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Research article

A model-based analysis for trapping suspended sediment in stormwater inlets of urban drainage network

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ABSTRACT

Raised awareness of environmental constraints in recent decades has led stormwater management to incorporate quality components and focus on the treatment of urban runoff water at pollutant source areas. This study evaluated the impact of a developed type of sediment trap, installed into stormwater inlets, on the total suspended solids (TSS) load in an urban city center catchment in Finland. The objective was to outline a modelling approach to assess efficiency of the traps to treat TSS originating from different land uses (green areas, pavement, parking, roof, street, and other areas not belonging to the main land uses).

A Storm Water Management Model (SWMM) parametrization of a 5.87 ha catchment in the Lahti city center, Finland was utilized as the computation engine. The model had separate subcatchments for each land use, allowing the use of literature-based Event Mean Concentrations (EMC) to estimate the TSS pollutant washoff for the land uses. A method to assess the individual stormwater inlet pollutant loads and potential removal effect of the sediment traps was introduced. The hydrological and TSS load simulations covered a period of 6 months.

The stormwater network inlets installed with sediment traps were ranked according to their potential removal of TSS. One out of five EMC sets was selected to be representative of the urban land uses in the study site (green areas 75 mg/l, pavement 46 mg/l, parking 44 mg/l, roof 20 mg/l, street 64 mg/l, other 46 mg/l). The simulation results showed the influence of land uses on the pollutant load and revealed the optimal set of locations for the sediment traps. Additionally, the effect of regular maintenance intervals on the pollutant load, given a maximum storage capacity of the traps, was explored. The results showed a large variation in TSS removal depending on the inlets chosen for the sediment traps, with removal rates ranging from about 0 % to 10 % of catchment TSS load. The maximum TSS removal was 63 %, which was the reported efficiency of the traps. These results highlighted the need for an informed decision when selecting trap locations. Streets and parking lots were the largest TSS contributors, with stormwater inlets on streets being the desired sediment trap locations. While the absolute level of simulated TSS load was found to be dependent on the EMCs, the ranking of sediment trap locations was similar for the simulations with different EMC data sets.

1. Introduction

Impervious or partially pervious areas in urban environments lead to increased runoff rates and volumes, and reduction of infiltration (Fletcher et al., 2013; Tuomela et al., 2019), raising the need for proper stormwater management to identify and deal with the stormwater-inflicted stresses (Kõiv-Vainik et al., 2022). The common approach to stormwater management has been to divert the runoff water from the built area through a drainage network to receiving waters in an efficient and rapid manner (Sillanpää, 2013), in order to secure drainage of urban structures and control the risk of pluvial flooding (Nix, 1994). In recent years, with increased public awareness of environmental concerns, the focus in stormwater management has turned towards finding solutions that reduce the pressure on the ecosystem and habitats through e.g., Low Impact Development (LID) solutions (Fletcher et al., 2015). LID solutions emphasize small-scale local solutions in the upstream rather than downstream locations at the catchment outlet (Eckart et al., 2018; Khadka et al., 2020; Sørup and Lerer, 2021). Stormwater management has also incorporated a quality management aspect in addition to the runoff quantity management and flood control (Nix, 1994; Valtanen et al., 2014b).

Current regulations on stormwater quality are disparate across countries. Sänkiaho et al. (2011) noted that stormwater legislation in

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Finland is lacking compared to other countries, due in part to the share of responsibility of stormwater management to various actors, such as municipalities, companies, and property owners. Existing legislation also tends to focus on stormwater quantity, disregarding the quality of urban stormwater (Sillanpää, 2013; Tuomela, 2017). The lack of national level regulations has lead city environmental and technical services to outline their own guidelines, which are not harmonized across the country.

One approach to reduce stormwater pollution is the use of Catch Basin Inserts (CBIs), which are placed at the inlets of the stormwater drainage system (Alam et al., 2018) to remove various types of pollutants, including debris, solids, oil and metals (Morgan et al., 2005; Remley et al., 2005). These inserts have the advantage of removing pollutants at or close to the source areas, rather than allowing transport of contamination downstream. The inserts can be installed in an existing urban infrastructure (Lau et al., 2001; Remley et al., 2005), reducing the costs of installation. Some caveats of the inserts on the other hand include filter clogging, low efficiency of pollution reduction (Pitt and Field, 1998), and a lack of overflow bypass for some devices, which may increase the flooding risk (Morgan et al., 2005). Poor planning may reduce the efficiency of the solution (Lloyd et al., 2002) and maintenance should therefore be performed regularly to ensure the proper functioning of the inserts (Morgan et al., 2005). For the current study, the examined CBI was a stormwater-inlet-installed sediment trap, where stormwater was filtered through and the sediment remained in the trap. Similar insert designs had been studied previously, although no studies were found from high latitude climatic conditions. Sediment loads in cold climate regions differ from warmer regions due to use of salts and sand during winter road maintenance and generation of snowmelt runoff entering the stormwater network (Vijayan et al., 2024), serving as contamination vectors (Marsalek, 2003). In addition, variations in stormwater runoff from land uses is season dependent in cold climates (Valtanen et al., 2014a).

