Assessment of sediment traps for controlling stormwater quality in a heavily urbanized area

Camilo Hernández Nyreen

School of Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 28.7.2022

Supervisor

Prof. Harri Koivusalo (Aalto University)
Associate Prof. Hjalte Jomo Danielsen Sørup (Technical University of Denmark)

Advisor

DSc Nora Sillanpää (Aalto University)

Aalto University
School of Engineering

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi
Abstract of the master's thesis

Author Camilo Hernández Nyreen

Title Assessment of sediment traps for controlling stormwater quality in a heavily urbanized area

Degree programme Nordic Master Programme in Environmental Engineering

Major Environmental Engineering **Code of major** ENG213

Supervisor Prof. Harri Koivusalo (Aalto University)
Associate Prof. Hjalte Jomo Danielsen Sørup (Technical University of Denmark)

Advisor DSc Nora Sillanpää (Aalto University)

Date 28.7.2022 **Number of pages** 46 **Language** English

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 through solutions at source, such as sediment traps. This study evaluated the impact of a developed type of sediment trap, installed into sewer inlets, on the total suspended sediments (TSS) load of an urban Finnish catchment through a modelling approach, as well as the contribution of different landuses on the TSS load.

The study utilized a Storm Water Management Model (SWMM) parametrization of the Taapelipolku catchment in Lahti, Finland with streets, parking lots, pavement, roofs, green areas and other (miscellaneous) defined as landuses, and literature Event Mean Concentrations (EMCs) were used to define the generation of TSS for each landuse individually. A method to implement the sediment traps in SWMM was presented, and the model was run for a 6 month period using the PySWMM module in Python.

The catchment sewer inlets were ranked according to the maximum potential removal of TSS, when installed with sediment traps, to determine the optimal set of locations for the sediment traps, and the influence of landuse on this ranking was analyzed. Additionally, the effect of regular maintenance intervals on the catchment TSS 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, highlighting the need for an informed decision when selecting trap locations. Streets and parking lots were the largest TSS contributors, with sewer inlets located on streets likely overall to be the optimal sediment trap locations. The results, however, were found to be highly dependent on the EMCs, adding some degree of uncertainty to the findings of this research.

Keywords Stormwater quality management, Sediment traps, Hydrological modelling, SWMM, Event Mean Concentration, PySWMM

Acknowledgments

This master's thesis was done at Aalto University, School of Engineering, Department of Built Environment, as part of the HuLaKaS project to investigate urban areas vulnerable to pollution through stormwater, identify the types of pollutants present in the runoff water and evaluate the usage of a developed type of sediment trap. The project was jointly conducted by the City of Helsinki, City of Lahti, Watec Oy and Aalto University, and funded by the Ministry of the Environment. I am thankful to have been a part of this project.

I would like to thank my supervisors, Professor Harri Koivusalo at Aalto Univesity and Associate Professor Hjalte Jomo Danielsen Sørup at the Technical University of Denmark, as well as my advisor, Adjunct Professor Nora Sillanpää, for all of their advice during the thesis process.

I would also like to thank D.Sc. Gerald Krebs for the SWMM parametrization used in this thesis, and D.Sc. Camilla Tuomela for her modifications on it.

Otaniemi, 28.7.2022

Camilo Hernández Nyreen

Contents

1 Introduction

Increased levels of runoff water in urban areas due to human development contributes to larger quantities of pollutants in the stormwater and reduced water quality downstream in the drainage system. The amount and type of pollution varies depending on the landuse, e.g. heavily industrialized areas, residential areas, green areas, etc. This study was motivated by the need for more research into the quality of urban stormwater in Finland and by the lack of research into the impact of different types of landuse on the runoff water quality.

The aim of the study was to examine how the placement of a developed type of sediment trap into sewer inlets affected the total stormwater pollutant load of an urban catchment in Finnish conditions. Accounting for the cost of maintenance and upkeep, it is not realistic to place the sediment traps in each inlet to the stormwater drainage system. Understanding of the catchment pollution was therefore needed.

The specific goals of this study were thus to

- Develop a computational method to determine the optimal set of sediment trap locations for maximal pollutant abstraction.
- Evaluate the influence of sediment trap location on the pollutant removal.
- Observe the effect of the sediment traps on the total catchment pollutant load.

The work utilized an existing Storm Water Management Model (SWMM) parametrization of an urban catchment in the City of Lahti, which was modified to include the sediment traps as treatment options. To simplify the objective, only the pollution of total suspended sediments (TSS) in the runoff water was assessed.

2 Literature review

2.1 Stormwater management

As urban settlements experience rapid growth, there is a need for a functioning management of water resources to accommodate these changes (Niemczynowicz, 1999). This increased urbanization has had an impact on the hydrology in urban environments, which can be observed in increased runoff rates and volumes, and loss of infiltration (Fletcher et al., 2013; Tuomela et al., 2019) due to larger amount of impervious or only partially pervious areas which prevent the stormwater from infiltrating through the surface. With the evolving infrastructure, there is a need to understand how the behaviour of water flows within the urban area is affected (Niemczynowicz, 1999). There is thus a need for proper stormwater management to investigate and deal with the stresses inflicted by the runoff water.

The common approach to stormwater management has usually been to divert the runoff water from the catchment area through a drainage network to receiving waters in an efficient and rapid manner (Suihko, 2016), in order to reduce the risk of flooding or stream erosion (Nix, 1994). In recent years, with increased public awareness of environmental concerns, there has been more focus on finding solutions that reduce the pressure on the ecosystem and habitats, e.g. through Low Impact Development (LID) solutions. These solutions put emphasis on smaller local solutions upstream, rather than at the catchment outlet, through nature-based approaches that try to mimic the natural conditions of an undeveloped catchment (Fletcher et al., 2015).

With the increased human activity of urban environments, there is an increased amount of waste, along with pollutants, produced, that might end up in the stormwater drainage network, where it is then transported to receiving waters further downstream (Nix, 1994). This pollution has led to stormwater management incorporating quality management in addition to the runoff management and flood control in recent decades (Nix, 1994).

Pollutant sources may be for example transportation, industry, fertilizers, and debris (Nix, 1994). Other emerging pollutants are pesticides, hormones and synthetic chemicals (Fletcher et al., 2013). Some pollution is characterised as non-point pollution, as it is diffuse and comes from all over a catchment, contrary to point-source pollution, collected in sewers and discharged at specific points in the catchment (Nix, 1994). These pollutants affect the quality of the runoff water both at the source and downstream (Niemczynowicz, 1999). It is therefore important to understand their properties and behaviour, in order to find possible solutions to manage their spread. According to Niemczynowicz (1999), solutions that manage the stormwater quality should be source oriented to prevent large amounts of runoff and pollution. This opens possibilities for implementing nature-based solutions, such as LIDs, for stormwater quality management as well (Freni et al., 2010).

2.2 Regulations and guidelines concerning stormwater quality

Regulations and recommendations have been set in Finland to assure an acceptable level of stormwater management. Some build on directives by the E.U. such as the Water Framework Directive (2000/60/EC) (EUR-Lex, 2000), which dictates the need for good ecological status in the environment. In Finland, the Land Use and Building Act (132/1999) and Law amending the Land Use and Building Act (682/2014) (Finlex, 1999) pose municipal requirements for proper stormwater management to be present in the planning of urban areas (Korkealaakso et al., 2016), the results of which can be seen for example in the City of Helsinki Storm Water Management Program (City of Helsinki, 2018). Another legislation is the Water Services Act (119/2001) and Law amending the Water Services Act (681/2014) (Finlex, 2001). Despite these regulations, Sänkiaho et al. (2011) notes that stormwater legislation in Finland is lacking compared to other countries, such as the U.S., where legislation has existed already for several decades (e.g. the Clean Water Act from 1972 (U.S. EPA, 2022)). One issue is the distribution of the responsibility of stormwater management to various actors, such as municipalities, companies and property owners, across the different directives and guidelines (Sänkiaho et al., 2011). Tuomela (2017) also notes that the existing legislation tends to focus on stormwater quantity, leaving an absence of regulations for the quality of urban stormwater.

2.3 Catch Basin Inserts

One of the recognised Best Management Practices (BMPs) for treating stormwater is through Catch Basin Inserts (CBIs), which are placed at the inlets to the stormwater sewage system (Alam et al., 2018) to remove various types of pollutants, such as debris, solids, oil and grease, and metals (Morgan et al., 2005; Remley et al., 2005). Pitt and Field (1998) listed the requirements of a stormwater drainage inlet device: (1) The device does not cause flooding when it is clogged and it has an overflow bypass functionality; (2) The device does not let the captured pollutants/material degrade the quality of the stormwater that passes through the device; (3) The device reduces pollutants as much as possible; (4) Maintenance of the device is inexpensive and infrequent.

There have been previous studies examining the usage of CBIs (e.g. Lau et al., 2001; Begum et al., 2008; Pitt and Field, 1998; Morgan et al., 2005), although a general consensus seems to be that further research is still needed to fully understand their effects. Common observed removal efficiencies for suspended solids are also rather diverse, ranging from low efficiencies, such as 11 % (Morgan et al., 2005), to high ones, such as 88 % (Alam et al., 2018). The high variability in efficiencies is likely due to the likewise high variation in CBI design and variability in pollutant levels.

As a treatment solution, CBIs have the advantage of removing pollutants at source, rather than allowing for them to spread downstream through the system. They can also be installed in existing urban infrastructure (Lau et al., 2001; Remley et al., 2005), reducing the need for costly installation and simultaneously being a viable option for cities to explore. However, clogging of the filter material may be a problem, depending on the filter fabric (Pitt and Field, 1998). Coarser filters, on the other hand, may not reduce the pollutant load to a satisfying degree (Pitt and Field, 1998). Furthermore, not all devices have an overflow bypass, increasing the chance of flooding, while other inserts have a problem with water bypassing the filter and not receiving treatment (Morgan et al., 2005). Begum et al. (2008) additionally notes that too-efficient removal of sediment may lead to higher erosion further downstream of the inlet. Maintenance should also be performed regularly, to ensure inserts are functioning properly (Morgan et al., 2005), as a lack of planning may reduce the efficiency of the solution (Lloyd et al., 2002).

The CBI used in this study, further described in Section 3.4, will be denoted as a sediment trap, due to its design with a "filter bag" where stormwater is filtered through and the sediment remains in the trap, as well as an overflow bypass at the top. Similar designs have been studied previously, for example by Morgan et al. (2005), although no studies were found to have been done in Finnish climatic conditions. General findings of these were that the removal of suspended solids tended to decrease with decreasing particle size and increasing flowrate (Morgan et al., 2005). Nonetheless, they provide a way to remove pollutants from the stormwater in a relatively easy manner.

2.4 Urban hydrological modelling

To understand how the stormwater drainage network behaves under changing conditions, it is possible to use hydrological models to simulate the behaviour.

Urban stormwater models have already been available for several decades, one of the first being the U.S. Environmental Protection Agency's (EPA) Storm Water Management Model, which also simulates runoff quality besides quantity (Nix, 1994). Other models are e.g. the Urban Drainage and Sewer Model (MOUSE), InfoWorks River Simulation (InfoWork RS), Hydrological Simulation Program-Fortran (HSPF), MIKE+ and Hydrologic Engineering Centre-Hydrologic Modelling System (HEC-HMS) (Haris et al., 2016).

An urban stormwater model represents the drainage system and catchment areas through mathematical relationships and simulates how the system acts over time for various inputs, e.g. rainfall and temperature, and outputs, e.g. runoff water. By understanding these processes, different scenarios, that would otherwise be difficult to estimate or measure can be predicted by modifying the input parameters to reflect these scenarios (Nix, 1994). However, it should be remembered that the model is only a representation, a simplification, and thus also has limitations to be accounted for. For example, continuous models usually contain less detail than single-event models (Nix, 1994). Despite this, models can be a useful tool to analyze large-scale problems (Nix, 1994).

Simulations of pollutant removal of CBIs has mostly been done on single sewer inlets, either in laboratory or field settings (e.g. Remley et al., 2005; Morgan et al., 2005; Lau et al., 2001). As far as this study finds, modelling of sediment traps on a catchment scale has not been widely examined. Notwithstanding the above, Fraser et al. (2000) developed a model of a catchment in Malaysia, using HYDROWORKS, to predict sediment deposition areas across the catchment drainage network, allowing for the calculation of optimal sediment trap locations. By determining the fill rate of the traps, a maintenance interval was also suggested for the sediment traps in the catchment in question.

2.5 Modelling water quality

To simulate water quality using hydrological models, functions are defined by which pollutants are generated and subsequently washed off into the drainage system with the runoff or infiltrated into the subsurface on pervious areas. These functions can be represented in the model as either buildup and washoff functions, describing how the pollutant accumulates in a catchment and is later washed off during rainfall events, or as simpler Event Mean Concentrations (EMC), where the pollutant load is dependent on the amount of runoff. In addition to this, to properly evaluate the water quality using a model, the pollutant generation functions should be defined separately for each distinct landuse type found on the examined model catchment (Butcher, 2003), as these are bound to vary in properties, e.g. imperviousness.

