Sensitivity analysis of long-term transformation strategies for sustainable rainwater and wastewater management within an integrated model

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Highlights

- A significant emissions reduction can be observed by using an integrated model to analyze the simultaneous implementation of rainwater and wastewater sustainable systems.
- Existing WWTP's performance decreases for certain pollutants due to modified COD:N ratios

Introduction

New water and nutrient recycling measures have become priorities for wastewater infrastructure's long-term design (cf. Wong and Brown, 2009). However, due to the long lifespans of these systems, the assessment of uncertainty sources and their impact on the existing infrastructure during the implementation process is of pivotal importance for the future-proof planning of sustainable water use (cf. Larsen et al., 2016, Kaufmann Alves, 2013). In addition, integrated models can show the impact of critical drivers on specific verification and operationalization parameters within the various water subsystems considered (cf. Mikovits et al., 2018, Bach et al., 2020).

The sensitivity analysis presented in this work seeks to understand the long-term behavior of wastewater systems using an integrated model while considering time-varying boundary conditions and system designs. The aim lies in evaluating system operation and functionality during long-term decentralized transformation processes, i. e., gradual implementation from centralized systems into sustainable drainage systems and rainwater and greywater reuse systems. The sensitivity approach builds upon a fictitious, representative integrated system of both sewer and a WWTP for a small city.

The systematic simulation presented herein aims to provide bases for extending the current planning and design concepts for sustainable water systems.

Methodology

The study area yields over 197 hectares and comprises nine subcatchments, whereby eight of them drain as combined sewer and one as a separate sewer. Moreover, the wastewater treatment stage consists of an aerobic activated sludge plant with upstream denitrification and P-precipitation. A fractionation estimation of the separated flows allows an integrated simulation of the drainage and wastewater treatment systems.

Model structure

In this analysis, the implemented software for dynamic modeling is the simulation platform SIMBA# water version 2.1. The developed detailed, dynamic model depicts decentralized sustainable drainage systems (SUDS) and new alternative sanitation systems (NASS). Furthermore, the model considers various wastewater processes (e.g., discharges, mass transport, and conversion) within each subsystem and considers the simultaneous operation of centralized and decentralized subsystems. The detailed model does not currently allow any dynamic changes within the pre-defined system design during the simulation runs.

A three fraction model, i. e., chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and total phosphorus (TP), describes wastewater at the source. Furthermore, the ASM3 Bio-P, including the SIMBA# components for the description of phosphorus precipitation and XMI-fraction, is the selected dynamic modeling method for assessing biochemical degradation processes within the study. Further, implementing decentralized SUDS and NASS occurs according to the presented methodology in Campusano Garcia and Kaufmann Alves, 2019. However, the assumed COD fractionation for the partial flows within this study corresponds to the values shown in Table 1.

Table 1. Implemented COD fractionation according to streamflow type

Fraction		Stormwater[1]	Wastewater[2]	Blackwater[3]	Greywater[3]
		Total COD share in the respective streamflow [%]			
f_{SI}	Fraction of soluble, inert fraction: SI to COD	14	2.5	4.5	0.35
f_{SS}	Fraction of soluble, biodegradable fraction: SS to COD	5	15.4	4.8	27
f_{XI}	Fraction of non-volatile TSS (FSS): XI to COD	76	20.3	21	20
f_{XS}	Fraction of biodegradable particulate COD: XS to COD	4	46.7	55	38
f_{XBH}	Fraction of biomass from COD: XBH to COD	1	15.1	14.7	14.65
VSS	Volatile suspended solids	81	82	91	72.7
$aXtss_{COD}$	Fraction TSS to COD	79	58.7	63.2	53.7
aBH_{CODbio}	Fraction of biomass from biodegradable COD: XBH to COD_{bio}	10	19.5	19.7	18.4

[1] Assumed values derived from literature values presented in DWA, 2012; [2] According to HSG (cf. Ahnert et al., 2015) and implemented in SIMBA#; [3] Assumed values derived from literature values presented in Tolksdorf et al., 2018

Sensitivity approach for the long-term simulation of adaptation strategies

The sensitivity approach builds upon three strategies concerning the adaptation pace of the measures' implementation: speedy and early adaptation (SEa), (ii) balanced adaptation (Ba), and (iii) speedy and late adaptation (SLa). The timeline for the adaptation pace spreads out over five decades. A simulation is carried out for one year long within each decade. Figure 1 shows the measure's implementation degree as a function of the system transformation time step - i.e., target adaptation system (TAS).

