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Towards an Integrated Monitoring and Modelling Approach for Particle-Bound Contaminants in Urbanised Catchments

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Abstract
Urban runoff is a pathway of particles and particle-bound contaminants (PBCs) towards urban water bodies. These contaminants are emitted from urban wet weather discharges (i.e., combined and separate sewer networks) during storm events, creating health risks for humans, ecosystems and degrading water quality downstream. Due to the spatial and temporal variability of PBCs associated with different urban sources, accurately quantifying, characterising and identifying their transport pathways remains a major challenge. Modelling is a useful tool to study the dynamic behaviour of urban drainage systems. Hence, to understand the PBCs pathways at the interface between sewer systems and streams, we have established an integrated monitoring network in a small stream located Dresden, Germany. We further developed an integrated model that incorporates both combined and separate sewer network discharges to evaluate their impact on the stream water quality. By integrating long-term, high-resolution monitoring with catchment-scale modelling, this study offers new insights into the export and dynamics of TSS and PBCs transport in urbanised catchments. Our findings highlight challenges and opportunities related to modelling PBCs with an integrated approach, showing that embracing the complexity of real-world settings is necessary to support the development of management alternatives to reduce the export of pollutants.

Highlights
- Integrated monitoring and modelling facilitate analysing the dynamic impact of urban discharges
- High-resolution data is a prerequisite for accurately capturing contaminant dynamics
- The integrated model includes a simplified description of in-sewer processes

Introduction
Urban runoff is a primary pathway for the release of pollutants into the environment, leading to the deterioration of the receiving water bodies. Particle-bound contaminants (PBCs) such as metals are attached to particulate matter and can be mobilised during heavy rainfall events. These contaminants enter rivers mainly through surface runoff (diffuse sources), combined sewer overflows (CSO) and stormwater outlets (SWO). The impact of urban wet weather discharges (UWWDs) is exacerbated by climate change and urban growth. Due to the spatial and temporal variability of PBCs, the quantification and characterisation of contaminant pathways remain a major challenge. Despite high investments, current management alternatives to improve water quality are inefficient, largely due to

the lack of a real paradigm shift towards integrated approaches for water management. Existing models, used to estimate pollutant loads for developing management alternatives, often underrepresent the high heterogeneity of urban drainage systems and receptors (i.e., different land uses, pollution sources, in-sewer processes) (Chrysochoidis et al., 2025; Vanrolleghem et al., 2019), resulting in an oversimplification which fails to represent the high variability of the system.

The urban hydrology group of TU Dresden has established an integrated monitoring network in a small stream (Lockwitzbach) in Dresden - Germany, to identify pollutant pathways at the interface between sewer systems and streams. This urban observatory has two water quality monitoring stations within the Lockwitzbach stream (Benisch et al., 2025) and three stations within the sewer network. Compound fluxes are monitored with state-of-the-art technologies to give detailed insights into complex runoff and discharge processes. The high-resolution data (1min) of discharge and turbidity allow understanding the transport mechanisms of particles and PBCs in the Lockwitzbach catchment. Few studies attempt to simulate the combined response of the sewer and stream systems in terms of particle and PBCs transport. To address this gap, we aimed to evaluate the impact of different sewer network discharges on the water quality of the urbanised catchment using an integrated approach. This includes combining long-term, high-resolution monitoring data with sewer network-catchment-scale modelling. We characterised the impacts of UWWDs along the urban stream to evaluate the export of PBCs and the dynamic response of the system. Our approach of coupling in-sewer processes with receiving water responses provides insights into PBCs pathways, considering the complexity of urban areas. This approach can be further developed to facilitate the selection of appropriate technologies and strategies to reduce the impact of urban discharges on the receiving water bodies.

Methodology

Study area, sampling campaign and online monitoring

The study area is a small upland stream (Lockwitzbach, mean flow 0.34 m^3, area 84 km^2) located in Dresden, Germany. The catchment is dominated by non-irrigated arable land (40%), pastures (21%) and urban areas (14%) with a main stream length of 29 km. The urbanised area is clustered towards the downstream (Fig. 1). Within the urbanised area, we have identified 17 CSO/SWO. We installed three monitoring stations at the outlets of three sub-catchments (i.e., MS5, MS2 and MS9) (Table 1).