A hydrological model is a transparent method to explore the behaviour of the stormwater drainage under changing conditions (Elliott and Trowsdale, 2007). Modelling is especially suited to describe larger systems where monitoring might be complicated. Water quality can be simulated with functions defining how pollutants are generated and washed off into the drainage system with surface runoff or retained with waters infiltrated into the subsurface soils on pervious areas. These functions can be formulated as pollutant buildup and washoff functions or as simple Event Mean Concentrations (EMC), where the pollutant load is directly related to the runoff volume. To properly evaluate water quality using a model, the functions should be defined separately for each distinct land use found in the examined catchment (Butcher, 2003). As concentrations of pollutants are usually measured from discharge draining a larger area or catchment, determining land-use-specific functions can be challenging. However, identifying pollution sources is necessary to implement stormwater quality measures (Müller et al., 2020). In this case, literature values of EMCs characterizing individual land uses may be adopted as a solution of water quality estimation (Järveläinen et al., 2017; Brudler et al., 2019). It is often possible to find multiple equivalents of EMCs in literature for similar conditions and land uses, whereas literature values for various land use buildup/washoff parameters can be scarce. However, Tuomela et al. (2019) noted that simulated pollutant loads using EMCs tended to exceed measured loads, adding uncertainty related to the stormwater quality modelling.

In this study, the Total Suspended Solids (TSS) in urban runoff was evaluated as pollutant. The suspended solids are a carrier of other pollutants and can serve as a general pollutant indicator. As data is often more available for TSS than other pollutants, water quality models are commonly built on simulation of TSS to facilitate calibration (e.g. Al Ali et al., 2018; Piro and Carbone, 2014). Various tools exist (e.g. SWMM, MIKE URBAN) to determine the TSS in stormwater through either deterministic or statistical approaches to estimate both load and concentrations (Vinck et al., 2023), using either buildup and washoff functions or EMCs, respectively. However, while the statistical approach may fail to capture the variability within singular rainfall events, the deterministic approach requires the identification of a ranging amount of site-specific parameter values (Vinck et al., 2023). Earlier TSS treatment studies on CBIs have been reported by e.g. Berretta et al. (2008) and Lieske et al. (2021). Berretta et al. (2008) studied CBI efficiency and found that the CBIs had no significant impact on the hydraulic loss of the stormwater through the drainage inlets, while Lieske et al. (2021) noted the uncertainty related to determining the CBI treatment efficiency. The effect of land uses on TSS has also been addressed by e.g. Wang et al. (2013) and Rio et al. (2020). A continuing need for research into these topics exists due to the variability among catchments (Simpson et al., 2022). Urban stormwater and sediment load generation are affected by weather patterns (Rentachintala et al., 2022), and using local precipitation and temperature data reduces modelling uncertainty (Chaudhary et al., 2023).

Table 1
Contribution of each land use to the total area of the catchment, and the number of stormwater inlets located on each land use.

	Green	Pavement	Parking	Roof	Street	Other	Total
m^2	6974	8458	16 348	11 493	11 258	4211	58 742
%	11.9	14.4	27.8	19.5	19.2	7.2	100.0
Inlets	12	60	58	0	18	11	159

Modelling of sediment traps and stormwater loads in an urban catchments has not been widely examined under northern conditions (Wei et al., 2021). This study was motivated by the prospects of model-based investigation of the quality of urban stormwater and the performance of a management solution in an urban mosaic with multiple types of land uses. Specifically, the study aimed to examine how the placement of a developed type of sediment trap in stormwater inlets affects the total stormwater pollutant load of an urban catchment. Accounting for the costs of the structure and the maintenance, it is not realistic to install sediment traps in all inlets of the stormwater drainage system. Computational quantification of the catchment pollution reaching the inlets was set as a basis for ranking performance of individual sediment traps.

The evaluation of sediment trap performance through a modelling approach had not previously been extensively explored. The study aims to outline a transparent computational method to determine the optimal set of sediment trap locations for the targeted pollutant abstraction. The method was built on the existing Storm Water Management Model (SWMM) parametrization of an urban catchment in Finland with modifications to produce the treatment scenarios.

2. Materials and methods

2.1. Catchment model

The study site was the Taapelipolku catchment (Fig. 1), located in the city center of Lahti, Finland (60.99°N 25.66°E) in the southern boreal climate zone. The annual precipitation in the area is 633 mm and mean air temperature 4.1 °C (Krebs et al., 2013). The catchment area is 5.87 ha, of which a large share (86%) is impervious. Parking lots are the largest land use, followed by other highly impervious surfaces such as roofs and streets (Table 1). The pervious green areas cover only a limited fraction (12%) of the catchment, while the “Other” land use category encompasses areas of miscellaneous land uses (e.g. bare or paved soil spots) and accounts for only 7% of the total catchment area.