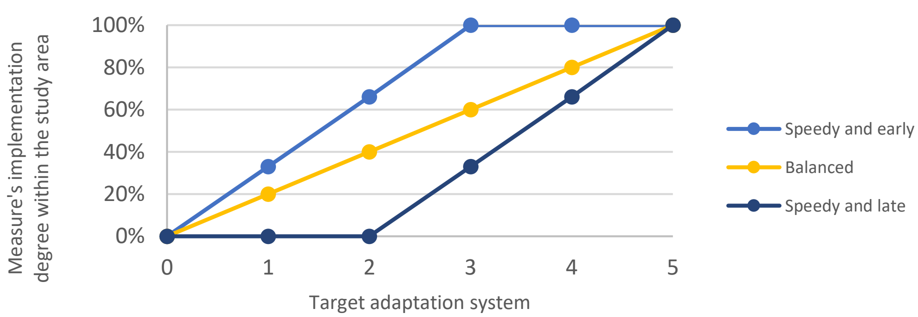

Figure 1. Adaptation pace strategies for the measure' implementation

Results and discussion

The decentralized SUDS implemented for both variants at a balanced pace comprise roof greening, desealing, and swale infiltration. Furthermore, these measures entail a complete disconnection of the stormwater flow from the combined sewer system.

Variants 1 and 2 are herein compared for a balanced implementation of the water reuse measures. In particular, variant 1 comprises the implementation measure of rainwater reuse. Both variants use the reused service water for toilet flushing, while the residual stormwater is assumed to infiltrate. Conversely, variant 2 incorporates greywater tanks with overflow function back into the sewer. Figure 2 shows long-term balance results of the pollutant mass transport into the water body.

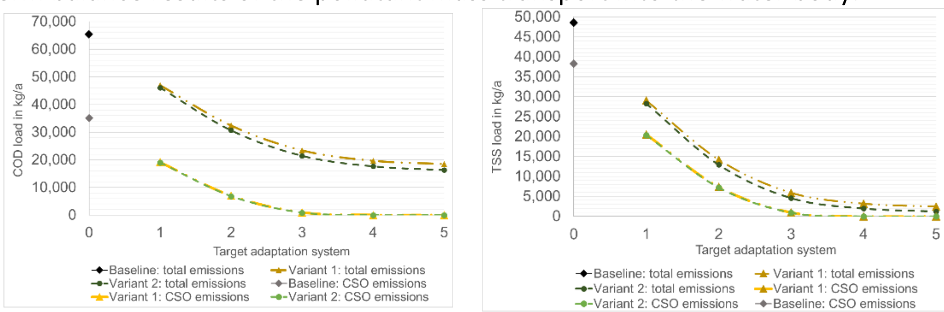

Figure 2. Pollutant mass balance of the CSO emissions and total emissions (CSO + WWTP effluent) as COD load per year (left) and as TSS load per year (right).

Both figures show the significant impact of the sustainable drainage measures on the total emissions into the water body in the first step of the target adaptation system. The implementation of the fourth target adaptation system eliminates any CSO, so the water body receives during the last decades only the emissions from the WWTP effluent.

Furthermore, figure 3 presents the contributing nitrate load from the WWTP effluent. Variant 2 shows that WWTP discharges even more nitrate compounds than the baseline. The increased nitrate elimination results from the modified COD:N ratio (only 25% of the greywater reaches the WWTP inflow).

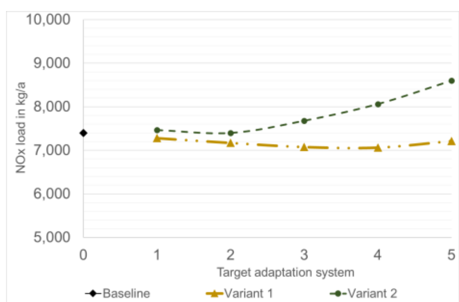

Figure 3. Pollutant mass balance of the nitrate load per year from the WWTP effluent.

Conclusions and future work

The resulting total stormwater runoff decrease through sustainable drainage systems significantly reduces pollutant emissions into the water body. Moreover, the decreasing performance of centralized WWTPs when treating dry weather flow with modified COD:N ratios requires the adaptation of wastewater management systems, e. g., by implementing decentralized sanitation systems.

Finally, implementing an optimization routine within the dynamic model is the next step to round up this integrated sustainable rainwater and wastewater management assessment. In doing so, the integrated analysis could also determine the optimal dimensioning of the infrastructures under changing boundary conditions.

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