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Modelling transportation of pollutants in urban drainage systems

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Abstract

Water bodies in Europe face pressure from multiple sources. This condition is especially critical in areas affected by combined sewer overflows, urban runoff from impervious surfaces and highways, agricultural land uses, forests, and leakages. Modelling and quantification of pollutant sources and transport in sewers are crucial to support municipal planning and design efficient mitigation measures. This study applied the SWMM model to simulate pollutant transportation, focusing on Total Nitrogen (TN) and Ammonia (NH4-N) in urban sewer systems. A lumped SWMM model demonstrated good performance in simulating stormwater runoff and NH4-N transport, showing reliable accuracy for estimating pollutant loads at the catchment outlet. However, the lumped model is limited in identifying specific pollution sources or problematic areas within the drainage network. To address this, a methodology was developed and demonstrated by analysing TN loads. The results revealed differences between observed and expected values based on land use, suggesting additional pollution sources in certain locations. The methodology also identified parts of the network requiring more attention due to large differences between measured and expected loads. Future work will focus on refining this methodology and applying it to multiple pollutants to improve urban water quality management.

Highlights

- SWMM has been used to simulate the transportation of pollutants in drainage network systems.
- A simple lumped model of the catchment yielded satisfactory performance in simulating drainage flow and Ammonia transport, after calibration.
- A methodology was developed and tested to identify potential sources of pollutions for urban catchments, using TN load as example.

Introduction

Water bodies across Europe are under increasing pressure from urban drainage and wastewater systems, posing a significant challenge to achieving sustainable water quality. According to the European Environment Agency (EEA, 2021), only 40% of European water bodies currently meet the good ecological status targets set by the EU Water Framework Directive. This issue is particularly severe in areas affected by combined sewer overflows, infrastructure leakage, and urban runoff from impervious surfaces, highways, and agricultural land. Understanding the transportation of pollutants through sewers, urban rivers, and receiving waters is essential for identifying key pollution sources and assessing their temporal and special contributions in different operation conditions. This knowledge is important for municipal planning and the development of effective mitigation strategies to protect the good quality and ecosystem condition of the water resources.

Numerical models simulate runoff and pollutant transport in urban areas, making them crucial tools for municipal planning and operation purposes. The EPA's Storm Water Management Model (SWMM) is among the most widely used tools for modelling runoff quantity and quality in urban areas. There are numerous studies that used the SWMM model to model stormwater quality (Ramovha et al. 2024). For instance, Zakizadeh et al. (2022) calibrated SWMM to runoff and concentrations (TSS, TP, TKN) in an urban catchments in Iran, reporting satisfactory model performance after calibration for both runoff quality and pollutant transport. Likewise, many studies found that SWMM models reproduce runoff volumes and pollutant transport with satisfactory accuracy after proper calibration (Assaf et al., 2024; Temprano et al., 2007; Zakizadeh et al., 2022).

Pollutants come from multiple sources in urban areas such as surface runoff from impervious and pervious areas, groundwater infiltrating into the drainage network, illicit discharges and misconnections from sewer pipes, including leaks from sewer pipes or septic systems. Most of the models focused on pollutant transport from surface runoff. Therefore, we observed a lack in the literature on using models to identify sources of urban pollutants (i.e., surface, groundwater, and sewer). Urban drainage pipes and sewer pipes are aging in most cities around the world, and as a result, issues like groundwater infiltration, sewer leakage, and misconnections are quite common globally. Consequently, when water quality is measured at any point in the system (particularly at the downstream parts of the network), it can be assumed that pollutant loads are combined from different sources. Most studies in the literature, however, only simulate pollutant load from surface runoff, hence arguably yielding higher estimation for the contribution of surface pollutants in order to achieve satisfactory model performance with calibration.