The hydrological and water quality model of the study area was modified from an existing SWMM parametrization of the Taapelipolku catchment, originally calibrated and validated by Krebs et al. (2013) against high temporal frequency measurements of stormwater discharge. The stormwater network had been outlined using digital sewer

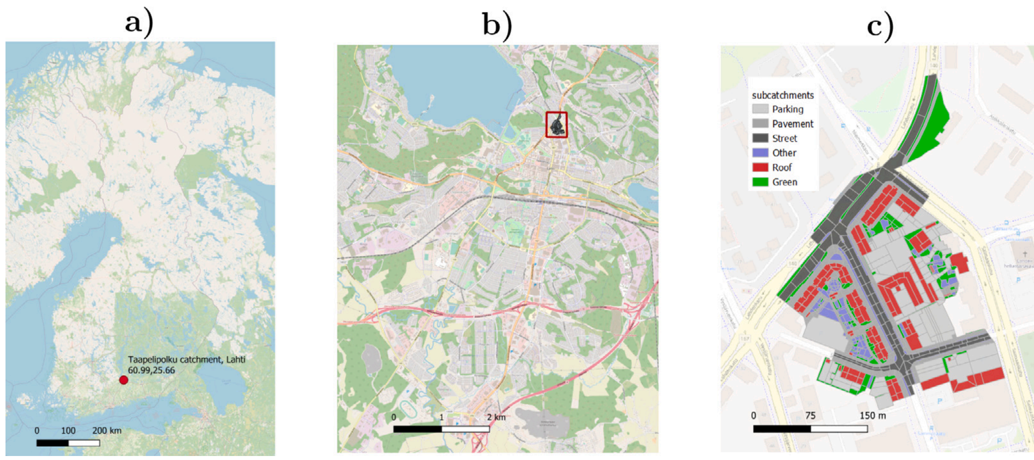

Fig. 1. (a) The catchment coordinates (60.99°N 25.66°E) and location in Finland. (b) The Taapelipolku catchment in the city of Lahti. (c) The modelled subcatchments with different land uses highlighted. Background map data provided by OpenStreetMap.

Table 2
Taapelipolku catchment SWMM buildup/washoff calibration parameters by Tuomela (2022).

Buildup		Washoff	
Function	EXP	Function	EXP
Max. Buildup	13.14	Coefficient	0.02
Rate constant	0.22	Exponent	2.22
Power/Sat. Constant	0.00	Cleaning Effic.	0.00
Normalizer	AREA	BMP Effic.	0.00

network map data and totalled 2.61 km of circular pipes, 159 inlets, 72 junctions and 690 subcatchments (Krebs et al., 2013). The subcatchments were separated into six categories based on their land use (Tuomela, 2022), determined using topographical data and in-situ observations (Krebs et al., 2013). Each subcatchment had their percentage imperviousness defined, and the parametrization had additionally been setup and calibrated for TSS pollution generation using the SWMM buildup/washoff functions by Tuomela (2022). The exponential buildup and washoff functions (Rossman and Huber, 2016) were parameterized with the values presented in Table 2. As such, the model reflected the inlets and catchment in detail without larger simplifications.

For this study, the model simulations covered the 6-month period from 1 May 2009 to 31 October 2009. However, because the maintenance impact calculations required a longer simulation period to perform, an additional 2 year period between 1 January 2009 to 31 December 2010 was chosen for these. For this purpose, the model was setup for snowfall periods using snowmelt parameters. The model used 1-minute interval precipitation data from the nearby Ainonpolku station in Lahti and temperature input data, as daily minimum and maximum, from the Laune station in Lahti (Krebs et al., 2013).

2.2. Sediment traps

The treatment solution examined in this study consisted of sediment traps installed into stormwater inlets (Fig. 2). The trap was a sock installed below the manhole cover with a metal collar. The trap had an estimated capacity of 40 kg of sediment. The upper edge of the sock had holes to allow overflow in the filter under extreme high flow conditions and under situations when the trap storage capacity was reached. The sediment traps had been tested in a laboratory setting by the developer of the traps, as well as under field conditions in the city of Lahti. For this study, a reported removal efficiency of 63% for suspended solids based on field site experiments (HuLaKaS, 2022) was used as a baseline performance measure.

2.3. Event mean concentration values

The concentrations of TSS and other pollutants, such as Nitrogen, Phosphorous and metals, had been previously measured at the Taapelinpolku catchment outlet (Valtanen et al., 2014b). The data was earlier included in the estimation of pollutant load accumulation across land uses in an urban catchment (e.g Järveläinen, 2014). To be able to assess the impact of individual subcatchments with homogeneous land use on the catchment pollutant load, the model was prepared to utilize Event Mean Concentration (EMC) values for all main types of land uses. EMCs were adopted instead of buildup/washoff parametrization, as literature-based EMCs are widely available and because the EMC-based water quality model is parsimonious from the point of view of the generalization of the results. The EMC values for TSS were chosen from Tuomela (2017), who presented several sets of EMC values collected from literature and evaluated them against a SWMM parametrization of an urban catchment in Espoo, Finland. This resulted in five separate model configurations, each with a different EMC set configured for the TSS calculations (Table 3). The land use characteristics in the Espoo catchment were assumed to be comparable to the Taapelipolku catchment in Lahti.