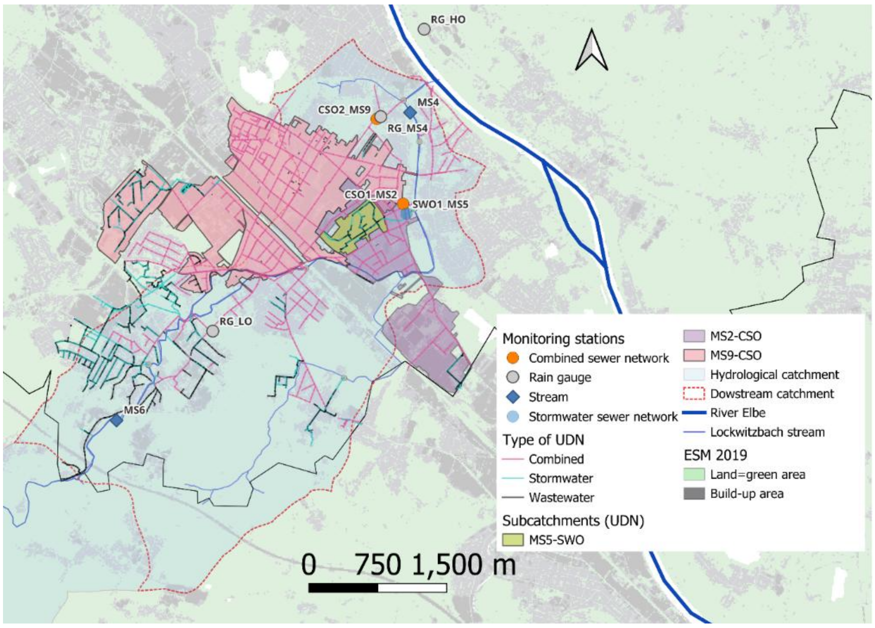

Figure 1. Analysed section of the Lockwitzbach river, including the locations of monitored combined sewer overflows (MS2 and MS9) and separate water overflow (MS5). Lockwitzbach catchment in blue and Dresden city limits represented by a black line

Table 1. Characteristics of the monitored urban sub-catchments

Sub-catchment UDN	Drainage type	Area (Ha)	Impervious surfaces %	Monitoring time	Data
MS5-SWO 1	Separated	23.6	43	2017-2023	Discharge, Turbidity, TSS, metals
MS2-CSO 1	Combined	129.0	53	2013-2023	Discharge, incomplete Turbidity (until 2018)
MS9-CSO 2	Combined	618.4	41	2022-2023	Discharge, Turbidity, TSS, metals

The monitoring stations are equipped with online sensors for turbidity, flow rate and automatic sampling during storm events. Additionally, suspended sediment samples were taken upstream/downstream the urban area (i.e., MS6 and MS4; Fig. 1). High-resolution discharge and turbidity data (1 min) were continuously monitored in the stream and the sewer network. However, continuous monitoring data and sampling cover different periods (Table 1). Hence, each monitored sub-catchment (UDN) was analysed individually before being integrated into the catchment model.

At the stormwater sewer network (MS5), the turbidity was measured by a Solitax-sc turbidity sensor (Hach), discharge was recorded using a wedge velocity sensor and water level with a pressure cell (POA sensor, NIVUS). Water samples were collected during rain events using an automatic water sampler (MAXX GmbH). We analysed total suspended solids (TSS), organic content and metals (Cr, Cu, Ni, Pb and Zn) in dissolved (filtrated sample <0.45 µm) and particulate phase (<63µm and 63-630 µm). Samples of suspended solids taken during rainfall events at the monitoring points located upstream/downstream the urban area were analysed for metal concentration, fine (<63 µm) and coarse fractions (>63 µm) of total and organic solids. Turbidity and contaminant concentrations were related by linear regression in both the stream (MS6, MS4) and sewer network outlets (MS5 and MS9).

Modelling approach

We integrated hydrological and hydrodynamic modelling using SIMBA# 5.0 (ifak, 2021) and EPA SWMM for evaluating the impacts of UWWD (CSOs and SWOs) (Fig.2). The SWMM model implementation included the use of the automatic sub-catchment generator GisToSWMM (Warsta et al., 2017); automated discharge calibration for the sub-catchments (MS5 and MS2) and surface build-up and wash-off of particles and PBCs (i.e., metals). The SWMM model included different parameters for simulating TSS transport, considering the heterogeneity of the land cover (i.e., streets, pedestrian areas, parking areas, roofs and green areas) (Rojas-Gómez et al., 2021).