The parameters affecting the buildup are for example the aforementioned landuse type, temperature and climate, while washoff is affected by parameters such as topography and slope, which affect runoff (Tu and Smith, 2018). However, these processes can be difficult to measure directly, and therefore determine properly, due to a lack of available data on the catchment conditions (Butcher, 2003). Moreover, as concentrations of pollutants are usually measured for a larger area or catchment, determining the separate landuse functions can be challenging, and there is likewise a gap in literature values for various landuse buildup/washoff parameters. Sage et al. (2015) noted that these accumulation models only provide accurate representations of the catchment pollutant concentrations for short periods, stating that simpler constant concentration functions (EMCs) can yield similar results, at least for the load of suspended solids.

EMCs are measured as concentrations of pollutants observed during storm/rainfall events, i.e. the measured pollutant in relation to the measured amount of water going through the point of observation. They are related to the washoff process, and attempts to establish relationships between washoff and EMCs have previously been done (e.g. Butcher, 2003). As the concentrations are determined on a per-event-basis, there is likely to be fluctuation in concentrations between different rainfall events, and the EMCs are subsequently often calculated as the average of the various single events (Wang et al., 2013). For cases where it is not possible to measure the EMCs, it is often possible to find suitable equivalents in literature for similar conditions and landuses. However, the EMCs chosen will then differ from the actual conditions, which may be reflected in the model results, that can vary considerably from the measured loads at the catchment outlet (Tuomela et al., 2019).

Tuomela et al. (2019) noted that there is some uncertainty related to the modelling of stormwater quality using EMCs. For example, it was observed that the simulated pollutant loads tended to exceed the measured loads, in particular during rainfall events. This was attributed in part to the dilution effect on the EMCs that occurred for large volumes of stormwater. Additionally, Tuomela et al. (2019) observed that for a single examined pollutant, only a couple landuses tended to contribute the most to the total catchment pollutant load, usually landuses with a lot of constructed and impervious areas. This was not necessarily enough to find the areas where treatment could be the most beneficial, as it was also noted that no single landuse clearly contributed the most pollutant when several pollutants were taken into account.

Nonetheless, EMCs provide a pathway for modelling the pollutant load in a catchment, as well as a way to distinguish the contribution to the pollutant load from various landuse types.

2.6 Research gap

From examining the available literature, it was found that not much stormwater modelling had been previously done to evaluate the effect of sediment traps on the pollutant load of a catchment, especially the suspended sediments, and even less so under Finnish conditions. From a stormwater quality management perspective, the development of a method to examine how the insertion of these sediment traps across a catchment consisting of various landuses affects the TSS load would therefore be useful, and could aid in understanding how the sediments are distributed.

3 Site description and data

3.1 Taapelipolku catchment

The study site was the Taapelipolku catchment, located in the City of Lahti, in the south of Finland at approximately 60.99 °N 25.66 °E, around 100 km from the capital Helsinki and 60-70 km from the coast. The catchment is an urban area, with highly impervious zones, such as streets and parking lots, as well as some green zones. Figure 1 shows the catchment map in QGIS.

A large share (86 %) of the 5.87 ha large catchment area is impervious (Krebs et al., 2013). Table 1 shows the distribution between landuses of the total area of the catchment. Parking lots were the largest landuse, followed by roofs and streets, while the undefined 'other' was the smallest. Their relative areas remained more or less close to each other in terms of order of magnitude.

Table 1: Contribution of each landuse to the total area of the catchment.

	Total	**Green**	**Other**	**Pavement**	**Parking**	**Roof**	**Street**
m^2	58742	6974	4211	8458	16348	11493	11258
%	100.0	11.9	7.2	14.4	27.8	19.6	19.2

3.2 SWMM Parametrization

The study utilized an existing SWMM parametrization of the Taapelipolku catchment, calibrated by Krebs et al. (2013) against stormwater discharge measurements. The stormwater network was outlined with the help of sewer network map data for both public and private areas, totaling 2.61 km of circular pipes, 160 inlets, 72 junctions and 690 subcatchments (Krebs et al., 2013). The subcatchments were separated into nine categories based on their land use and ownership (public/private), determined using topographical data and in-situ observations (Krebs et al., 2013). However, for this study, a simplified parametrization, where public and private similar categories (i.e. Green, Other, Pavement) had been merged, was used, reducing the number of categories to six (Tuomela, 2022). For each subcatchment, the % imperviousness had been defined. Additionally, the parametrization used for this study had been setup for TSS pollution generation using buildup/washoff functions by Tuomela (2022). Finally, the time step parameters of the model had been optimized to maintain reasonable accuracy while improving performance (Krebs et al., 2013).

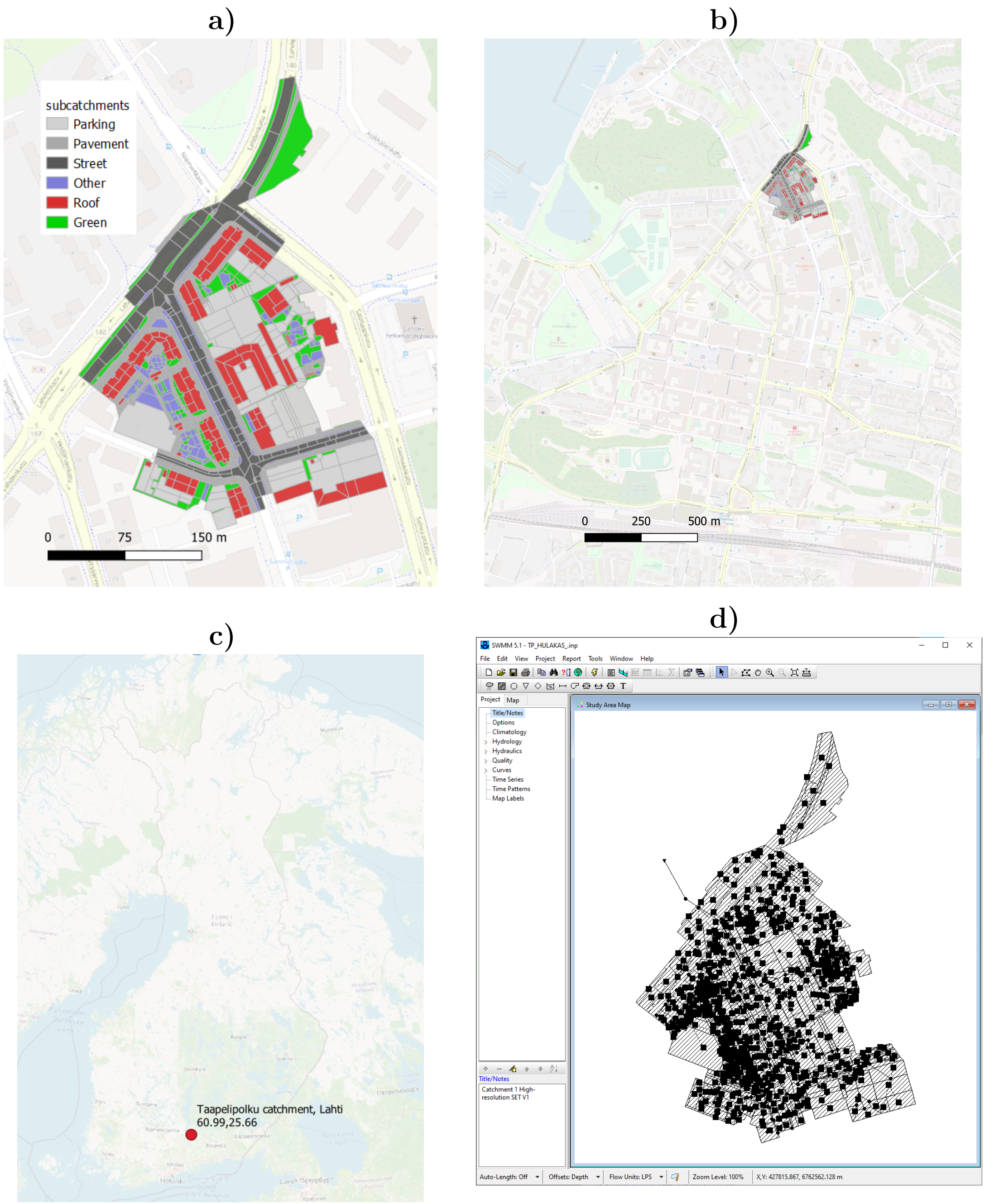

Figure 1: (a) The modeled subcatchments with different land uses highlighted. (b) The Taapelipolku catchment as located in the City of Lahti, around 1 km north from the city centre. (c) The City of Lahti, Finland. (d) The SWMM parametrization of the Taapelipolku catchment, as seen within the SWMM user interface. Background map data provided by OpenStreetMap.

3.3 Meteorological data

The model used 1-minute interval rain data from the nearby Ainonpolku station in Lahti, with measurements from 2008-2010, while daily temperature, evaporation rate and wind speed data were from the Laune station in Lahti, with measurements from between 2008-2011 (Tuomela, 2022). It was observed that the rain data was not complete, as there were missing measurements in the data set, but it was still deemed sufficiently accurate for the purpose of this study.

The City of Lahti belongs to the southern boreal climate zone, and the mean annual precipitation is 633 mm (Krebs et al., 2013). For this study, a 6-month period from 1.5.2009-31.10.2009 was chosen as the main observation period, as it was seen that the most rainfall events occurred during summer/late summer, with the largest events during late July/early August, besides a few in late spring - and because 2009 had more events during summer season (Figures 2 and 3). Furthermore, estimating pollution during winter would have required additional setup of the model to account for snowmelt, due to the precipitation being found in the form of snowfall and rain, which also increases the amount of especially suspended solids that go into the stormwater network due to snow ploughing and the use of sand as a road maintenance control during icy conditions. The use of the sediment traps were therefore primarily investigated during non-snow periods. Figures 2 to 4 show the meteorological data over time. For the chosen 6 month period, it was seen that the average temperature generally stayed above 0 °C (Figure 4), and it was presumed that precipitation was not stored as snow.

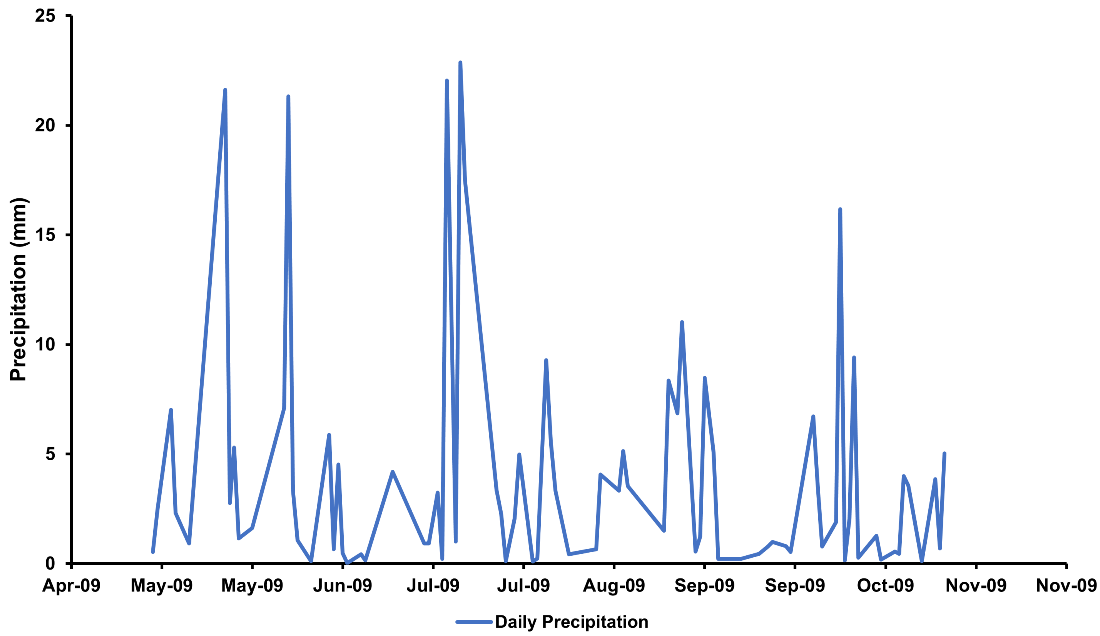

Figure 2: Precipitation over the period 1.5.2009-31.10.2009. Daily rain data from the Ainonpolku measuring station.