2.4. Implementing sediment traps in SWMM

Contrary to standard treatment options in SWMM, where treatment is applied to the routed water within the drainage network, the sediment traps treat only stormwater inlet inflow, and thus were conceptually approached as an additional step between the washoff and pipe routing (Fig. 3).

The SWMM water quality routine (Rossman, 2015) allowed treatment for removing pollutants from the outflow of a node, but not from inflows which included water from nodes further upstream in the network and from the local subcatchment. To circumvent this issue, the study utilized the PySWMM module with the possibility of constructing user-defined subcatchment inflow treatment. PySWMM was further tailored to retrieve mid-simulation outputs regarding the sediment traps (Mcdonnell et al., 2020). The simulations of different trap designs were automated by editing model parametrization in the SWMM input text files.

The sediment trap functionality was emulated in the PySWMM simulations by identifying the catchment stormwater inlets in the model, along with the subcatchments. The relative relations of inflows and outflows were mapped out, i.e. where each inlet or subcatchment received their inflow from and directed their outflow to. This allowed for the calculation of the incoming surface pollutant load in each inlet by subtracting the outgoing pollutant load of the inlet's immediate upstream nodes in the stormwater network, if any, from the outgoing pollutant load of the inlet.

Fig. 2. The sediment traps installed into the stormwater inlets. Images by Watec Oy.

Table 3
EMC sets for TSS (units in mg/l), as presented by Tuomela (2017), and their corresponding land uses in the Taapelipolku parametrization.

Source area	Land use	EMC set 1	EMC set 2	EMC set 3	EMC set 4	EMC set 5
Parking areas	Parking	1660	440	150	173	44
Paved walkways	Pavement, Other	20	20	7.4	58	46
Roads	Street	242	232	163	662	64
Roof	Roof	13	41	43	27	20
Open rock	–	11	11	11	11	11
Stone/tile paving	–	20	20	15.8	15.8	15.8
Sand, gravel	–	810	810	33.7	33.7	33.7
Vegetation, lawns	Green	11	71	12	397	75

2.5. Evaluation metrics

By identifying the catchment stormwater inlets in the model, the pollutant load entering the drainage system through each individual inlet was tracked. In conjunction with the removal efficiency of the sediment traps, the effect of the traps on the total catchment pollutant load was then calculated. The inlets were subsequently ranked according to the pollutant load that is potentially removed by installing sediment traps in them. Since the model had been setup for pollutant generation using the land-use-specific EMC values, the influence of land use and inlet location on this ranking was determined, and the effect of regular maintenance intervals on the traps was additionally examined.

Water quality simulations were run for each of the EMC sets, as well as for the unmodified model with buildup/washoff functions. For every simulation, information about stormwater discharge, pollutant concentration and the associated continuity errors were collected for every time step, which allowed for the subsequent calculation of the runoff volume and pollutant load through the inlets during the examined time period. The ranking of the stormwater inlets (sediment trap placements) was ordered from the highest potential removal to the lowest removal, to determine the most optimal and sub-optimal placements regarding the catchment pollutant load. For each inlet, the total area of subcatchments contributing to stormwater was summed, and the fractional area of each land use calculated.

The total removal potential achieved by only placing sediment traps on publicly owned land was examined. However, precise ownership data was not available, and an assumption was therefore made that for each separate land use, all subcatchments belonging to that land use had the same ownership, either public or private. Additionally, the developed method was extended to estimate the impact of regular maintenance on the pollutant removal in the catchment. The assumption was that the traps had a maximum capacity that, when exceeded, causes the traps to overflow and no longer capture pollutant until emptied during maintenance. For the study, the estimated maximum capacity of 40 kg for TSS was used, and the model was simulated for an extended period of 2 years.

3. Results

3.1. EMC set comparison

The land uses in the Taapelinpolku catchment were given the EMC values of the closest corresponding land uses from Table 3. A set of simulations were run to evaluate how appropriate the EMC sets were when compared against a reference model's results (Table 4). The condition for evaluation was chosen to be the difference between the total TSS load at the outlet after the defined 6-month period between the unmodified reference model using the calibrated buildup/washoff functions, and the modified versions where the different EMC set values were used as the source area concentrations. This evaluation was performed due to the lack of catchment-specific EMC values to assess how close they approximated the catchment conditions. From Table 3 it was observed that the relationships between land use EMCs remained similar across EMC sets, with parking lots and streets tending to higher EMCs compared to other land uses. Because the study focused on the relative removal achieved by the sediment traps rather than the absolute value of TSS removed, the discrepancies between TSS loads from the EMCs and buildup/washoff models were deemed acceptable.

The TSS load observed when using the EMC set 5 model most closely resembled that of the reference model results Table 4. It was therefore assumed that these EMC values approximated the conditions of the catchment, and they were chosen for the sediment trap assessment. The EMC set 5 for the dense urban catchment in Lahti was different to Tuomela (2017), who found EMC set 3 to be the most appropriate for the urban Espoo catchment. This reflects differences between superficially similar catchments and the necessity for site specific data when examining the pollutant generation of urban catchments.