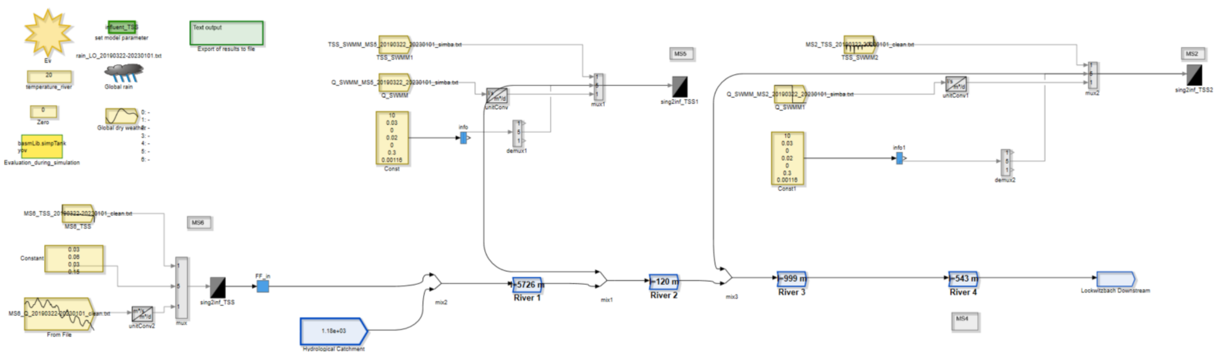

Figure 2. Representation of the integrated model in Simba# 5.0, including the coupling with SWMM

Additionally, we studied the impact of sedimentation, accumulation and re-suspension of particles and metals within the sewer network and river using a simplified block in SIMBA# 5.0 (Rojas et al., 2017). Turbidity was used as a proxy for TSS and PBCs in the catchment (Rügner et al., 2014). The integrated model was calibrated and validated using the online monitoring data and grab samples from 2019 - 2023 in the stream (MS6 and MS4) and SWO (MS5). In SIMBA# 5.0, water fluxes were characterised using discharge, concentration of metals (Cr, Pb, Cu, Zn, and Ni) and TSS. The continuous time series of discharge and predicted TSS served as a boundary condition for the upstream part of the catchment (MS6).

Results and discussion

Turbidity and contaminant concentrations (i.e., TSS and metals) were related by linear regression in both the stream and sewer network outlets. The goodness of fit of the linear regressions has a high variability (e.g., Turbidity vs TSS, R^2 = 0.41 - 0.86). The monitoring point with less urban influence (MS6, R^2=0.86) shows a better correlation between turbidity and TSS compared to the downstream point (MS4, R^2=0.68) or the UWWDs. In the monitored sewer networks, not all analysed metals showed an acceptable goodness of fit or strong correlations with turbidity. In particular, relationships computed in MS9 are poor ($R^2 < 0.5$), likely due to insufficient samples across different turbidity ranges. Hence, only MS4 (stream) and MS5 (SWO) were calibrated and validated for TSS and metals in the integrated model.

The discretised land covers in SWMM, for the urban sub-catchments MS2 and MS5, suggest that the highest export of TSS is related to the wash-off from streets (43.7%). Therefore, the implementation of management and mitigation measures, such as street sweeping, to reduce the exported TSS could be further analysed using our existing models. Additionally, coupling a hydrodynamic and a simplified physically-based model was important to capture the dynamics of the UWWDs, allowing a better representation of the mobilisation of sediments in the stormwater network (MS5), considering in-sewer processes. Further details regarding the calibration and validation results of MS5 are presented in Rojas-Gómez et al. (2022).

Our integrated model was used to analyse the impact of UWWDs on the water quality of the Lockwitzbach stream (Fig. 3). Although the model showed high goodness of fit for discharge (e.g., NSE values > 0.6) during continuous simulation, the quality model should be further improved to represent with more accuracy the transport of TSS and PBCs such as metals (Table 2). Previous studies highlighted the variability of contaminant flushes in urban areas and the consequent challenges of simulating TSS export due to the high uncertainty (Chrysochoidis et al., 2025; Qin et al., 2016; Reinholdt Jensen et al., 2022). Although our modelling approach accounts for the land cover heterogeneity and in-sewer processes, results showed an incomplete representation of intra- and inter-event TSS mobilisation, likely due to the inability to represent all contaminant flushes. Further efforts to simulate in-stream TSS and PBCs transport are needed.