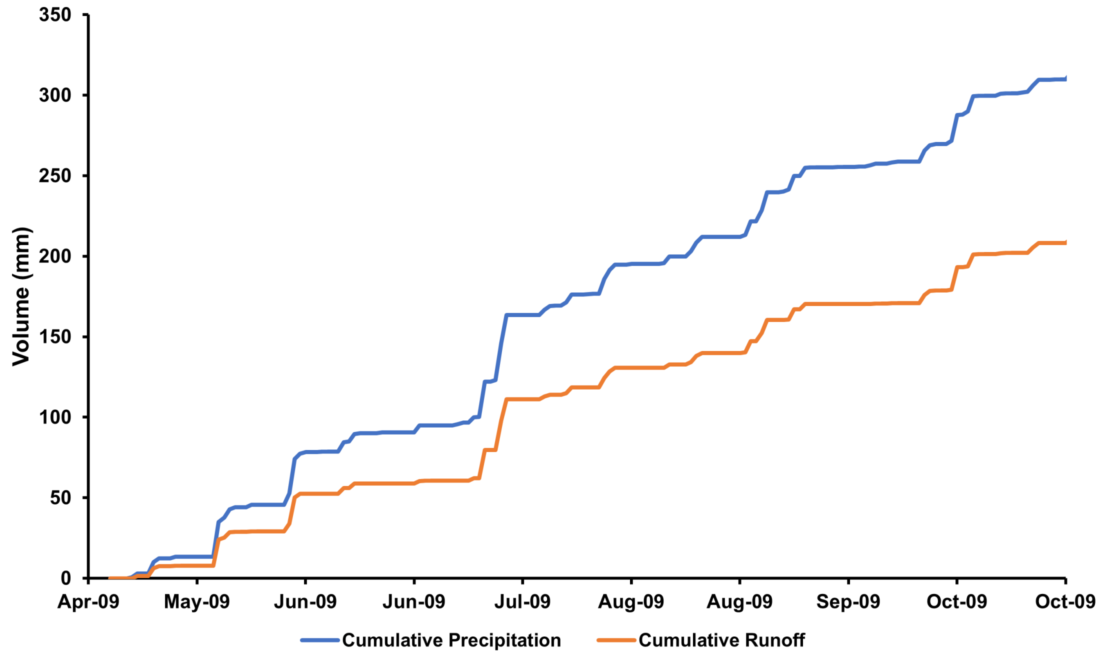

Figure 3: Cumulative precipitation and runoff in the catchment over the period 1.5.2009-31.10.2009.

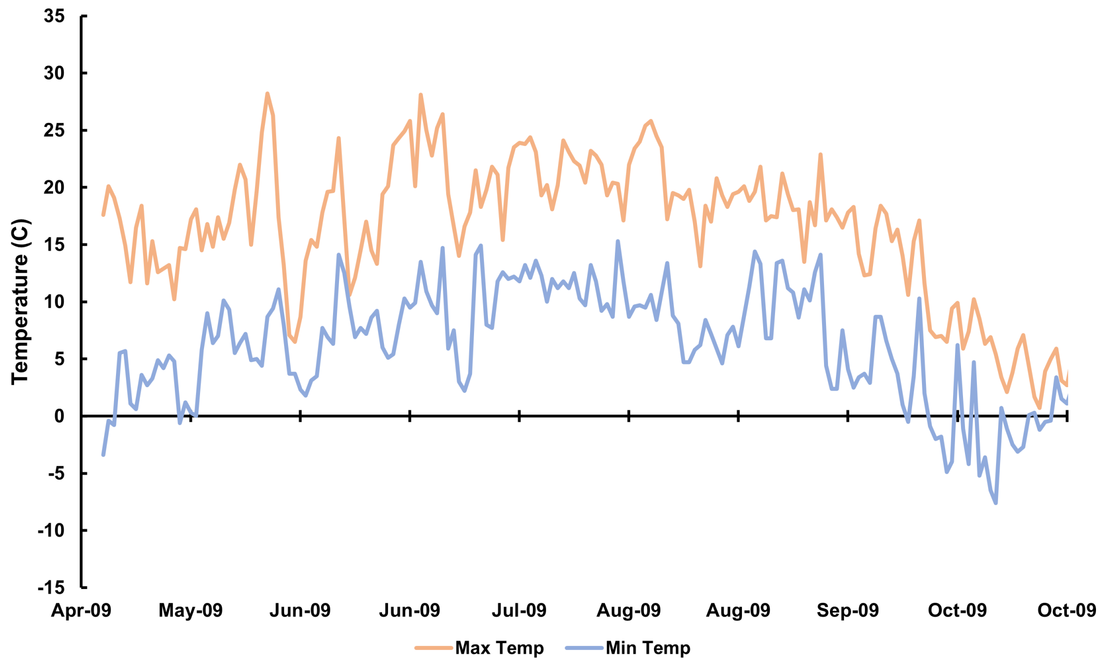

Figure 4: Temperature over the period 1.5.2009-31.10.2009. Daily temperature data from the Laune measuring station.

3.4 Sediment traps

The treatment solution examined in this study consisted of sediment traps installed into sewer inlets (Figure 5). The sediment traps had been tested in a laboratory setting, although there had not been extensive field sampling conducted (Antikainen and Koskenlahti, 2019). The laboratory experiments, conducted using a typical particle size distribution from literature, showed a removal efficiency of on average above 90 % for suspended solids, with the smallest particle size reliably removed being 0.125 mm (Antikainen and Koskenlahti, 2019). For this study, an average reported removal efficiency of 91.7 % was used as a baseline performance measure. A later field measuring reported a removal efficiency of 63 %, which was not used for the model simulations in this study, although its impact on the model output was demonstrated in Section 5. This was possible, as the output could be scaled to accommodate this efficiency since the removal efficiency was fractional without dependency on any parameters.

Figure 5: The sediment traps installed into the sewer inlets. Images by Watec Oy.

3.5 Event Mean Concentration values

The SWMM parametrization by Krebs et al. (2013) had been modified by Tuomela (2022) to include the generation of total suspended solids (TSS) as a pollutant. The concentrations of TSS, along with other pollutants such as Nitrogen, Phosphorous and various metals, had been previously measured in the catchment (Valtanen et al., 2014), along with various studies on the pollutant load in the catchment (e.g. Järveläinen, 2014). Using the measurements, the model had thus been calibrated for pollutant generation using buildup/washoff functions. However, the measurements were solely conducted at the catchment outlet, and the model therefore lacked separated buildup/washoff functions for the various landuses. To be able to assess the impact of the landuses on the catchment pollutant load, the model was modified to utilize Even Mean Concentration (EMC) values, as these were easier to obtain from literature, and buildup/washoff functions were generally deemed to be more site-specific. The EMC values for TSS were chosen from Tuomela (2017), which presented several sets of EMC values collected from literature and evaluated against a SWMM parametrization of an urban catchment in Espoo, Finland, which was assumed to have similar conditions to the Taapelipolku catchment in Lahti. Table 2 shows the EMC sets presented by Tuomela (2017).

Table 2: EMC sets for TSS (units in mg/l), as presented by Tuomela (2017).

Source Area	**EMC set 1**	**EMC set 2**	**EMC set 3**	**EMC set 4**	**EMC set 5**
Parking Areas	1660	440	150	173	44
Paved Walkways	20	20	7.4	58	46
Roads	242	232	163	662	64
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	11	71	12	397	75

4 Methods

The main hydrological processes modeled in SWMM and the relationships between them were examined. Figure 6 displays the processes, beginning with precipitation, moving into runoff water before being routed through the stormwater network to the system outlet. This figure is a simplification of the standard SWMM system presented by Rossman and Huber (2016b, Figure 1-3), where e.g. snowmelt, aquifers and LID controls have been omitted, as they were not modeled in the Taapelipolku model. Buildup processes of pollutant were excluded as well, since the model was modified to use EMC values for pollutant generation, which only apply to the washoff component of the model. Moreover, sediment traps were added as a step between washoff and pipe routing, which is also a difference to the standard SWMM system, where the treatment/diversion component is located after channel, pipe and storage routing. This change was done to clarify that the sediment traps only apply treatment to the stormwater flowing into the drainage network and not any water within the network itself.

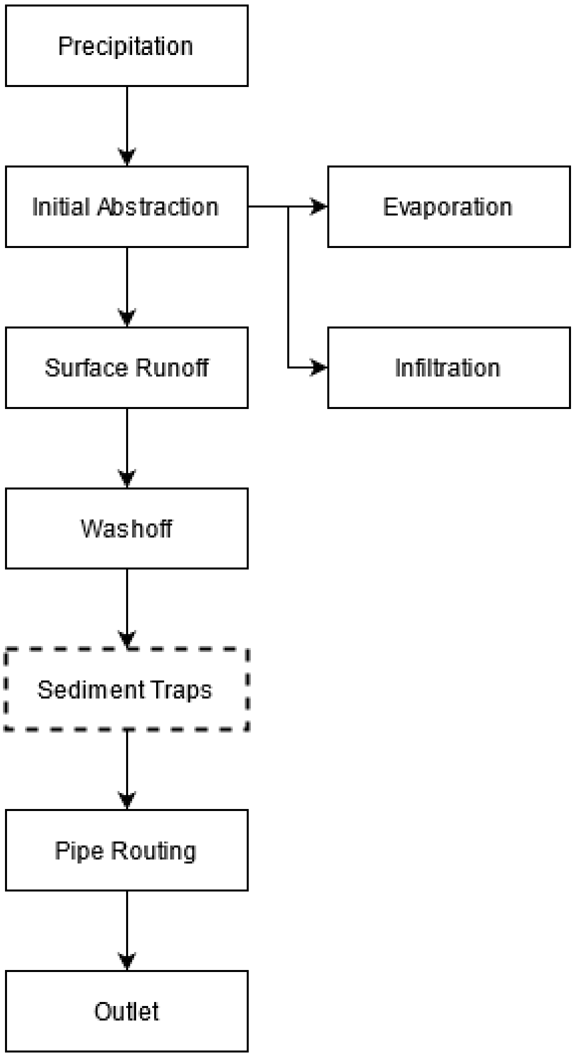

Figure 6: Processes modeled in the Taapelipolku catchment SWMM parametrization, with the addition of the sediment traps as a treatment option.

Figure 7 highlights the steps in the developed method for introducing the sediment traps to the existing SWMM parametrization. The first part consisted of preparing the model by identifying the nodes corresponding to the sewer inlets, as well as separating nodes which acted as both inlets and junctions within the drainage network. Following this, the pollutant generation was defined by setting the washoff function to the chosen EMCs, after which the treatment solution was defined as the removal efficiency of the sediment traps. A set of simulation scenarios were created, where each scenario represented placing a sediment trap in an individual sewer inlet, so that the effect of it on the total catchment pollutant load could be examined after running the simulations. The inlets could subsequently be ranked according to the pollutant that could potentially be removed by installing sediment traps in them. The influence of landuse and inlet location on this ranking was determined, and the effect of regular maintenance intervals on the traps was additionally examined. This method is described in further detail in this section.

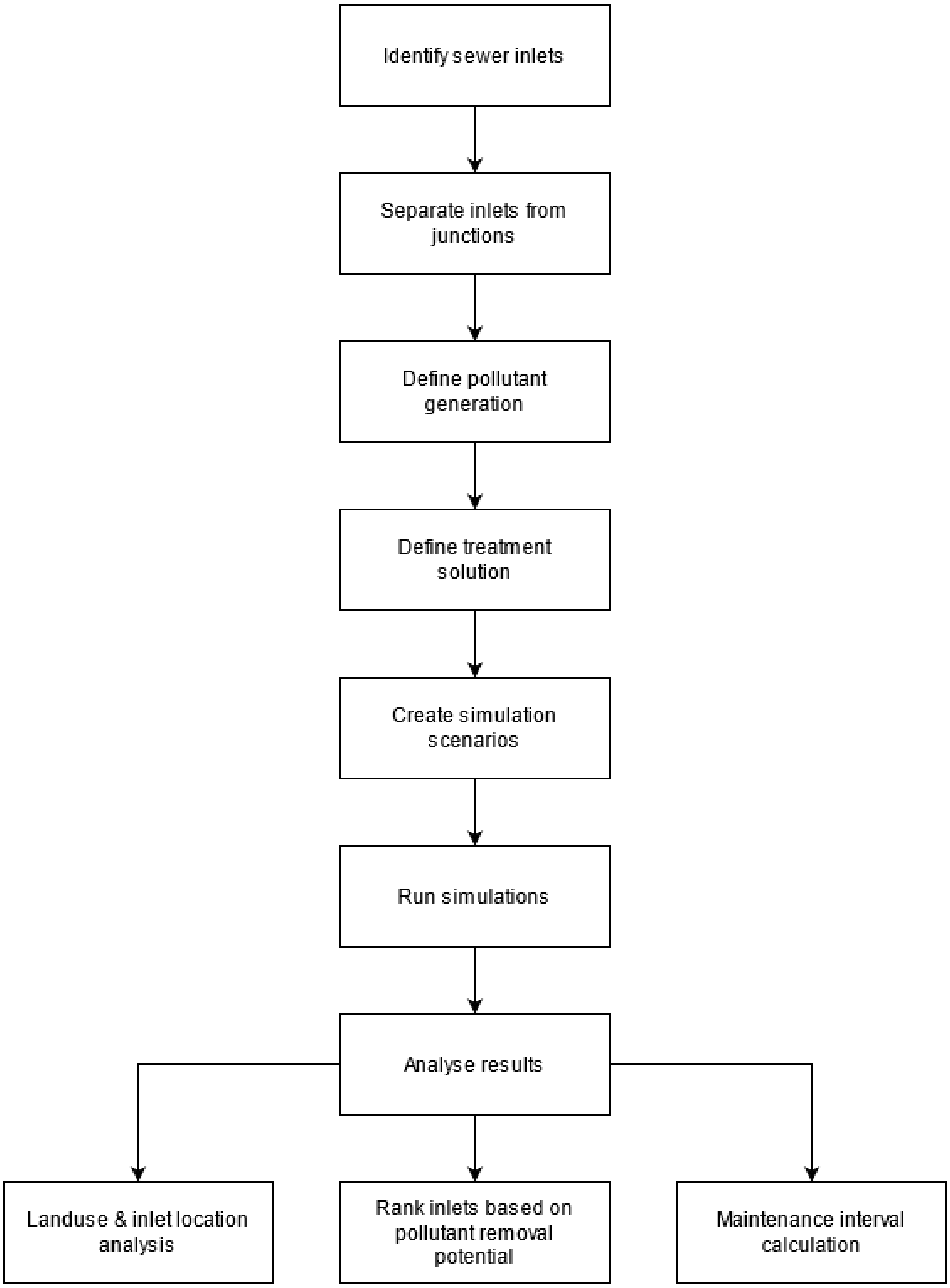

Figure 7: The step-wise approach to evaluate the impact of the sediment traps on the total catchment pollutant load.