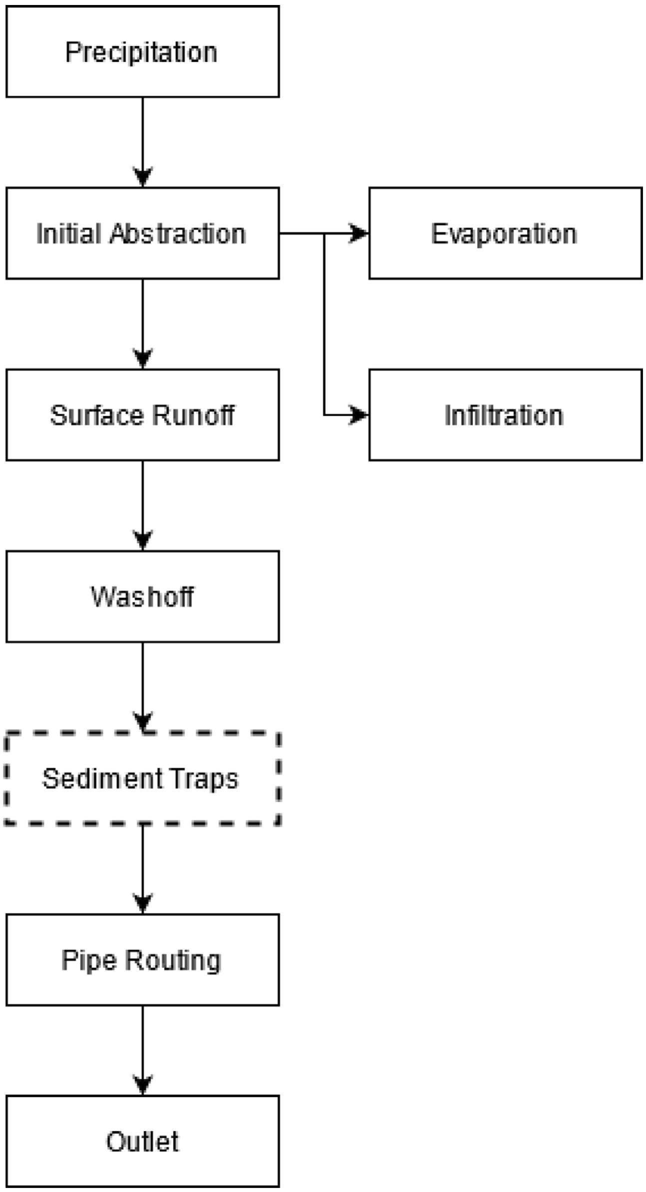

Fig. 3. Processes modelled in the Taapelipolku catchment SWMM parametrization, with the addition of the sediment traps as a treatment option.

Table 4
Comparison of simulated pollutant load in SWMM for the various land use EMC value sets presented by Tuomela (2017), when simulated for the period 1.5.2009–31.10.2009.

Function	Total TSS (kg)	Difference to calibrated value (%)
Buildup/Washoff	701.60	0.00
EMC set 1	970.44	38.32
EMC set 2	997.43	42.17
EMC set 3	850.22	21.18
EMC set 4	988.17	40.85
EMC set 5	645.12	−8.05

3.2. Stormwater inlet ranking

Simulation results for the optimal ranking of the stormwater inlets showed a steep increase in achieved removal with just a few installed traps (Fig. 4), as the highest ranked traps were able to remove large amounts of pollutant, regardless of the EMC set used. This highlighted the need for a conscious and informed decision when selecting trap locations, since a set of poorly chosen trap locations can have a negligible effect on the total pollutant load.

Table 5
Amount of removed pollutant removed by sediment traps placed at inlets located at specific land uses for the different EMC set models.

Land use	EMC set 1	EMC set 2	EMC set 3	EMC set 4	EMC set 5
Green	0.9%	1.4%	1.6%	1.0%	1.1%
Other	6.4%	5.6%	5.4%	5.0%	4.1%
Pavement	4.2%	8.1%	8.7%	8.0%	9.9%
Parking	47.9%	45.4%	45.6%	39.0%	33.4%
Roof	0.0%	0.0%	0.0%	0.0%	0.0%
Street	40.6%	39.5%	38.7%	47.0%	51.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

As most trap locations did not contribute significantly to the total removal, the results indicated that it is not necessary to install traps in all inlets of a catchment, as long as the locations are chosen in an informed manner. The ranking of the stormwater inlets remained consistent regardless of the removal efficiency of the sediment traps, because the inlets were independent from each other.

Over a longer time period up to 6 months, the simulated total catchment pollutant load differed notably between the EMC sets (Fig. 5), showing the need for catchment-specific EMC values to accurately estimate the absolute level of pollutant load. The difference in the loads is reflected in the treatment capacity exceedance time and the maintenance interval of the sediment traps. This divergence between the various EMC set models was seen also in Table 4, showing a large discrepancy to the unmodified buildup/washoff calibrated model for some EMC set models. As seen from Fig. 4, Fig. 5 represented a removal of around 35%–40% of the total catchment pollutant load of TSS with sediment traps installed in the 20 highest ranked stormwater inlets.