While a well-calibrated SWMM model can be useful for estimating pollutant loads at the outlet (or the locations used for calibration) and can therefore be used for operation purposes, such models cannot be used for estimating sources of pollutants or areas in the catchment that can be targeted with mitigation measures. This study is divided into two parts. In part 1, we used SWMM to model transport of Ammonia in an urban area, showing that with proper calibration, a satisfactory model can be achieved from a relatively simple lumped model of the urban area, thus adding to the body of literature showing that a well-calibrated SWMM model can yield satisfactory performance at the measuring station used for calibration. Secondly, we suggest a simple methodology for identifying sources of pollutant loads, showing where possible areas of the catchment can be targeted by mitigation measures for municipalities. Several tools such as SWMM, GIS, and RStudio were applied to develop and calibrate the hydrological model for simulating runoff and pollutant transport in sewers for an urban catchment located in Nordre Follo Municipality, Norway.

Case study

The case study focuses on an urban catchment in Nordre Follo Municipality, situated in the southeastern part of Norway illustrated in Figure 1. The climate of the municipality is classified as humid continental climate (Dfb) (Kottek et al., 2006), characterized by cold winters with significant snowfall and mild summers with moderate rainfall. The urban catchment in the study is about 115 hectares and comprises primarily residential areas. The SWMM model developed for the study includes 238 sub-catchments, 307 junctions, and 313 pipes, providing a detailed representation of the area's drainage infrastructure, as presented in Figure 1. Stormwater flow data at the outlet of the catchment were measured at a resolution of 10-minutes. In addition, precipitation was measured in a station near the catchment with 10 minutes resolution as well. The precipitation data were also available in several other gauge stations in the region or Oslo.

Figure 1. Map of the case study area placed on Norway map.

Measured water quality indicators and data

Several indicators, such as Ammonium, Phosphate, Nitrate, Total Phosphorus, Total Nitrogen and Total Phosphorus have been measured daily, usually one a month, or once a day in short periods by the Municipality in collaboration with NVE- the Norwegian Water Resources and Energy Directory, which is also a national agency for Hydrology illustrated in Figure 2. The measured indicator values formulated a basis for model calibration and simulation of transportation of pollutants in sewer systems and urban rivers. This study sets focus on the pollutant build up and flush away of Total Nitrogen and Ammonia.

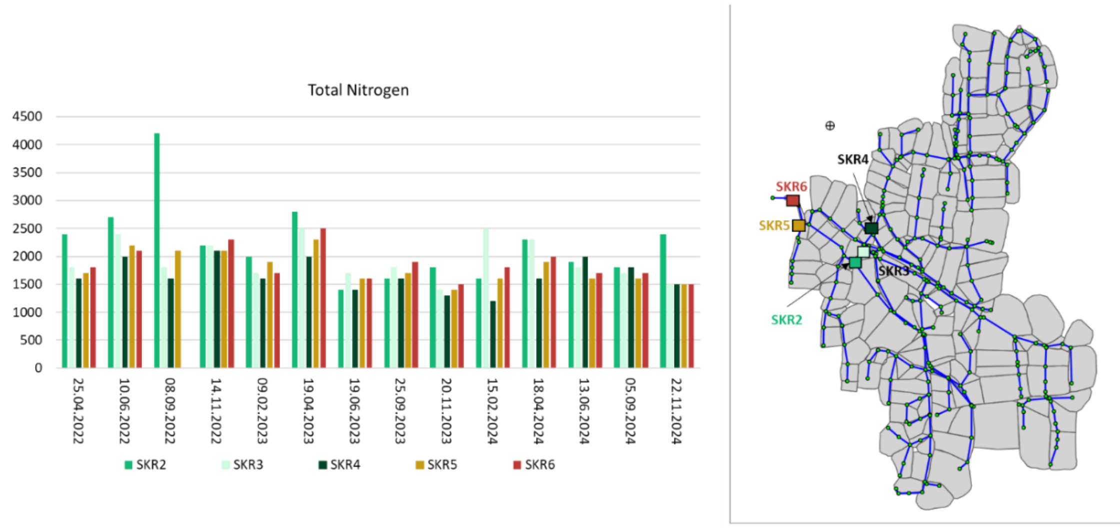


Figure 2. Measured Total Nitrogen at several locations during 2022-2024 at Skredderstubekken, Nordre Follo

Methods

The study area and system are modelled using the EPA's Storm Water Management Model (SWMM), an open-source tool originally developed in 1971 and widely adopted for the planning, design, and analysis of stormwater systems (Rossman, 2010). In this study, the model was development based on SWMM and GIS data. The calibration was performed in R programming language using the swmmr package (Leutnant et al., 2019).

