded by more than 50% of the simulations with a frequency greater than 10 times/yr in both scenario A2 (Figure 6a) and C2 (Figure 6b).

The simulation results thus suggest that additional pollution control strategies, specifically targeting dissolved fractions (e.g. filters at the pond outlet, such as the one presented in Vollertsen et al., 2009), should be included as potential scenarios for pollution control. Also, further development of the catchment quality sub-model to include phase distribution might improve the assessment of the different strategies with regards to the dissolve MP phase.

3.1.3 Sediment accumulation

An additional factor that should be considered in the assessment of different pollution control scenarios is the MP fate in the analyzed system. Given the relevant role played by settling removal processes for all the three simulated MPs, information about the total MP mass accumulated in the pond sediments (Figure 7) is relevant for assessing the maintenance requirements of the system. In the majority of the source-control scenario, no significant reduction in the total sediment mass is noticed: the decrease in the inlet loads due to source reduction is in fact compensated by better settling condition in the pond (i.e. less particles escaping the pond and greater sediment accumulation). This is especially noticed for scenarios C, where catchment disconnection contributes to significantly reduce the hydraulic overload of the pond, increasing the overall treatment efficiency. Clearly, scenarios focusing on enhanced treatment (D, E) resulted in an increased amount of MP in the sediments.

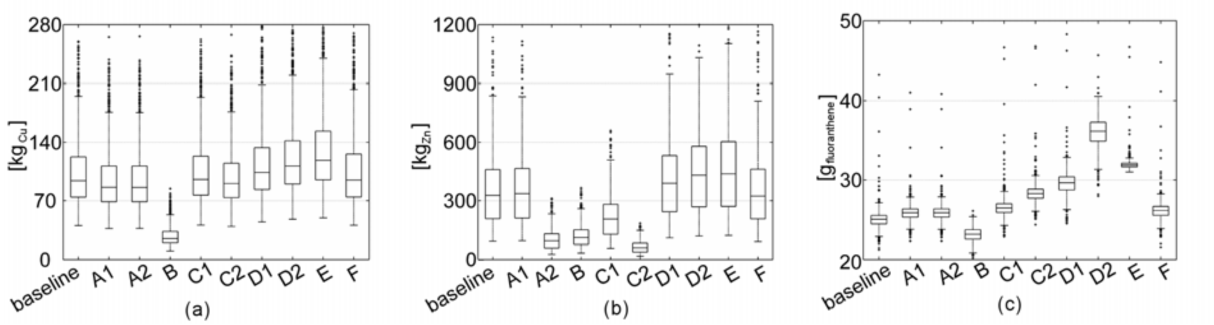

Figure 7. Comparison of simulated total MP mass accumulated in the pond sediment after a 10-year period: Cu (a), Zn (b) and fluoranthene (c).

For example, the greater residence time in scenario D2 and the lower sediment resuspension resulted in an increasing fraction of fluoranthene being sorbed to particles and removed by settling processes. The presence of fish in the pond (F) did not result in significant changes in the MP accumulated in the sediments.

3.1.4 Overall assessment

By comparing the results illustrated in the previous paragraphs, source-control scenarios appear to be the most effective strategies in reducing the impact caused by stormwater discharge. Namely, scenario B (swale trenches) and C2 (disconnection of all the roofs) provided the greater benefits.

This evaluation is however based only on MP load reduction, and should be combined with additional consideration regarding, among others, construction and maintenance costs, social acceptance, technical and financial feasibility. Nevertheless, the analysis of these factors is beyond the scope of this paper. Also, scenario uncertainty (e.g. the simplified model used to represent swale trenches) might affect the scenario comparison and the final ranking of the pollution control strategies. Similarly, detailed hydrodynamic models can be used to evaluate the effect of the changes in pond configuration (deepening of the unit, subdivision into sub-basins), before implementation in the conceptual model.

4 CONCLUSIONS

The investigations performed in this study illustrate the potential for the application of integrated dynamic models as a tool to evaluate pollution control strategies dealing with discharge of stormwater micropollutants. This study shows that:

- The proposed modelling approaches can be integrated to estimate MP fluxes across stormwater systems. The flexibility of the model allows the simulation of different substances by employing information that can easily be retrieved (e.g. rainfall data, flow measurements, MP inherent properties, MP release factors)
- Uncertainty analysis showed the model limitations, but also allowed a robust use of the simulation results in a context highly affected by various sources of uncertainty.
- The integrated model, supported by field measurements, can be used to compare different pollution control strategies, focusing on source control or on end-of-pipe treatment, by estimating the effect on different environmental indicators (e.g. discharged loads, exceedance of water quality criteria, mass of accumulated sediments).

The proposed approach represents an important decision support tool for urban water management. The example proposed in this article show how the integrated model can readily be applied in full-scale applications with minimum data and knowledge requirements. Thus, urban water managers can greatly benefit from the application of these modelling tools while developing, assessing and benchmarking different scenarios for stormwater pollution control strategies.

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