4.1 Running SWMM in Python

In addition to the SWMM parametrization of the catchment, this study utilized Python to automate the execution of simulations in the model and process the results. For this, the PySWMM module was used. This module provided much of the same functionality seen in the standard SWMM user interface, but also the possibility of step-wise going through the simulations and accessing otherwise unobtainable simulation results, as well as modifying model properties mid-simulation (Mcdonnell et al., 2020).

4.2 Modifying the SWMM input file

SWMM utilizes text-based files (.inp) to store project data. This made reading and modifying the input file to achieve the desired treatment scenarios through Python possible, without the need for manually changing parameters in the SWMM user interface. This allowed for the automatizing of simulation runs and catchment property modification. In this way, data about subcatchments, junctions (nodes), conduits (pipes), as well as land uses and their coverage, was obtained. Additionally, it provided the possibility for the method to be applied to any catchment of similar parametrization, for any number of subcatchments and nodes.

4.3 Treatment in SWMM

The SWMM documentation (Rossman, 2015) identifies 5 steps required for the implementation of treatment solutions in SWMM: (1) identifying the pollutants of interest; (2) defining the land use types present in the investigated catchment; (3) defining the properties governing pollution generation of each land use; (4) defining the spatial distribution of the various land use types across the subcatchments; (5) defining the removal functionality for each node within the stormwater network. As the model of the Taapelipolku catchment parametrized by Tuomela (2022) was already set up for analyzing TSS, with various land use types set up for the subcatchments, only step (5) needed implementation in accordance with the properties of the examined sediment traps. However, since the model was calibrated to the measured pollutant load at the system outlet, the various land uses were all setup to generate pollution at the same rate using identical buildup and washoff functions. To properly assess the impact of each individual land use on the pollutant load, the land use pollutant generation properties thus needed to be re-defined (as per step 3), as discussed in Section 3.5.

Before introducing treatment solutions to the model, the flow calculations in SWMM were examined on a conceptual level. In SWMM, each conduit (link) between nodes is seen as a storage, to which there is an inflow and outflow occurring for each time-step of the simulation. From a conduit, the outflow goes to its attached node at the endpoint. In the node, the inflow is calculated as the sum of all conduit inflows leading to the node, as well as other inflows (such as those from subcatchments) to the node. The user-specified treatment formula is then used in conjunction with this total inflow to calculate the outflow that goes on to be the inflow of the next conduit (Rossman and Huber, 2016a).

Treatment of a pollutant in SWMM can be defined as either a resulting concentration or a fractional removal, and is expressed as a mathematical expression, which can depend on external variables such as incoming flow, depth, other pollutants or the incoming pollutant concentration itself (Rossman, 2015; Rossman and Huber, 2016a; Open SWMM, 2013). As discussed in Section 3.4, the efficiency of the evaluated sediment traps was reported as fractions of the total pollutant load through the sewer inlets, and the treatment in SWMM could therefore be set as a fractional removal without dependency on other parameters:

$$R = f \tag{1}$$

where R is the resulting fractional removal, and f is the fraction of the incoming pollutant that is removed. The treatment formula could alternatively be similarly expressed as

$$C_{out} = C_{in} f \tag{2}$$

where C_{out} is the outgoing pollutant concentration, f is the fractional removal, and C_{in} denotes the inflow concentration of the pollutant, TSS in this case.

4.4 Implementing the sediment traps in the model

Before introducing the sediment traps to the model, the sewer inlets, or nodes suitable for receiving the treatment, were identified. The input file was read, and the outlets of the subcatchments examined to find the subcatchments with nodes as outlets, as opposed to other subcatchments. These nodes could then be presumed to be sewer inlets.

As discussed in Section 4.3, treatment in SWMM is applied to the outflow of a node. Moreover, the treatment formulas do at present not allow for the treatment of only the incoming flow from subcatchments (the lateral inflow) in a node. This presented a problem, as the investigated treatment of the study would only remove pollution from the water flowing in through the sewer inlet of a node in the stormwater network, and not from nodes further upstream also leading to the node. To circumvent this restriction, the catchment parametrization was modified to introduce new nodes at each location that consisted of a combined sewer inlet and connection to upstream nodes, separating these two into one node acting as the inlet, with a direct connection to the second node, acting as the network junction, as seen in Figure 8. This allowed for treatment to be done on only the sewer inlet nodes, treating only the runoff water from the subcatchments.

Since the pipes in SWMM are considered storages, it was therefore not possible to create new nodes at the exact same location as the existing ones, as the pipes would then have lengths of 0 m. Additionally, the new nodes for the sewer inlets needed to be placed at a higher elevation than the junction nodes, allowing for the water to flow. Per contra, creating excessively long pipes would have had a detrimental effect on the accuracy of the produced results and how well they represented the actual catchment conditions. To assert the validity of the method, and evaluate the uncertainty introduced, the model was run for various sets of parameter combinations to find a reasonably accurate set, as described in subsection 5.1, where-after an elevation drop of 0.001 m and pipe length of 2.3 m were chosen.

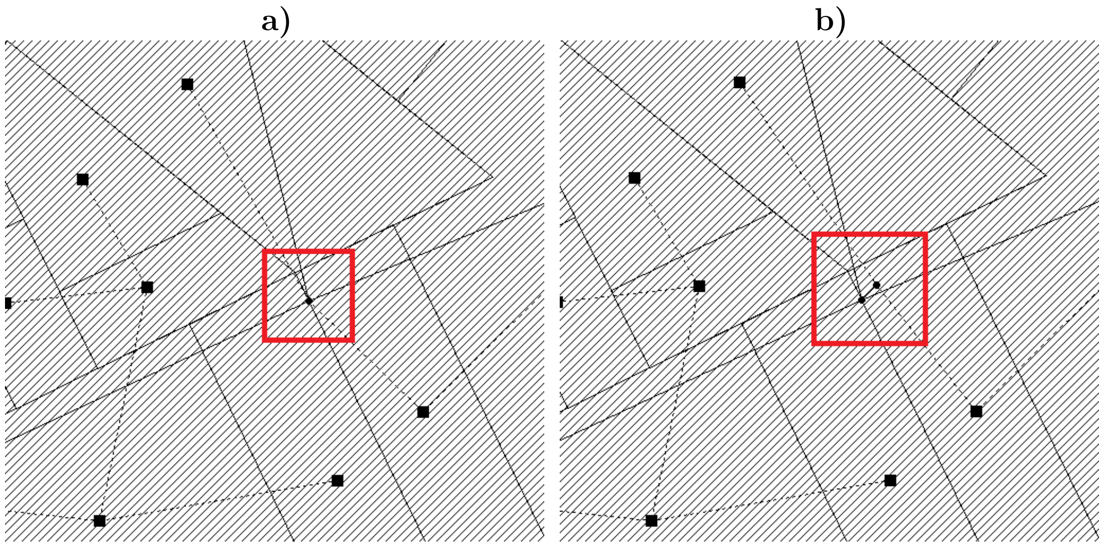

Figure 8: Separation of the network nodes into sewer inlet nodes and network junctions. (a) no modification to the model. (b) a new node has been added and the subcatchment runoff has been diverted to it, while its outflow is directed to the old node, now acting as the junction.

Finally, with the sewer inlet nodes identified and separated from the junctions, the sediment traps could be implemented as a treatment by specifying the related node, the pollutant to be treated (TSS) and the treatment formula for each inlet receiving a sediment trap.

4.5 Defining pollutant generation

As the landuses in the Taapelipolku SWMM model and the model by Tuomela (2017), discussed in Section 3.5, were named differently, the link seen in Table 3 was made between the landuses of the two models. Because there was no direct match to the miscellaneous Other landuse category, it was given the same value as the Pavement landuse, due to its close proximity across the catchment to pavement areas. Additionally, as seen in Table 1, the Other landuse category was the smallest of landuses in terms of area, encompassing only 7 % of the total catchment area, and it was therefore assumed that it was sufficiently small to not significantly impact the results.

Table 3: Link between landuses in the Taapelipolku SWMM parametrization and those in the model by Tuomela (2017).

Taapelipolku catchment	**Source (by Tuomela, 2017)**
Green	Vegetation, Lawns
Other	Paved Walkways
Pavement	Paved Walkways
Parking	Parking Areas
Roof	Roof
Street	Roads

With the link between the landuses in the models made, a set of simulations were run to determine the most appropriate set of EMC values to use for the study. The condition for evaluation was chosen to be the difference between the total TSS outflow at the outlet after the defined 6 month period between the unmodified model using the calibrated buildup/washoff functions, and modified versions where the different EMC set values were used. The results of these simulations are summarised in Table 4.

Table 4: Comparison of simulated pollutant load in SWMM for the various land use EMC value sets presented by Tuomela (2017)

Function	**Total TSS (kg)**	**Difference to calibrated value (%)**
Buildup/Washoff	618.16	0.00
EMC set 1	665.26	7.62
EMC set 2	739.68	19.66
EMC set 3	652.09	5.49
EMC set 4	774.74	25.33
EMC set 5	544.19	-11.97

As seen in Table 4, the TSS load observed when using EMC set 3 most closely resembled that of the unmodified model. It was therefore assumed that these EMC values approximated the conditions of the catchment, and they were therefore chosen for the rest of the study. A similar result was also found by Tuomela (2017), indicating that the values in EMC set 3 could be considered relatively representative of urban impervious areas in Southern Finland.

4.6 Creating simulation scenarios

With the method for introducing the sediment traps into the model outlined (Section 4.4), the next step was to determine the steps for properly assessing the sediment trap placement influence on the catchment pollution removal. All sewer inlets located in the catchment were considered as possible placements, leading to a total of 159 different locations. Moreover, since the inlets were independent from each other, as they received water only from separate subcatchments and not from other nodes within the stormwater network, it was concluded that applying treatment to one inlet would solely affect the pollutant load at the system outlet and not at the other inlets. This meant that the impact of placing the sediment traps at any given inlet could be determined by comparing the outflow at the system outlet to the default outflow when no sediment trap was placed. Acknowledging this relationship, a systematic approach was chosen for determining the inlets with the highest pollution removal potential, i.e. where the most pollutant could be removed by installing the sediment traps. 159 simulations were run using PySWMM for any defined time period, each with treatment setup for a single inlet, different for each run, in addition to the default run without any treatment that was used for the comparison.

The simulations were run using the time steps from Krebs et al. (2013), with a wet step of 4 seconds, a dry step of 10 seconds and a routing step of 3 seconds. For every simulation, information about discharge, pollutant concentration and the associated continuity errors were collected for every time step. This allowed for the subsequent calculation of the outlet total runoff volume and total pollutant load during the examined time period.

4.7 Exporting the simulation results

When computing the simulations with the Python implementation of the method, it was seen that storing the simulation results (especially the time step data) in computer memory required substantial resources, especially for longer simulation time periods. This would pose a problem particularly for larger catchments with many sewer inlets to be evaluated. A solution that was tested and implemented was to export each individual simulation result as an external file after execution, reducing the need to store it in memory, and later re-importing the data when processing the results. Upon importing the data for analysis, the time step data was concatenated into larger time steps, reducing the memory resource requirements drastically. The downside of this approach was the loss of resolution detail in the data.