SWMM hydrological model for runoff

In SWMM hydrological model was developed. The Green-Ampt equation is used to simulate the infiltration in the rainfall-runoff process and the kinematic wave formula for runoff routing (Rossman *et al*., 2016[a] and Rossman, 2017). The calibration process focused on eight parameters: the Green-Ampt infiltration equation parameters (saturated hydraulic conductivity and suction head); the depression storage volumes for both pervious and impervious zones for all subcatchments; Manning roughness for both pervious and impervious zones; Manning's roughness coefficients for the pipes; and the baseflow of the drainage pipes. Boundaries for the infiltration, depression storage, and seepage rate were set according to the SWMM User Manual (Rossman, 2010). Notably, the baseflow represented processes was not modelled in this study, such as leakage from the drinking water system and connections to the wastewater system. Instead, baseflow boundaries were established around the minimum measured outflow from the timeseries. To account for model delays and network irregularities (e.g., obstructions, singular energy loss points, or unforeseen leakages), pipe roughness was calibrated beyond the recommended range outlined in the SWMM manual. Calibration was conducted using the Differential Evolution algorithm through the DEoptim library in R (Mullen et al., 2011).

Modelling transportation of pollutants

As illustrated in Figure 3 for the SWMM's water quality module, pollutant build-up and wash-off processes are simulated as key mechanisms of urban runoff pollution. During dry periods, pollutants from atmospheric deposition, traffic emissions, urban land uses and other activities accumulate on catchment surfaces. When rainfall occurs, these pollutants are mobilized through a wash-off process, with removal rates dependent on rainfall intensity and surface characteristics.

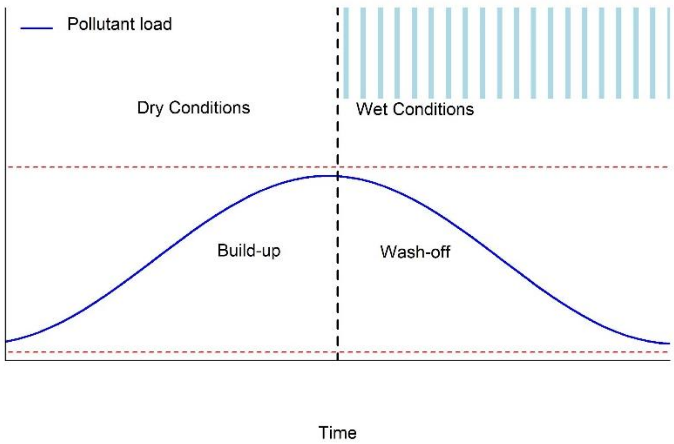


Figure 3. Build-up and wash-off processes for modelling pollutant transports in SWMM

In this study, we applied the exponential equation to estimate pollutant buildup in SWMM as, presented by equation (1).

$$B = C_1(1 - e^{-C_2 t})$$ **Equation 1**

Where, B is the pollutant buildup (kg/ha); C_1 is max buildup (kg/ha) that can occur of the pollutant for a specific land type; C_2 is the rate constant (1/day) that controls how quickly the pollutant builds up toward the maximum, and time (day).

SWMM incorporates three different choices of empirical models to represent pollutant wash off: exponential wash-off, rating curve wash off, and event mean concentration (EMC) washoff (Rossman *et al.*, 2016[b]). The exponential wash-off equation was applied in this study (equation 2).

$$W = C_3 q^{C4} B$$ **Equation 2**

Where W is the pollutant wash-off (kg/ha.day); B is the pollutant buildup (kg/ha) decided by equation (1). C_3 is Coeff. of wash-off (1/mm), $C4$ is a scaling factor that determines how much pollutant is washed off during a rain event; represents the exponent of wash-off [-], controls how sensitive pollutant wash-off is to runoff intensity.