3.3. Land use and inlet pollution contribution

Using the EMC set 5 simulation results, the pollution contributions from each land use were examined. The highest ranked inlets received the largest pollution amount from streets (Fig. 6) along with parking lots, which was a finding observed across the different EMC set models. This was in part attributed to these two land uses representing a large fraction of the total catchment area, with the 20 most efficient inlets receiving water from 52% of the total catchment area, but also to the high EMC values defined for these land uses. Conversely, the low pollution contribution of roofs was explained by the small value in the EMC set. A correlation between EMCs and inlet pollutant load was clearly seen. However, because the different land use EMCs varied in magnitude across the distinct EMC sets, the importance of selecting catchment-specific EMC values was noted.

A majority (>70%) of the stormwater inlets were located on either pavement or parking lots (Table 1). Despite this, the results suggested that inlets located on streets were generally the most optimal locations to install the sediment traps (Fig. 6). In fact, the inlets located on pavement were not as efficient trap locations, despite their large amount. Inefficient locations were also identified on green areas and the miscellaneous Other land use category. Overall, the stormwater inlets located on streets and parking lots contributed the most pollutant removal by far across all EMC sets (Table 5).

3.4. Land ownership

Land ownership is an issue regarding the question of who is responsible for maintenance of the sediment traps. As a result of maintenance breaks the stormwater may become untreated. A scenario examined in this study was to only install sediment traps into inlets located on public land, placing the responsibility for maintenance solely on municipalities or governmental organs. The results indicated that among the land

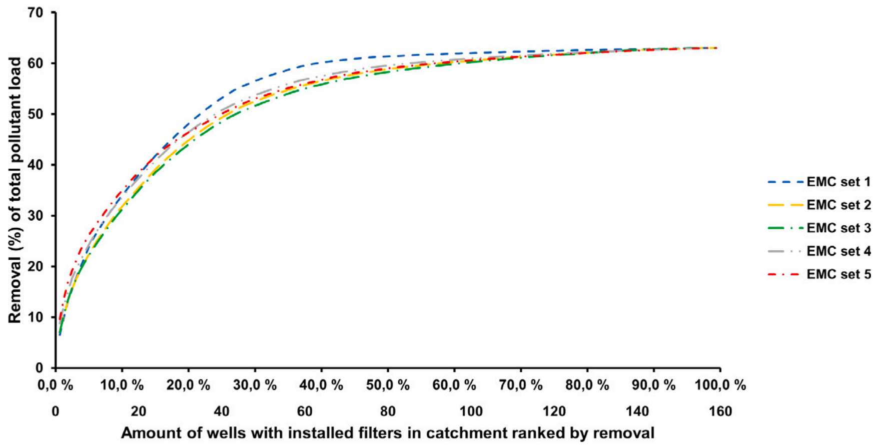

Fig. 4. Removal of TSS depending on the amount of stormwater inlets with installed sediment traps, for the different EMC set models, with a trap removal efficiency of 63%.

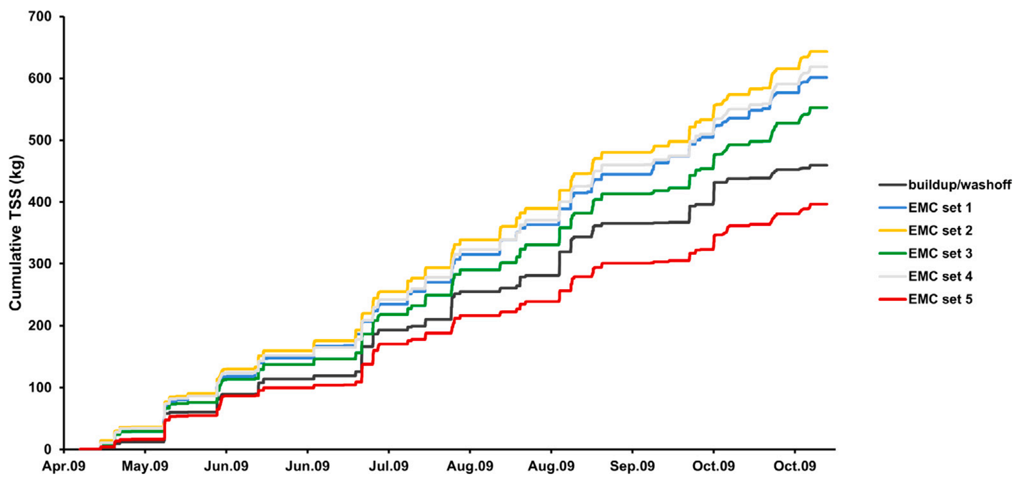

Fig. 5. Accumulation of TSS in the catchment for the different EMC set models over the period 1.5.2009–31.10.2009, when the 20 most optimal stormwater inlets for each model had sediment traps installed.