4.8 Ranking the sewer inlets

The set of simulation results were ranked according to the removal potential of the sediment trap placements (nodes) in the model, where the removal potential was calculated from the difference of the total pollutant load of TSS between the no-treatment scenario and each individual simulation run, as described in Section 4.6. This allowed for the ordering of the different scenarios (sediment trap placements), from the traps that removed the most pollutant, and would thus be the most optimal placement for the traps, to the ones that would have the least effect on the total catchment pollutant load. As the simulated time period was 6 months, this meant that the discrepancy of stored mass in the system would likely not be reflected in the results, as also pollution from 'slow-moving' nodes would reach the outlet.

4.9 Impact of landuses

With the ranking of the sediment traps available, the landuses of the subcatchments contributing stormwater to each sewer inlet were examined, to see if any patterns could be observed through the optimal order of inlets. For each inlet, the subcatchment area was thus summed up into a total, and the fractional area of each landuse was calculated. In addition to this, the actual landuse on which each inlet was located was also identified through GIS. By analyzing how landuse impacts the ranking of the inlets, a strategy for installing sediment traps without knowing the specific removal potential of each individual inlet could potentially be established.

With the removal potential tied to the landuse contributions, the removal potential of only placing the traps on publicly owned land was examined. As the parametrization had been simplified (as described in Section 3.2), the subcatchments had no division of public and private land, and no external data could be found on this. A simplified assumption was therefore made that for each separate landuse, all subcatchments belonging to that landuse had the same type of ownership, either public or private. Two variations were made, one with pavement, green areas and streets defined as public land, and one with only streets defined as public land.

4.10 Calculating maintenance

Given an input of the maximum pollutant capturing capacity of the sediment traps (mass) and the maintenance interval between the emptying of the traps (time), the developed method was extended to also determine the impact regular maintenance would have on the pollutant removal in the catchment, under the additional assumption that the traps had a maximum capacity that, when reached, would cause the traps to overflow and no longer capture pollutant until emptied during maintenance. This was achieved by going step-wise through the simulation results for each node (sediment trap), adding the pollutant passing through to a variable representing the stored pollutant in the trap. Once the trap reached the defined maximum capacity, the node 'overflowed', instead adding the pollutant to an overflow variable. At the time steps where maintenance was scheduled to occur, the stored pollutant variable was reset to zero to resemble the emptying of the trap. Finally, after all time steps had been processed, the value of the overflow variable, the amount of pollutant escaped from the trap, was subtracted from the total pollutant removal, so the effect of the maintenance on the maximum removal potential could be evaluated. For the study, an estimated maximum capacity of 40 kg (as reported by Watec Oy) for TSS was used, as well as a lower capacity of 20 kg for comparison.

5 Results

5.1 Calibration of node characteristics

Table 5 shows the results of the test simulations ran to determine appropriate values for the elevation drop and conduit length parameters related to the insertion of the new nodes in the model, as described in subsection 4.4. First, the sensitivity of the conduit length parameter was investigated (a). An elevation drop of 0.9 m and conduit length of 2 m were chosen as starting values. It was found that smaller lengths lead to a higher degree of divergence in the mass difference. Next, the sensitivity of the elevation drop (slope) parameter was investigated (b), where it was seen that a smaller elevation drop reduced the mass error. The elevation drop was chosen to be 0.001 m, taking into account that the minimum allowed value by SWMM is 0.00035 m Rossman (2015), and that the elevation drop should be less than the conduit length. Following this, the conduit length was calibrated (c), and was chosen to be 2.3 m, as the error was reasonably low, while the model was determined to not exceed a state of representing the actual conditions of the catchment with the introduction of the new nodes. The test simulation (d) was conducted for a longer period of two months, and it was seen that accuracy was still retained, while the test simulation (e) was run using PySWMM, showing that accuracy was held here as well.

Table 5: Conducted tests to find reliable parameter values for the inserted new nodes. The mass difference is calculated by comparing the TSS pollutant load at the outlet when the new nodes are inserted and when no modification is done to the model. (a), (b), (c) and (e) where simulated for the period 1.6.2009-16.6.2009, while (d) was simulated for the period 1.6.2009-31.7.2009.

	Elevation drop (m)	**Conduit length (m)**	**Mass difference (%)**
(a)	0.9	2	-6.62 %
	0.9	1.6	-8.47 %
	0.9	1.5	-9.07 %
	0.9	1.4	-9.63 %
	0.9	1.3	-10.34 %
	0.9	1	-15.18 %
(b)	0.001	2	-2.11 %
	0.05	2	-3.79 %
	0.1	2	-4.06 %
	0.15	2	-4.33 %
	0.2	2	-4.72 %
	0.25	2	-5.05 %
(c)	0.001	1	-5.78 %
	0.001	1.5	-2.99 %
	0.001	2	-2.11 %
	0.001	2.2	-1.95 %
	0.001	2.3	-1.86 %
	0.001	2.5	-1.65 %
(d)	0.001	2.3	-2.99 %
(e)	0.001	2.3	-1.54 %

5.2 Validation of model consistency

To validate that the simulation results from the different simulation runs, with different inlets receiving treatment, could be compared, it was verified that the default simulation run, without any defined treatment, always produced the same result in terms of runoff volume and pollutant load at the outlet, when given identical input parameters and for the same simulation period. This was achieved by running 10 identical 1 month simulations, where the same result was observed each time. This indicated that the only factor affecting the pollutant load would then be the inserted treatment. To further validate this, 8 identical simulation sets were performed and the results examined. From these, it was seen that the pollutant removal from each sediment trap in the model remained identical across each simulation set, and the ranking of the sediment traps hence remained constant, given the same input parameters.

5.3 Sewer inlet ranking

Figure 9 shows how the removal of pollutant in the system increased with an increasing number of installed sediment traps, before reaching its plateau at 91.7 %, the specified removal efficiency of the sediment traps. This corresponded with expectations, as all of the inlets would receive treatment and the total removal therefore also should be equal to the trap efficiency (under the assumption that the only pollution source at the outlet was from the runoff water going into the inlets). As seen in the figure, for the optimal solution, there was a steep increase in achieved removal with just a few installed traps, as the highest ranked traps were able to remove large amounts of pollutant. In contrast, from the worst solution it could be seen that even selecting a large number of wells for installing sediment traps could have a negligible effect on the total pollutant load, if poorly chosen. Only as the number of treated inlets greatly increased did the impact of location chosen lessen. This highlighted the need for a conscious and informed decision when selecting trap locations. Although the average removal could be considered sufficient for larger numbers of installed traps, the difference to the optimal solution was still significant for lower amounts of installed traps.

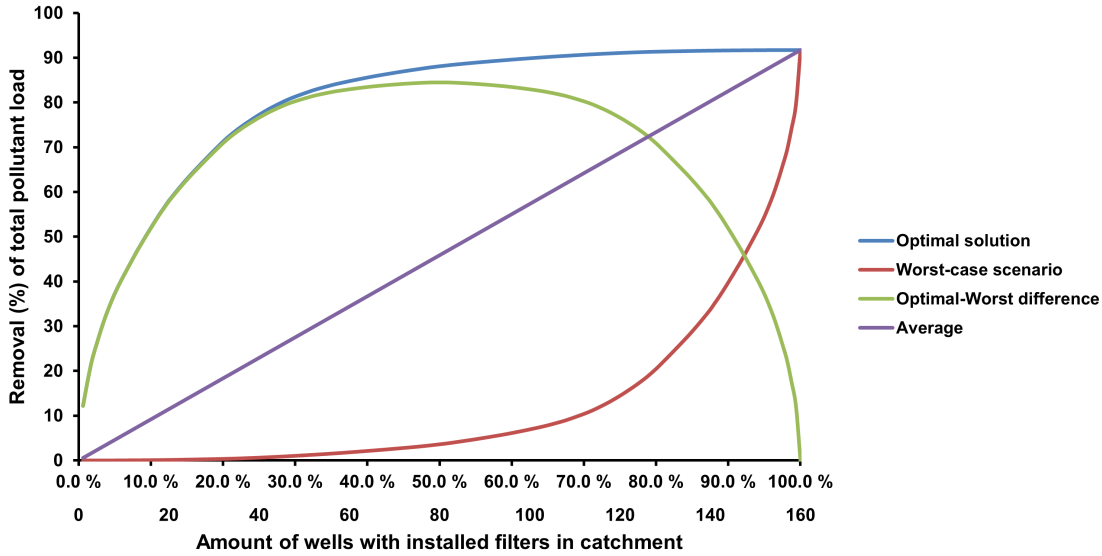

Figure 9: Removal of TSS depending on the amount of sewer inlets with installed sediment traps, for various rankings of the sewer inlets.

Similar to Figure 9, Table 6 shows a comparison between various chosen solutions, but in numerical form for various amounts of installed sediment traps. In conjunction with the figure, it was observed that the return of investment on increasing numbers of installed traps became increasingly small, indicating that there could be a reduced necessity to install traps in all inlets of a catchment, as long as the inlets were chosen in an informed manner, as most locations did not contribute significantly to the total removal. For example, in the worst case, reaching over 10 % removal would require installing sediment traps in over 100 inlets, but in the best case, using the optimal solution, less than 10 sediment traps were needed to far exceed the 10 % removal threshold, while on average it would require close to 20 traps to pass the threshold. This average was, however, skewed, as it relied on a few efficient trap locations that contributed with a high removal. This could be shown by comparing the average removal per well (0.57 % of total pollutant load) to the median removal (0.12 % of total pollutant load). In fact, only 26 % of the inlets achieved removal above the average.

Table 6: Achieved removal of catchment TSS pollution for various amounts of wells according to different ranking solutions. Catchment coverage refers to the percentage of the total catchment area where the runoff water goes into sewer inlets with installed sediment traps, for the optimal solution.

Wells	Optimal (%)	Worst (%)	Average (%)	Optimal solution catchment coverage (%)
10	41.3	0.0	5.7	36.5
20	58.0	0.1	11.5	50.1
50	82.0	1.2	28.7	75.6
100	89.9	7.0	57.3	88.6

To further highlight the impact of installing the sediment traps in sewer inlets within the catchment, Figure 10 shows how the amount of accumulated pollution diverged greatly over time depending on how many inlets had traps installed in them.

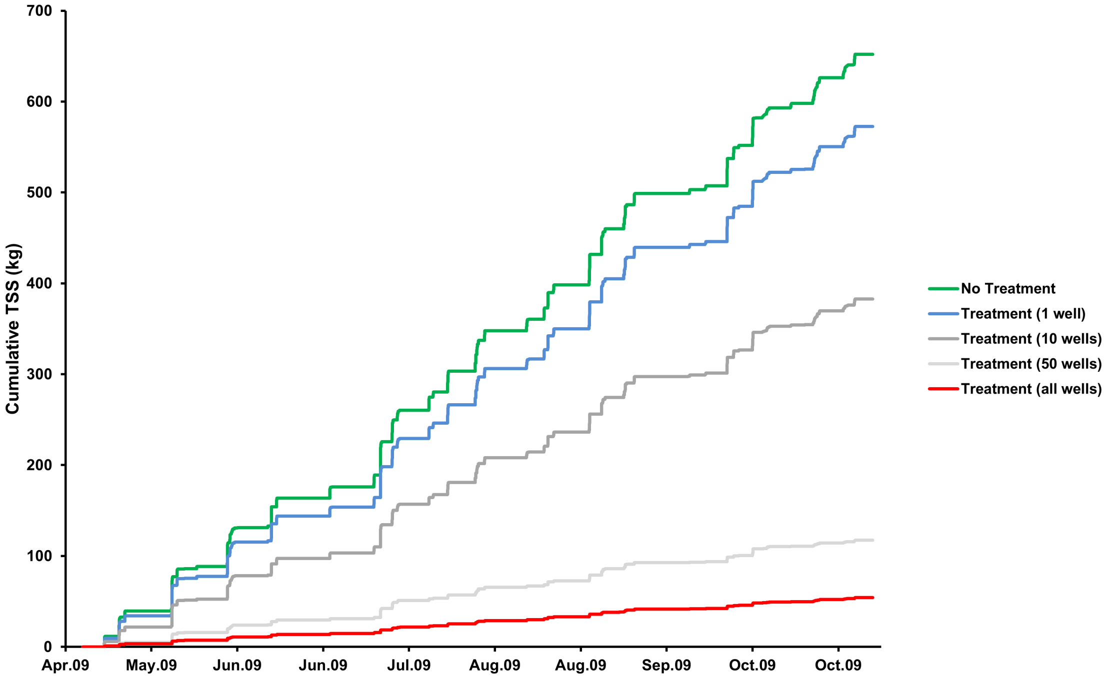

Figure 10: Accumulation of TSS in the catchment for various amounts of installed sediment traps over the period 1.5.2009-31.10.2009. The sediment traps were chosen according to the optimal ranking (1 well indicates the most efficient trap, 10 wells the 10 most efficient etc.).