Part1: Calibration of the SWMM model at the catchment outlet for Ammonia (NH4-N) transport

In part 1 of the study, we modelled the transport of Ammonia at the catchment outlet using a simplified lumped model of the catchment in which all sub-catchments were treated as homogenous unit with the same parameters for both drainage flow quantity and transport of Ammonia. The transport of Ammonia was calibrated by modifying parameters C1-C4 of the lumped catchment model where all sub-catchments were treated equally with the same parameters for all sub-catchments. Measured Ammonia transport at the outlet was used for the calibration.

Part2: A methodology for identifying potential sources of pollutions.

In this methodology, as illustrated in Figure 4, water quality parameters (i.e., C1-C4) were not calibrated but instead assigned randomly from values in the literature according to land use. Here we used studies that explicitly measured the quality of surface runoff before entering the network, for instance (Behrouz et al., 2024) to avoid possible effects of the other sources of pollutions.

An ensemble of model runs was then compared with the measured pollutant load at the monitoring stations. If the observed load was higher than the modelled, the difference was assumed to indicate seepage from the sewer network. The percentage of seepage was estimated based on the upstream population and average pollutant contribution per person. When 100% leakage was calculated (i.e., the total contribution from all people upstream), any remaining load was assumed to originate from groundwater infiltration or other unidentified sources requiring further investigation.

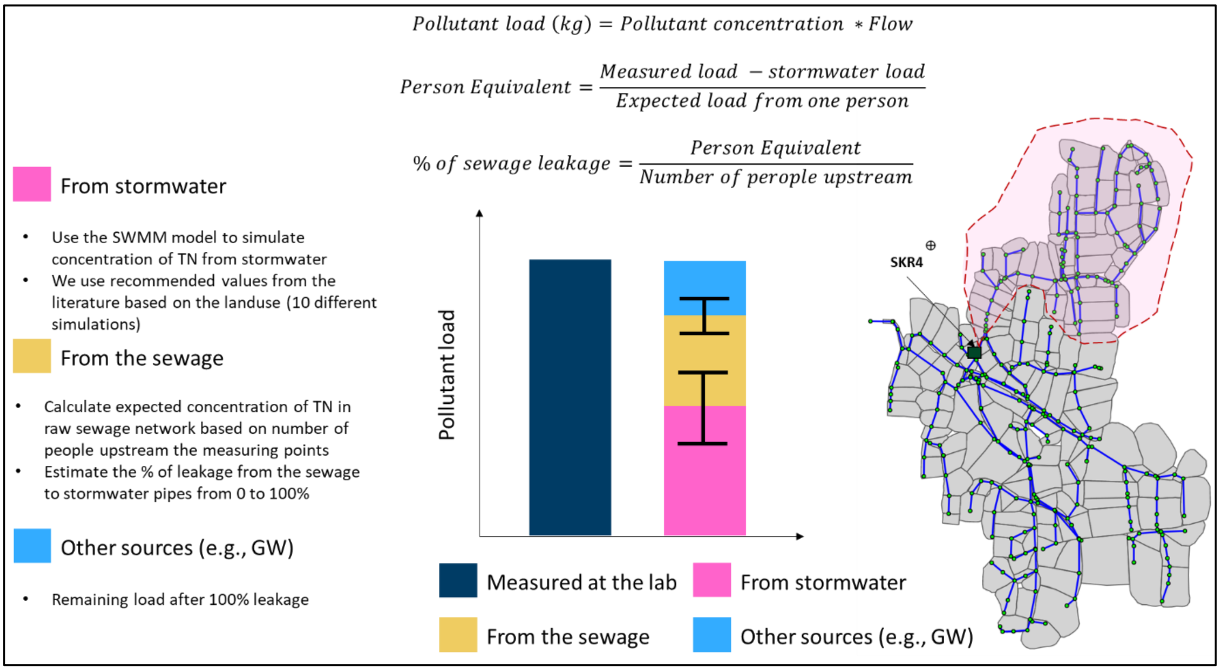
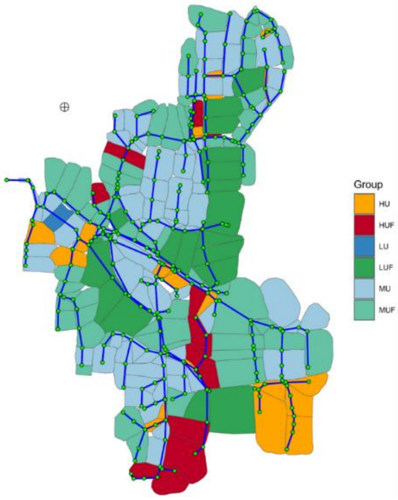