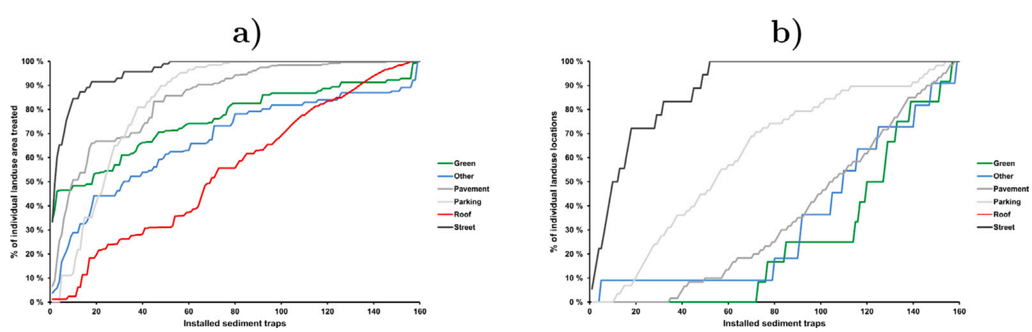

Fig. 6. (a) Cumulative land use with installed sediment traps. Number of stormwater inlets required to have sediment traps installed, according to the inlet ranking of the EMC set 5 model, before all the area of each land use has its runoff water leading to an inlet with installed sediment traps. (b) Number of wells required to have sediment traps installed, according to the inlet ranking of the EMC set 5 model, before all possible stormwater inlets on different land uses have sediment traps installed.

uses assumed to be public land, streets clearly contributed to significant pollutant removal (Table 6), indicating that placing the sediment traps only on streets is likely enough to see a noticeable effect on the catchment pollutant load. Moreover, extending the placements to include pavement and green areas would not contribute an improvement in relation to the much larger amount of traps required to cover these areas. If desired, even further removal could instead be achieved by additionally setting requirements on parking lot owners to install the sediment traps.

3.5. Maintenance

The 2-year simulation results for the EMC set 5 model showed that for a maintenance interval of 365 days, only the sediment trap in the stormwater inlet contributing the most pollutant would reach maximum capacity and overflow, removing around 30% of the pollutant, compared to the 63% maximum removal set by the efficiency threshold. For shorter maintenance intervals of 90 and 180 days, the inlet contributing the most pollutant reached a removal of 63% and

Table 6
The cumulative removal potential of the catchment total TSS pollutant load achieved by placing sediment traps in all stormwater inlets located on public land. Two categorizations of the land uses into public and private land have been compared (left and right).

Land use	Public/private	Land use	Public/private
Green	Public	Green	Private
Other	Private	Other	Private
Pavement	Public	Pavement	Private
Parking	Private	Parking	Private
Roof	Private	Roof	Private
Street	Public	Street	Public
Land use	Inlets	Land use	Inlets
Public	90	Public	18
Private	69	Private	141
Land use	Cum. Removal (%)	Land use	Cum. Removal (%)
Public	39.3	Public	32.4

56%, respectively. Similar results were seen for the models configured using the other EMC sets, with nearly all inlets achieving the potential removal set by the efficiency threshold, and only a slight overflow observed at the highest ranked inlets.

4. Discussion

The simulation results indicated that a few well-placed sediment traps have a large impact on the total pollutant load of the catchment. Similarly, it was shown that poorly chosen trap locations have a negligible effect on the pollutant load. As such, the results suggested a reduced need for installing sediment traps in every stormwater inlet to achieve noticeable pollutant removal, consequently reducing potential installation and maintenance costs. This finding reinforces the GIS-based model results by Hipp et al. (2006), who likewise determined the optimal stormwater inlets for sediment trap installation in a catchment with separate land uses defined. They found that only 30% of the inlets needed traps to meet the local U.S. stormwater quality threshold.

In practice, determining the actual efficiency of the sediment traps through measuring and sampling is difficult, since there are large fluctuations in pollutant concentrations between storm events, even for the same catchment (Wang et al., 2013). This uncertainty about the sediment trap removal efficiency directly affected the modelled effect of the sediment traps on the total catchment pollutant load. Given that the efficiency in the current study was defined as a fractional removal, the water quality impact of varying efficiencies can be estimated by scaling the results of load reductions.

As shown in Section 3.3, streets and parking lots contributed the largest share of pollution to the drainage network, due to their high EMC values, and large fractional areas, and subsequently large runoff volumes. These land uses were large pollutant contributors across all the examined EMC sets, confirming that the results were indicative of actual conditions. For example, Wang et al. (2013) studied stormwater quality and land uses in Chongqing, China, and found that urban traffic roads had the highest observed EMCs. In this study, the stormwater inlets located on streets had the highest potential removal of pollution, followed by inlets located on parking lots. Given no additional catchment information, these inlets can be assumed to be the optimal locations for sediment trap installation for similar urban catchments in Nordic conditions. The current simulations were limited to TSS, while Tuomela et al. (2019) noted that for several pollutants no single land use dominated all pollution contributions, which suggests that the findings of this study are applicable for only TSS.