5.4 Impact of varying sediment trap removal efficiencies

Although the simulations were carried out using the reported removal efficiency of 91.7 % from laboratory experiments, the results could be scaled due to the sewer inlets being independent from each other, meaning the ranking of the inlets in the optimal solution remained identical, and it was subsequently possible to understand how a different removal efficiency affected the quantities of pollutant discussed above, without the need for running the set of simulation scenarios repeatedly for each separate removal efficiency. This is visualised in Figure 11, where it can be seen that the curves of the different removal efficiencies maintained the same shape.

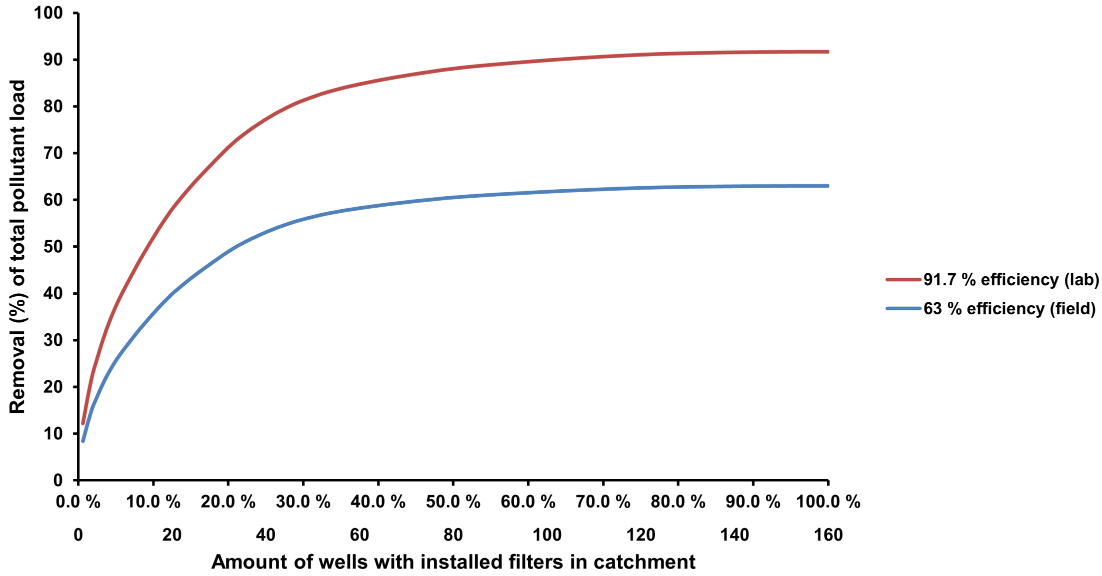

Figure 11: Comparison between removal of TSS depending on the amount of sewer inlets with installed sediment traps (optimal solution) using laboratory and field measured removal efficiencies.

5.5 Landuse contribution

The landuse in the catchment was investigated to understand the effect the landuse of the subcatchments had on the selection of the optimal order of sediment trap placement. Figure 12 displays how the combined area of subcatchments, whose runoff water was directed to sewer inlets with installed sediment traps, was divided among the various landuses, as the number of inlets with installed traps was increased following the optimal ranking. As the total catchment area was fixed, the landuse curves would gradually trend toward their respective fraction of the total area, and the landuses at certain points of the plot should therefore be compared to their endpoints.

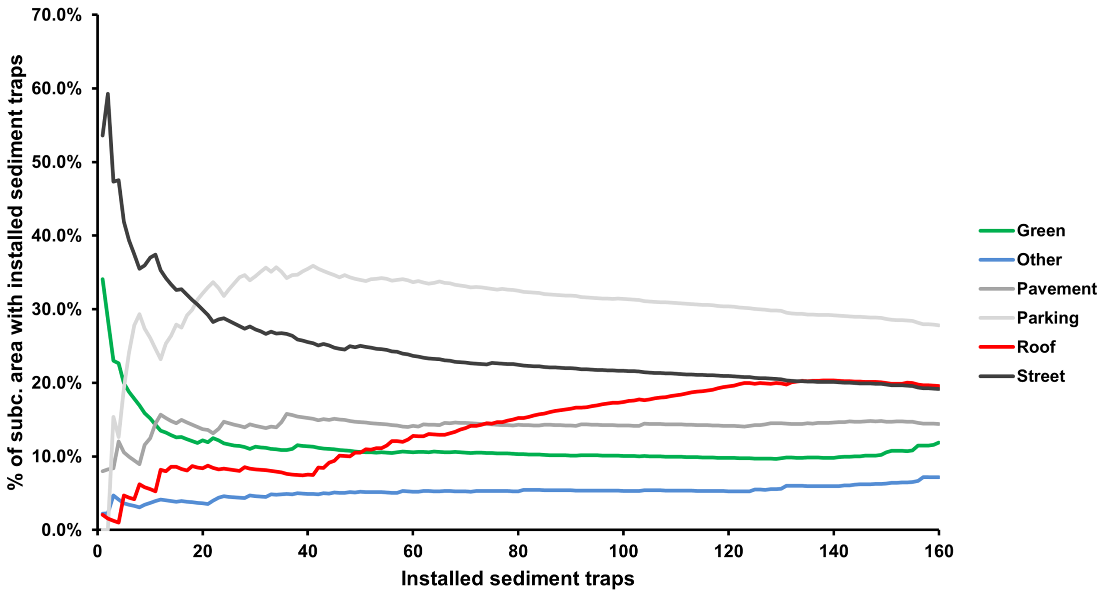

Figure 12: Percent of subcatchment area, pertaining to the different landuses, where the runoff water leads to sewer inlets with installed sediment traps, depending on the amount of sewer inlets with installed sediment traps, with the traps ordered according to the ranking of removal potential.

It was observed that streets were the initially largest landuse, indicating that the inlets that were able to remove the most pollutant could receive significant water quantities from streets (Figure 12). The second large landuse were parking lots, which became the largest landuse, as more sediment traps were installed. This could be attributed in part to it being the largest landuse, when examining the total catchment area, but also to the high EMC value defined for the landuse and subsequently its high pollutant generation characteristics. This would also explain the high percentage of streets initially, and how roofs, despite being the second largest landuse in the total catchment area, did not have notable presence in the optimal sediment trap placements.

Figure 13 shows the sewer inlets with the highest removal of TSS, and additionally visualizes the subcatchments whose runoff water lead into those inlets. From the figure, it was seen that within the 10 most optimal sewer inlets to be considered for treatment a large amount of street area was included, in addition to parking lots, while for the 50 most optimal inlets, mostly roof was excluded. Furthermore, Figure 13 highlights how many of the optimal inlets were those receiving runoff water from a large area; as shown in Table 6, the 10 most optimal inlets (6 % of all inlets) received runoff water from 36 % of the total catchment area, while the 50 most optimal inlets (31 % of all inlets) already covered 76 % of the total area.

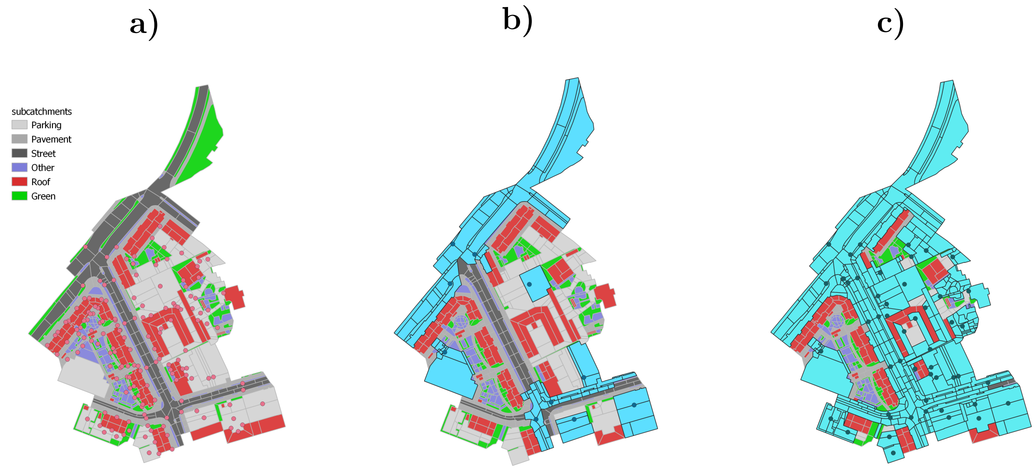

Figure 13: The subcatchments, visualized through QGIS. Sewer inlets are represented by points. From left to right: (a) The inlets and subcatchments, (b) The 10 inlets with the highest TSS removal and their subcatchments (highlighted in cyan), (c) The 50 inlets with the highest TSS removal and their subcatchments (highlighted in cyan).

The influence of area on the optimal solution is further displayed in Figure 14, where it was seen as the steep initial increase in the curve. Additionally, the separate increase in subcatchment landuse distribution could be analysed through the increase in area of each landuse, where the runoff water was led to sewer inlets with installed sediment traps, as visualised in Figure 15. Here, it was seen that around 70 % of the street area would be accounted for already with 10 sediment traps placed according to the optimal solution.

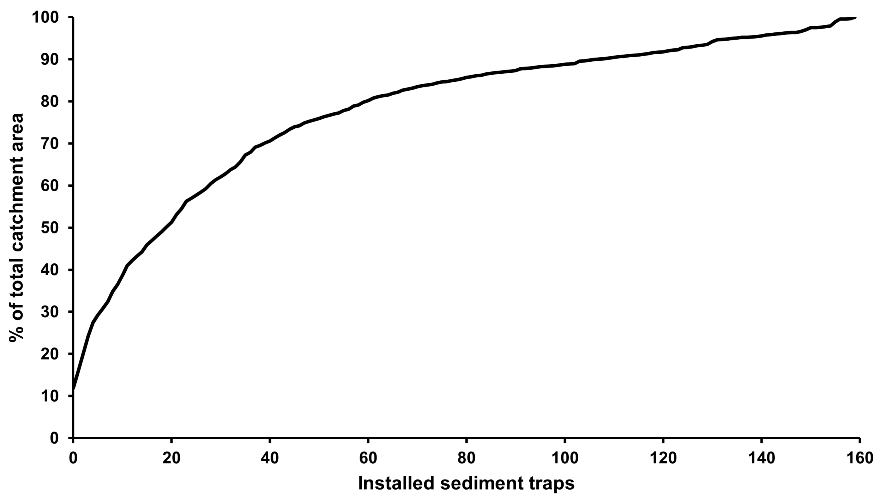

Figure 14: Cumulative area covered by sediment traps. Increase in fraction of total catchment area pertaining to subcatchments where runoff water is treated with sediment traps, depending on amount of installed traps.

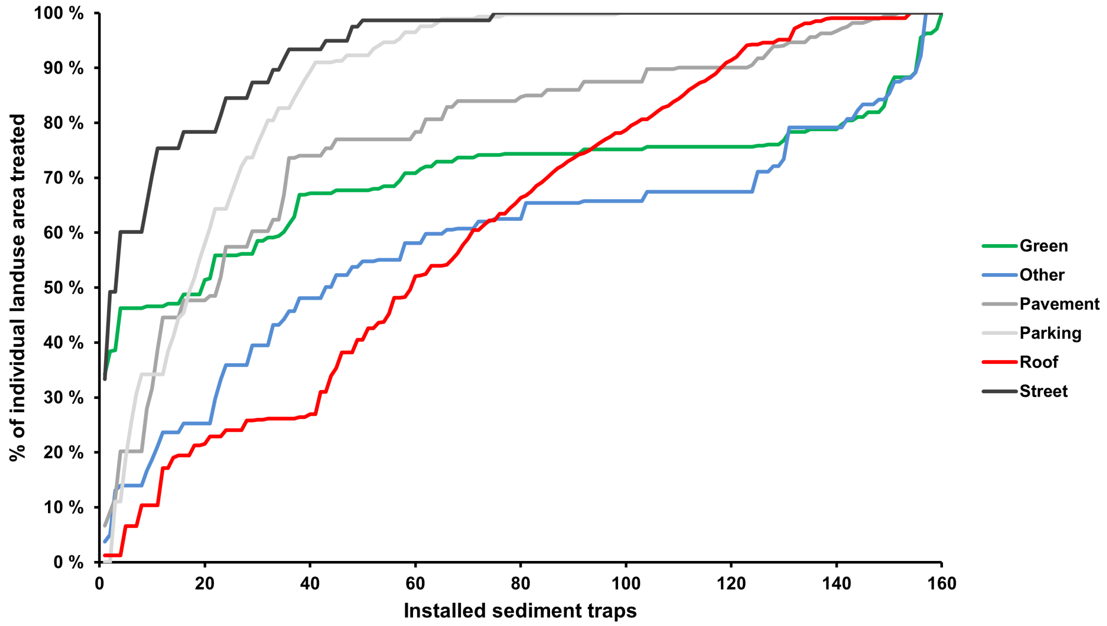

Figure 15: Cumulative landuse with installed sediment traps. Number of wells required to have sediment traps installed, according to the optimal solution, before all the area of each landuse has its runoff water leading to an inlet with installed sediment traps.