Figure 4. Methodology for identifying pollutant sources in the urban catchment. Pollutant loads simulated by SWMM using ensemble of parameter values from the literature (based on land use) were compared with measured loads at the monitoring station (SKR4). Differences between modelled and observed loads were attributed to sewer leakages, estimated from upstream population and per capita contribution, while any remaining load was assumed to originate from groundwater infiltration or other unidentified sources.

To generate an ensemble of parameter values (C1–C4) from the literature for the catchment, we first identified the land uses of the subcatchments in the study area. Based on the land use map, the C value components were then assigned for all subcatchments in this case study (see Equation 3).

$$C = Road\,\% \,*\, C_{Road} + Residential\,\% \,*\, C_{Residential} + Forest\,\% \,*C_{Forest} + Grass\,\% \,*C_{Grass} \qquad \textbf{Equation 3}$$

We generated 10 parameter sets by randomly selecting parameter from values reported in the literature (Behrouz et al., 2024; Tu & Smith, 2018; Yan et al., 2022).
In this part, we calibrated the SWMM model for runoff differently. Here, we grouped the catchments into six groups based on land use and level of imperviousness as shown in Figure 5. As shown in the figure, the study catchment was categorised into High, Medium and Low impervious Urban and mixed Urban and Forest areas, named HU, HUF; MU, MUF and LU, LUF. The infiltration parameters (saturated hydraulic conductivity and suction head) were calibrated differently for each group.



Group	Description
HU	High imperviousness, Urban area
HUF	High imperviousness, Mixed area (Urban + forest)
LU	Low imperviousness, Urban area
LUF	Low imperviousness, Mixed area (Urban + forest)
MU	Medium imperviousness, Urban area
MUF	Medium imperviousness, Mixed area (Urban + forest)

Figure 5. GIS based land use analysis and sub-catchment categorization for part 2 of the study

Results and discussion

Part1: Calibration and validation of the lumped model

Figure 6 shows the results of the SWMM model calibration and validation for stormwater runoff in the lumped model. During the calibration period, the model performance as measured by KGE (Kling-Gupta Efficiency) and NSE (Nash-Sutcliffe Efficiency) were 0.61 and 0.35, respectively, indicating a reasonably good model fit. In the validation period, higher KGE and NSE values of 0.84 and 0.76 were obtained, which can be classified as good model results (Thiemig et al., 2013).
Figure 7 presents the results of the simulation of ammonia (NH4-N) transport in the sewer system, as measured at the catchment outlet. The simulated concentrations closely follow the observed data, suggesting that the model effectively represents the build-up and wash-off processes governing pollutant transport. These results show that the model can simulate runoff and pollutant transport with good accuracy and can therefore be applied for operational purposes, such as estimating annual and expected pollutant loads at the calibration point (catchment outlet in this case). However, as discussed earlier, the model is limited in its ability to identify problematic parts of the network and cannot be used to determine the specific sources of pollution.
As discussed earlier, the simple lumped model can be effectively used to simulate the runoff and transportation of Ammonia.