In Finland, stormwater management in urban areas is the responsibility of the local municipalities. It was therefore examined how much pollutant is removed by installing sediment traps on public land. As the largest removal occurred on inlets located on either streets or parking lots (Table 5), the achievable removal from inlets located on public land is largely attributable to inlets on streets (Table 6). The result demonstrated the impact that the municipalities may have on stormwater quality by just focusing on the areas under their responsibility. Depending on the desired total removal of pollutant in the catchment, achieving this threshold can be reached by installing the sediment traps only on public land. However, since there are currently no regulations regarding the TSS concentration in the stormwater in Finland, the exact number of installed sediment traps in a catchment is limited by budget rather than quality constraints.

From the perspective of maintenance costs, the simulation results of the different EMC set models showed that, aside from the highest ranked stormwater inlets, maintenance intervals on the sediment traps could potentially extend to over a year. However, the highest ranked inlets were also the ones contributing the most pollutant to the drainage system. Therefore, the total efficiency of the catchment treatment design would significantly decrease if the sediment traps were to overflow. Considering this, a strategy could be planned with trap maintenance interval depending on their performance gauged from the inlet ranking. Intervals of varying length could be scheduled, reducing maintenance costs by not emptying sediment traps that are only partially full. With proper scheduling it appears that the sediment traps would last through a complete wet season without requiring maintenance.

The simulation results using different EMC sets tended to overestimate the pollutant load to a varying degree, compared to the reference setup using buildup/washoff functions (Table 4). Regardless of the overestimation, the stormwater inlet ranking and proportional statistics of the results were consistent. However, the overestimation causes biases in the assessment of the actual amount of pollutant within the drainage network and the removed pollutant. To better evaluate the absolute level of catchment pollutant load, more site-specific data on the land use EMCs (or buildup/washoff functions) is warranted, and the model output requires validation through additional field measurements. Additionally, the SWMM parametrization itself contributed uncertainty regarding the results. Krebs et al. (2013) noted that the parametrization uncertainty is reduced using high-resolution catchment discretization with separation of homogeneous land uses into subcatchments. Nonetheless, both the original work by Krebs et al. (2013) and the addition of buildup/washoff functions by Tuomela (2022) had been calibrated, thereby reducing the uncertainty and providing sufficient basis for the TSS simulations.

Despite the uncertainty regarding the absolute quantities of pollutant within the catchment system, the results implied a noticeable effect of the sediment traps on the total pollutant load. For a more accurate estimate, EMC values approximating the actual catchment conditions better would be required, as well as more rigorous field measurements on the removal efficiency of the sediment traps. A further development step in the TSS modelling would be to consider the particle size differences of TSS from different sources (e.g. Lieske et al., 2021). The results were deemed to merely relate to TSS, and the model would have to be reconfigured to evaluate other pollutants. Nonetheless, this study outlined a transparent method, utilizing open-source software, for stormwater treatment design in an urban catchment by identifying the optimal stormwater inlets for sediment trap installation and evaluating their impact on TSS load. The method is transferable to other similar catchments, provided they are discretized in the same manner as Krebs et al. (2013) proposed, using land use specific subcatchments.

5. Conclusions

The study aimed to assess the impact of installing a type of sediment traps into the stormwater inlets of an urban catchment on the total load of suspended solids in catchment drainage network. A computational method was outlined using SWMM and PySWMM to rank the stormwater inlets according to their contributed pollutant loads and identify the optimal sediment trap locations. The results showed that, for the evaluated trap efficiency, a substantial removal of TSS could be reached already by installing a limited number of traps only in the most efficient stormwater inlets. Inlets receiving runoff from large areas, especially streets and parking lots, were seen to contribute the most TSS. The inlets located on streets were observed to be the ones with the highest removal, and it was therefore concluded that, given no other information about a catchment, inlets located on streets would be the optimal locations for sediment trap installation. However, it was noted that the absolute quantity of TSS load was dependent on the EMC values defined for each land use. The results of proportional load reductions suggested that optimal land use locations remained similar for the examined EMC sets, even though the absolute pollutant load differed between the EMC sets.

When installing sediment traps in stormwater inlets located on public land, it was found that the achieved removal was satisfactory (>30%), as inlets located on streets on public land were among the main TSS contributors. The required maintenance interval of the traps was evaluated, showing that most traps could be installed for over half a year without reduced performance.

The results of TSS loads using different EMC sets for the simulations indicated that the pollutant load accumulation was uncertain and easily overestimated. To improve the accuracy of the model, the need for catchment-specific EMC values was identified. Additional field measurements of the sediment trap performance are also required, as the model output otherwise lacked validation against a counterpart field assessment of the traps. Furthermore, it was noted that the results were limited to TSS, and a further step is to apply the proposed methodology to assess the stormwater inlet ranking with the inclusion of several pollutants.

Resources

The model code is available at https://github.com/blobbeliblob/swmm-sediment-traps.

CRediT authorship contribution statement

Camilo Hernández Nyreen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Harri Koivusalo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Hjalte Jomo Danielsen Sørup:** Writing – review & editing, Supervision, Software, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Harri Koivusalo reports financial support was provided by Finnish Ministry of the Environment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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