Table 2. Goodness of fit for the integrated model for discharge, TSS and TSS mass during continuous simulation (2019-2023)

	Discharge			TSS			Mass TSS		
	NSE	R^2	KGE	NSE	R^2	KGE	NSE	R^2	KGE
Downstream	0.86	0.87	0.82	0.13	0.25	0.32	0.49	0.5	0.46

In this study, we focused our modelling efforts on the most relevant UWWDs located upstream of the calibration point (MS4). Nevertheless, representing the remaining UWWDs as a single sub-catchment block may not adequately reflect the spatial heterogeneity and variability of contaminant flushes discharging into the stream. Our results highlight the potential of using integrated simulation as an effective approach to assess the impact of UWWDs along the stream. This allows identifying and prioritising areas generating the highest load of sediments to recommend strategic locations to reduce water pollution. Hence, our integrated model is a tool to predict the impact of PBC under various conditions, supporting future urban planning and decision-making. This is crucial for formulating targeted water pollution strategies.

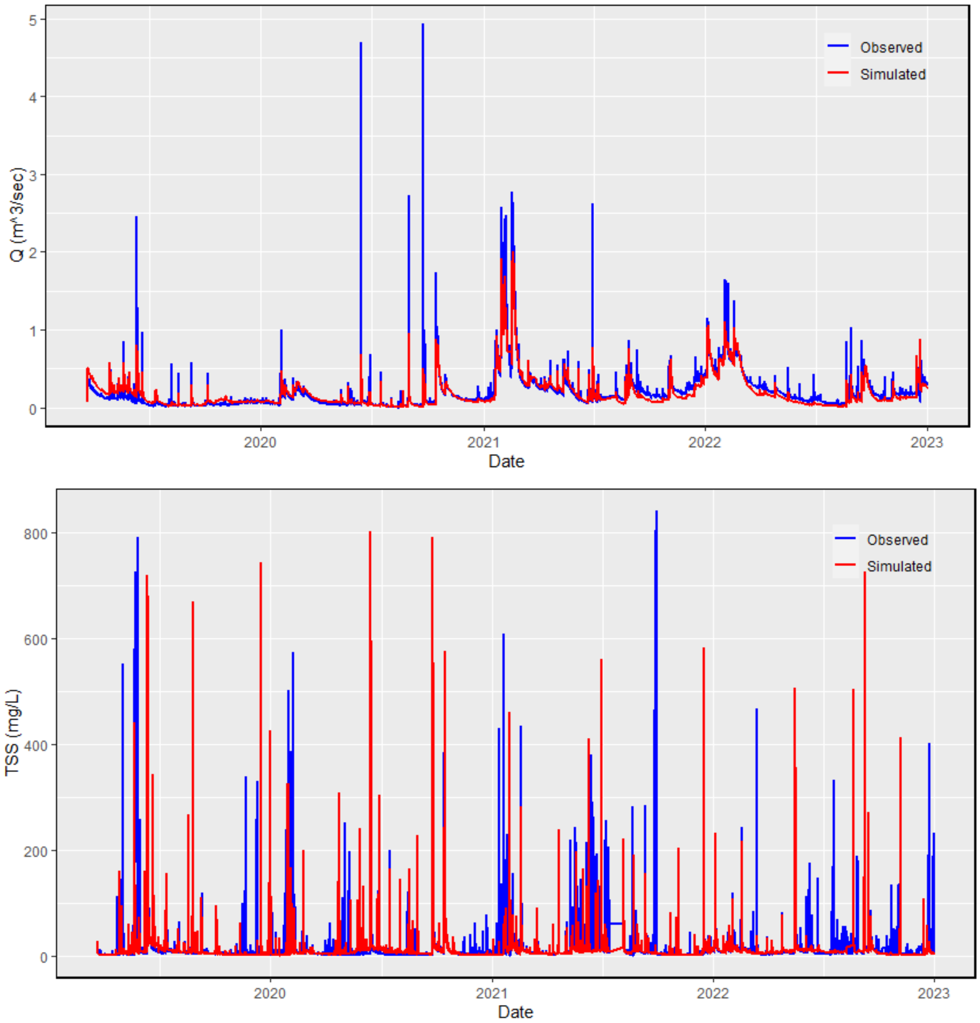

Figure 3. Observed and simulated values of the discharge and TSS downstream Lockwitzbach catchment (MS4)

Conclusions and future work

Our results suggest that integrated simulation is an effective approach to analyse transport mechanisms and pathways of sediments and PBCs within urban catchments. High-resolution data and continuous monitoring are a prerequisite for accurately capturing the dynamics of contaminant export. This is useful to represent the wash-off of contaminants and different flush processes during rainfall events. However, we still face challenges in simulating particle transport due to the complex export dynamics. Future research should further explore the prevalent dynamic transport mechanisms of particles and relevant PBCs in the urban stream, considering complex runoff and discharge processes.

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