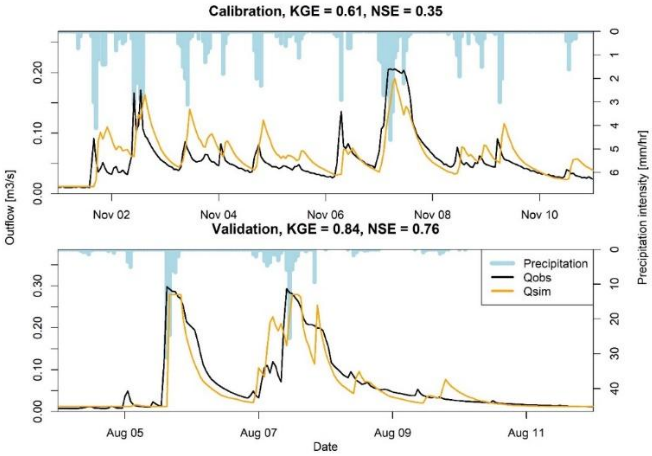


Figure 6. Performance of the model in simulating runoff during calibration and validation periods

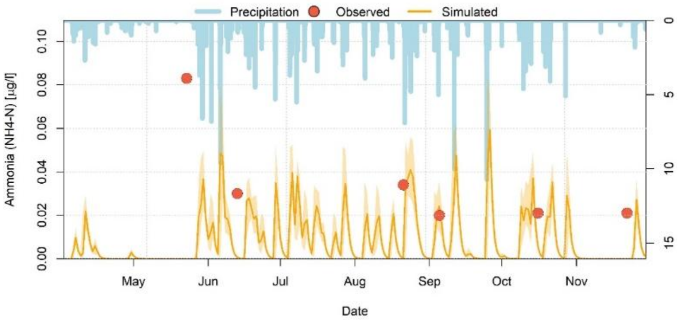


Figure 7. Performance of the model in simulating transport of Ammonia (NH4-N)

Part2: identification of pollution sources and potential issues in the network

Figure 8 presents the comparison between observed and simulated Total Nitrogen (TN) at the measurement stations. The results show differences between measured and expected loads based on land use, indicating possible contributions from additional sources. Larger discrepancies suggest areas of the network that may require further investigation. For example, the SK3 station shows a much higher measured TN load compared to the expected values from surface runoff, suggesting a greater contribution from other sources. Hence, the network upstream SK3 can be investigated further by the municipality to identify possible issues. At this stage of the study, potential leakage from sewers was not included to highlight the percentage of possible leakage as explained earlier. This aspect will be incorporated in future work.

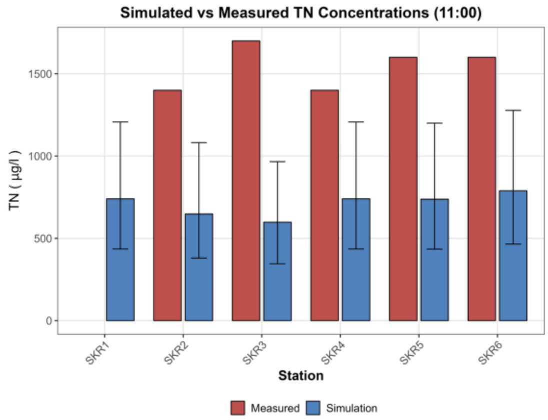


Figure 8. Observed versus simulated Total Nitrogen (TN) at the measurement stations. The results show differences between measured and expected loads based on land use. These differences indicate possible contributions from other sources, with larger differences highlighting parts of the network that may require further investigation

Conclusions and future work

The lumped SWMM model demonstrated good performance in simulating stormwater runoff and Ammonia (NH4-N) transport, indicating reliable accuracy for operational use, such as estimating pollutant loads at the catchment outlet. However, the model is limited in its ability to identify specific pollution sources or problematic areas within the sewer network.

A methodology was developed to address this issue and was demonstrated in this case study by analysing Total Nitrogen (TN) loads in the catchment. The results revealed differences between observed and expected values based on land use, suggesting additional pollution sources in certain locations. In addition, the methodology allowed identification of parts of the network that require more attention based on the large differences between measured and expected loads from land uses. Future work will aim at refining this methodology further and applying it to several other pollutants.

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