5.6 Impact of inlet location on optimal solution

Aside from the subcatchments, the relationships that might be present in the specific locations of the sewer inlets were also studied. Table 7 shows the distribution of inlets across the landuses in the catchment. Inlets located on pavement and parking lots made up the majority, accounting for > 70 % of the inlets. Meanwhile, the inlets found on street areas was lower compared to the subcatchment area counterpart, and the roof landuse did not have any inlets at all, instead the runoff water was led to nearby subcatchments and inlets, mostly pavement and parking lots (Figure 13).

Table 7: Amount of sewer inlets located on each landuse.

Landuse	**Inlets**
Green	12
Other	11
Pavement	60
Parking	58
Roof	0
Street	18

Despite the lower amount of sewer inlets located on streets, it was observed that they were overall the most optimal locations to place sediment traps at to reduce the TSS load, along with inlets on parking lots (Figure 16). As the number of available inlets on streets was reduced as more sediment traps were placed, more inlets from parking lots were chosen, explaining the increase in the parking curve. From the figure, it was also seen that, in spite of their large amount, the inlets located on pavement were not as efficient trap locations, as the pavement curve increased only as the other major curves decreased. This was also observed in Figure 17, where it was seen that inlets placed on streets and parking lots initially reached a high percentage of sediment traps installed. It was however noted that here, the miscellaneous Other landuse category was in fact the landuse to most slowly approach a high percentage of traps installed, indicating that it might be the least desirable landuse for installing the traps, while pavement and green areas were less desirable than streets and parking lots, but once sediment traps had been placed at those, these increased at a similar rate.

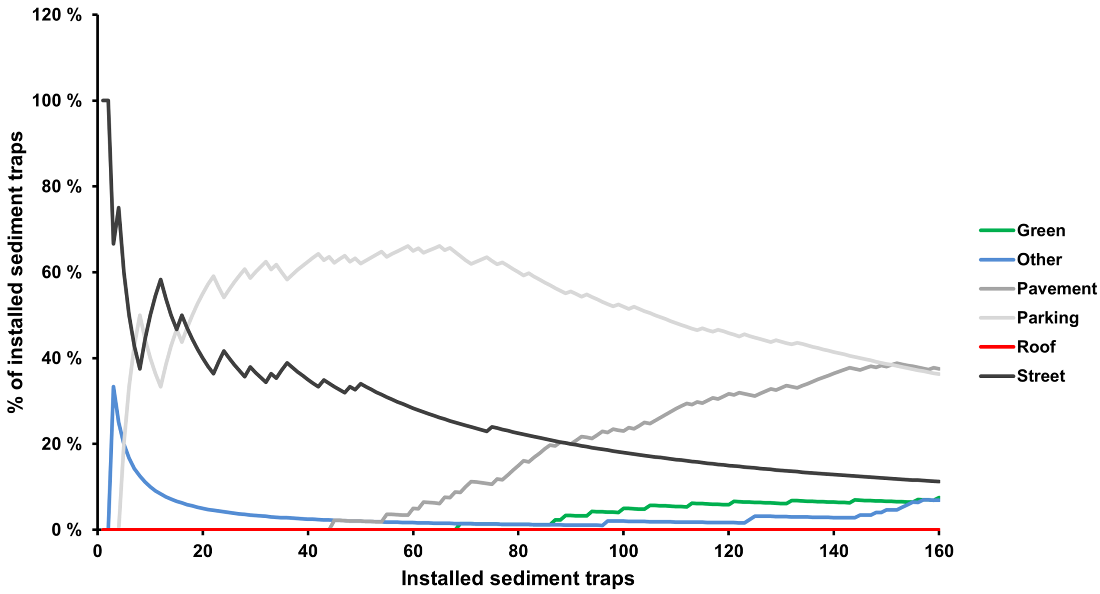

Figure 16: Location of the sewer inlets with installed sediment traps as number of inlets with installed traps increase, according to the optimal solution.

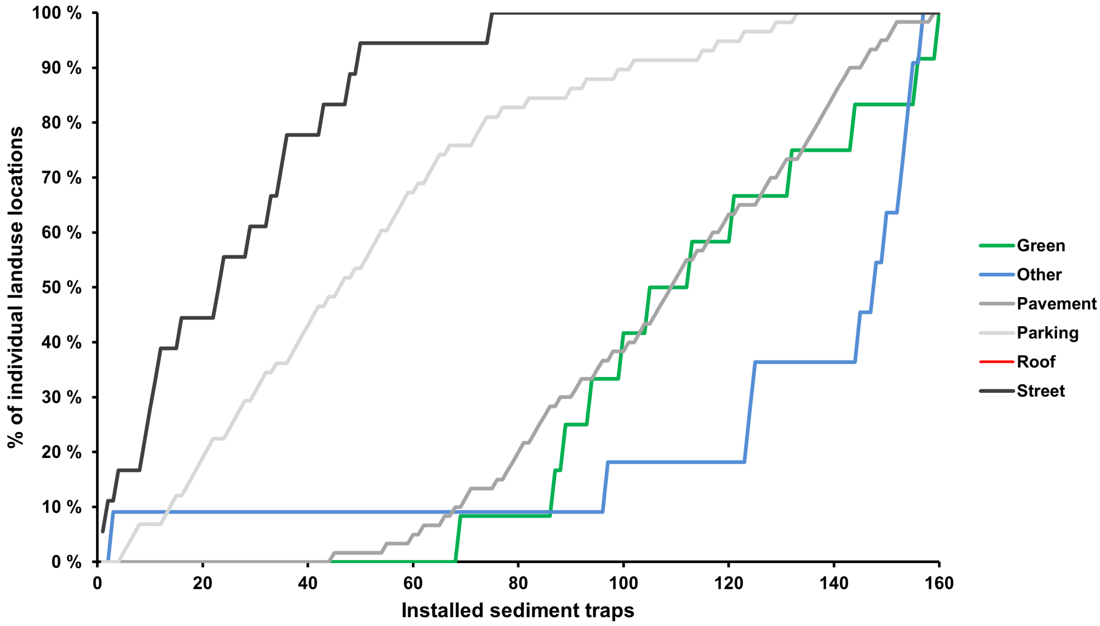

Figure 17: Number of wells required to have sediment traps installed, according to the optimal solution, before all possible sewer inlets on different landuses have sediment traps installed.

Overall, it appeared as though sewer inlets at streets would be the optimal placements for installing the sediment traps, followed by inlets at parking lots. However, by looking at Table 8, it could be seen that actually the sediment traps located on parking lots represented the largest removal in total, accounting for 47 % of the removed TSS, whereas removal through inlets located on streets amounted to 41 %. Notably, although the number of inlets located on pavement areas was the highest (Table 7), sediment traps located on pavement only accounted for 5 % of the removal. Nonetheless, from the table it was possible to see that, as previously observed, sewer inlets on streets and parking lots were by far the landuses with the highest potential pollutant removal.

Table 8: Amount of pollutant removed by sediment traps placed at inlets located at specific landuses.

Landuse	**Cum. Removal (%)**	**% of Removed Pollutant**
Green	0.7 %	0.8 %
Other	5.0 %	5.5 %
Pavement	4.7 %	5.1 %
Parking	43.4 %	47.3 %
Roof	0.0 %	0.0 %
Street	37.9 %	41.3 %
Total	91.7 %	100.0 %

5.7 TSS removal at public inlets

In actuality, installing sediment traps into all sewer inlets is not realistic from an economic point of view, especially on larger catchments. Aside from budget constraints, challenges relating to land ownership can lead to uncertainty regarding who is responsible for maintaining the sediment traps and, by extension, the stormwater quality. A solution to this is to only install sediment traps into inlets located on public land, thus placing the responsibility for maintenance solely on municipalities/governmental organs. Table 9 shows the result of this analysis. For both the examined scenarios, it was assumed that streets were always public land, while parking lots, roofs and other (miscellaneous) were always located on private land. The landuses whose ownership changed between the two variations were thus green areas and pavement. It was observed that the cumulative removal for either of these variations was relatively similar, again highlighting the low removal of the traps placed on inlets located on pavement areas.

Table 9: The cumulative removal potential of the catchment total TSS pollutant load achieved by placing sediment traps in all sewer inlets located on public land. Two categorizations of the land uses into public and private land have been compared (left and right).

Landuse	**Public/Private**	**Landuse**	**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

Landuse	**Inlets**	**Landuse**	**Inlets**
Public	90	Public	18
Private	69	Private	141

Landuse	**Cum. Removal (%)**	**Landuse**	**Cum. Removal (%)**
Public	43.3	Public	37.9

5.8 Impact of sediment trap maintenance on pollutant load

The impact of scheduling regular maintenance on the sediment traps was investigated, as described in Section 4.10. For a trap maximum capturing capacity of 40 kg for TSS, it was seen that for a maintenance interval of 180 days (around 6 months), only the sediment trap with the highest reported TSS removal removed less than the maximum removal potential (i.e. the removal without any defined maximum capacity), reaching about 50 % of the removal potential. This indicated that for the simulated 6 month period, the traps could in theory be installed without any need for maintenance without too large a loss of total catchment pollutant removal, as the traps did not reach full capacity during the period. A second calculation was done, using a lower maximum capacity of 20 kg, and it was observed that even with the lower capacity, only the five most efficient traps reached full capacity (removed less than maximum removal potential). Nonetheless, as these were the most efficient sediment traps, the loss of pollutant removal was still noticeable, reaching 93 % and 85 % of the maximum removal potential (i.e. a loss of 7 % and 15 %) for the 40 kg and 20 kg capacities, respectively, when maintenance was performed.

The results showed that, for a catchment in Finnish urban conditions where it was not realistic to maintain the sediment traps for more than 6 months, for example due to snow during winter, there might not be a need to perform maintenance on the installed sediment traps, as they would likely not reach full capacity and overflow, with the exclusion of the highest performing traps. As such, maintenance could at most be chosen to only focus on the highest performing traps, with a maintenance interval of several months.

6 Discussion

6.1 Finding the optimal sediment trap locations

The results found in the study indicated that a few well placed sediment traps could have a large impact on the total pollutant load of the catchment. Similarly, it was shown that if the locations of the traps were chosen poorly, they would have next to no effect on the pollutant load. It was also found that the average trap placement performed well below the most efficient ones for lower amounts of placed sediment traps. As was observed in the results, the return of investment on larger amounts of installed sediment traps became increasingly small, which suggested that there might not be a need for installing sediment traps in every sewer inlet, as in fact placing traps in less than one third of the inlets could achieve a potential removal of more than 80 % of the total catchment pollutant load (Table 6). This also served to highlight the advantage of identifying the optimal sewer inlets for sediment trap installation. A similar study was published by Hipp et al. (2006), albeit with a GIS-based model, to find the optimal sewer inlets for sediment trap installation in a catchment, which also included separated landuses and investigated the amount of traps required to meet the local U.S. stormwater quality thresholds. There it was found that only 30 % of the inlets needed traps to meet the requirements.

In practice, it can be difficult to determine the actual efficiency of the sediment traps through measuring and sampling, since there are large fluctuations in pollutant concentrations between storm events, even for the same catchment (Wang et al., 2013). This uncertainty regarding the sediment trap removal efficiency directly affected the subsequent observed effect of the sediment traps on the total catchment pollutant load. For example, the modeled removal efficiency of 91.7 % was noticeably higher than the later reported measured efficiency of 63 % (Section 3.4). Nonetheless, as was observed in the results, due to the removal efficiency being treated as a fractional removal on the pollutant load through the sewer inlets, the removal potential of the sediment traps could be scaled linearly to various removal efficiencies. This property also opens up the possibilities of exploring different types of sediment traps with varying removal efficiencies, which could be useful, given the high variability in efficiencies noted in Section 2.3.

For the landuses, it was seen that the sewer inlets that received runoff water from subcatchments categorized as streets were the ones to contribute the largest amount of pollutant to the drainage network, followed by the parking lot subcatchments. It was also observed that these inlets received water from large areas across the catchment. Both street and parking lots had high EMCs defined for their pollutant generation, which together with the large areas (and subsequently large amounts of runoff water) would explain their high relevance for pollution removal solutions (Tuomela, 2017). Here, the results therefore showed a large reliance on the specific EMCs chosen, which the model used to determine the pollutant loads generated on the landuses. However, the variability in the results related to the EMCs was not further explored in this study, although it proves an important point of interest for further research. Nonetheless, from Table 2 it was seen that generally, parking lots and streets tended to have higher EMCs than other landuses, and it could be assumed that to some degree the order of importance as to the pollution generation among the landuses remains the same, even as the EMCs themselves may fluctuate to some extent. For example, Wang et al. (2013) found that for their study catchment, urban traffic roads similarly had the highest observed EMCs.

With the likelihood of streets and parking lots being the primary contributors to the total pollutant load in the catchment established, the locations of the sewer inlets themselves was also investigated, as was shown in the results. Here it was seen that again, streets and parking lots were the primary landuses in the optimal ranking of the inlets. Although the fraction of inlets located on streets to the total amount of inlets in the catchment was not that large, streets were still the best performing locations for the sediment traps, with parking lots being second, while it was on the contrary found that inlets located on pavement areas were not nearly as efficient. From these results, it was concluded that inlets located on streets were likely to be the optimal locations for the sediment traps, although if sediment traps were installed in all inlets on a certain landuse, and on no other landuses, parking lots would be the optimal landuse for the traps.

6.2 Translating results to practical application

As discussed in subsection 2.2, in Finland stormwater management in urban areas is the responsibility of the local municipalities. The study therefore examined how much TSS could be removed by installing sediment traps only on public land (as opposed to privately owned land). The results showed that placing traps only on street areas would achieve a 38 % removal, whereas including also sediment traps on pavement and green areas would increase the removal to 43 %, at the expense of requiring a substantially larger amount of traps (which could pose an unnecessary investment under budget constraints). Here, the influence of the street areas on the removal potential is once again observed, but again it is noted that this removal potential assumes the likely over-optimistic trap removal efficiency of 91.7 %, and the impact of solely installing the sediment traps on public land could therefore be considerably smaller. Since there are currently no regulations as for the specific amounts of TSS in the stormwater in Finland, determining the exact number of sediment traps that should be installed might well at present be limited by budget rather than quality constraints. It should however also be noted that other solutions such as LID controls can be used in addition to the sediment traps to reduce the catchment pollutant load.

Regarding maintenance, the results indicated that possibly no maintenance would be needed during the examined time period of 6 months. This is increasingly likely in the case that the sediment traps are not installed according to the optimal ranking, or if the reference removal efficiency is lower than the modeled one (e.g. the field measured 63 %). While not explicitly evaluated for this type of sediment trap, Kostarelos et al. (2011) examined the performance of several CBIs and found that for some it was possible to have the devices installed for longer than a year without the need for maintenance. Moreover, their study noticed the influence of season on both the maintenance process (e.g. obstructing snow on top of the inserts) and how the sediment accumulated.

Another point to consider in relation to maintenance, is the aforementioned budget constraints. Allison and Pezzaniti (2006) noted the difficulty of implementing a cost-effective distributed network of sediment traps, because of the different rates at which the traps fill up, as well as the potential hazards that may arise from the treatment solution becoming a source of pollution itself if not regularly emptied.

6.3 Consideration of uncertainties

As the method developed was applied to an existing SWMM model, the uncertainty of the method was more closely related to the difference between the modified model (with the separated inlets and junctions) to the original model (as seen in Table 4) than to the actual uncertainty of the SWMM parametrization itself. The practical application of the model would then on the contrary be more dependent on how successful the original model was. Some of the uncertainty of the model used was reduced as a result of the high resolution of the parametrization, with detailed separation of the landuses into subcatchments (Krebs et al., 2013).

The model assumed all pollution observed at the outlet was from the runoff water going into the stormwater network. Therefore, all of the difference caused on the total catchment pollutant load at the outlet was a direct result of the installed sediment traps. In reality, other factors might influence the pollutant load at the outlet as well, for example leaks in the pipe network.

Furthermore, the model only examined one pollutant, TSS, which meant that no information was obtained on other pollutants, such as nutrients or metals. As noted by Tuomela et al. (2019), no single landuse dominated pollution contribution when several pollutants were examined, which in the context of this study would mean that the optimal locations for the sediment traps determined through the method only apply for TSS. To evaluate this possibility, the catchment model should be expanded to include more pollutants and the method extended to account for this.

6.4 Improving the method

Although the method produced results in accordance with the desired objectives, it was observed that the computational performance of the method was rather slow, requiring several days to run the set of simulation scenarios on the utilized computer (laptop). This poses a problem, as it implies that larger catchments with more subcatchments, nodes and conduits would require even more time to run, especially for longer time periods. A solution to this problem could be to fully utilize the capabilities of the PySWMM module, and apply the sediment trap treatment to the nodes within the simulation execution, instead of by externally modifying the SWMM input file. This way, the pollutant removal potential could also be estimated by calculating the pollutant passing through each inlet, rather than through the outlet. By doing this, only one simulation run would be necessary, drastically reducing the required computation time. The downside would however be the reliance on the PySWMM module, as no modified input file would be produced so that the simulations could be replicated in the SWMM user interface.

6.5 Recommendations

Despite uncertainty regarding the specific results obtained in the study, it is believed that they do imply a noticeable effect of the sediment traps on the total pollutant load in the examined catchment. To more confidently assess the actual impact of the traps, more site specific data would be needed on the EMCs (or buildup/washoff parameters) of the landuses to better estimate the pollutant generation, in addition to more field measurements on the removal efficiency of the sediment traps. Depending on the interest of which pollutants require removal, information on these other types of pollutant (such as EMCs) would be required as well.

Nonetheless, this study presented a transparent method, utilizing open source software, for stormwater treatment design in an urban catchment by identifying the optimal sewer inlets for sediment trap installation and evaluating their impact on the 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 landuse specific subcatchments.

7 Conclusions

The study aimed to assess the impact of installing a type of sediment traps into the sewer inlets of an urban catchment on the total load of suspended solids in the catchment. A computational method was developed in SWMM to compare the removal potential of each sewer inlet when installed with a sediment trap, and the results were ranked to find the most optimal placements for the traps. It was found that to reach substantial removal of TSS, there was no need to install traps in every inlet, but by installing traps only in the most efficient ones, a large amount of pollutant could already be removed. The specific amount depended on the removal efficiency of the sediment traps.

The landuse contribution to the total catchment pollutant load was also evaluated, and it was seen that inlets receiving runoff water from large areas, especially from streets and parking lots, contributed the most TSS. However, it was noted that this was heavily dependent on the designated EMCs of the landuses. By examining the locations of the optimal sewer inlets, it was observed that the best performing inlets were located on streets (followed by parking lots). Overall, it is therefore likely that installing sediment traps in sewer inlets located on these landuses achieves the highest removal of TSS (if no ranking of the inlets is available).

An analysis was done to evaluate how installing sediment traps only in inlets located on public land would perform, and additionally, the effect of regular maintenance on the traps was calculated, although it was found that for the simulated 6-month period, no maintenance was required.

As the only TSS pollution was modelled, no information was obtained on the efficiency of the sediment traps for removing other types of pollutants, and further research would be needed to assess how the optimal inlet locations vary with the inclusion of several pollutants.

References

M. Z. Alam, A. F. Anwar, A. Heitz, and D. C. Sarker. Improving stormwater quality at source using catch basin inserts. *Journal of Environmental Management*, 228:393–404, 12 2018. ISSN 03014797. doi: 10.1016/j.jenvman.2018.08.070.

R. Allison and D. Pezzaniti. *Gross pollutant and sediment traps.* PhD thesis, EA Books Melbourne, Australia, 2006.

E. Antikainen and A. Koskenlahti. Testausraportti - Hulevesisuodattimen tutkimus. Technical report, Savonia University of Applied Sciences, 2019. URL `https://www.watec.fi/tuotteet/p/filtro`.

S. Begum, M. Rasul, and R. Brown. Stormwater treatment and reuse techniques: A review. *Transactions on Environment and Development*, 4(11), 2008. ISSN 1790-5095. URL `https://hdl.handle.net/10018/28578`.

J. B. Butcher. Buildup, Washoff, and Event Mean Concentrations. *JAWRA Journal of the American Water Resources Association*, 39(6):1521–1528, 12 2003. ISSN 1752-1688. doi: 10.1111/J.1752-1688.2003.TB04436.X.

City of Helsinki. City of Helsinki Storm Water Management Program, 2018. URL `https://www.hel.fi/static/liitteet/kaupunkiymparisto/julkaisut/julkaisut/julkaisu-03-18-en.pdf`.

EUR-Lex. Water Framework Directive, 2000. URL `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0060`.

Finlex. Land use and building act (132/1999), 1999. URL `https://www.finlex.fi/en/laki/kaannokset/1999/en19990132`.

Finlex. Water services act (119/2001), 2001. URL `https://www.finlex.fi/en/laki/kaannokset/2001/en20010119_20150979.pdf`.

T. D. Fletcher, H. Andrieu, and P. Hamel. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, 51:261–279, 1 2013. ISSN 03091708. doi: 10.1016/J.ADVWATRES.2012.09.001.

T. D. Fletcher, W. Shuster, W. F. Hunt, R. Ashley, D. Butler, S. Arthur, S. Trowsdale, S. Barraud, A. Semadeni-Davies, J. L. Bertrand-Krajewski, P. S. Mikkelsen, G. Rivard, M. Uhl, D. Dagenais, and M. Viklander. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7):525–542, 10 2015. ISSN 17449006. doi: 10.1080/1573062X.2014.916314.

A. G. Fraser, R. M. Ashley, and A. A. Ghani. Inlet and sewer traps for sediment control in stormwater drainage - a Malaysian case study. In *Proceedings of the ASCE Joint Conf. on Water Resources Engg and Water Resources Planning and Management*, 2000.

G. Freni, G. Mannina, and G. Viviani. Urban Storm-Water Quality Management: Centralized versus Source Control. *Journal of Water Resources Planning and Management*, 136(2):268–278, 2010. doi: 10.1061/ASCE0733-94962010136:2268.

H. Haris, M. F. Chow, F. Usman, L. M. Sidek, Z. A. Roseli, and M. D. Norlida. Urban Stormwater Management Model and Tools for Designing Stormwater Management of Green Infrastructure Practices. *IOP Conference Series: Earth and Environmental Science*, 32(1):012022, 3 2016. ISSN 1755-1315. doi: 10.1088/1755-1315/32/1/012022.

J. A. Hipp, O. Ogunseitan, R. Lejano, and C. S. Smith. Optimization of stormwater filtration at the urban/watershed interface. *Environmental Science and Technology*, 40(15):4794–4801, 8 2006. ISSN 0013936X. doi: 10.1021/ES060520F.

J. Järveläinen. Land-use based stormwater pollutant load estimation and monitoring system design: Case of Lahti city, Finland. Master's thesis, Aalto University. School of Engineering, 2014. URL `http://urn.fi/URN:NBN:fi:aalto-201404161691`.

J. Korkealaakso, H. Kuosa, T. Kling, O. Wahlroos, S. Holopainen, E. Inkiläinen, K. Loimula, S. Holopainen, and G. Krebs. Urban needs and best practices for enhanced stormwater management and quality - State-of-the-Art. Technical report, VTT Technical Research Centre of Finland, 2016.

K. Kostarelos, E. Khan, N. Callipo, J. Velasquez, and D. Graves. Field Study of Catch Basin Inserts for the Removal of Pollutants from Urban Runoff. *Water Resources Management*, 25(4):1205–1217, 2011. ISSN 09204741. doi: 10.1007/S11269-010-9672-2.

G. Krebs, T. Kokkonen, M. Valtanen, H. Koivusalo, and H. Setälä. A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization. *Urban Water Journal*, 10(6):394–410, 12 2013. ISSN 1573062X. doi: 10.1080/1573062X.2012.739631.

S.-L. Lau, E. Khan, and M. K. Stenstrom. Catch basin inserts to reduce pollution from stormwater. *Water Science and Technology*, 44(7):23–34, 10 2001. ISSN 0273-1223. doi: 10.2166/wst.2001.0381.

S. Lloyd, T. H. Wong, and C. J. Chesterfield. Water Sensitive Urban Design - A Stormwater Management Perspective. Technical Report September, CRC for Catchment Hydrology, Australia, 2002. URL `www.catchment.crc.org.au/publications`.

B. E. Mcdonnell, K. Ratliff, M. E. Tryby, J. Jia, X. Wu, and A. Mullapudi. PySWMM: The Python Interface to Stormwater Management Model (SWMM). *Journal of Open Source Software*, 5(52):2292, 8 2020. ISSN 2475-9066. doi: 10.21105/JOSS.02292.

R. A. Morgan, F. G. Edwards, K. R. Brye, and S. J. Burian. An Evaluation of the Urban Stormwater Pollutant Removal Efficiency of Catch Basin Inserts. *Water Environment Research*, 77(5):500–510, 9 2005. ISSN 1554-7531. doi: 10.2175/106143005X67412.

J. Niemczynowicz. Urban hydrology and water management – present and future challenges. *Urban Water*, 1(1):1–14, 3 1999. ISSN 1462-0758. doi: 10.1016/S1462-0758(99)00009-6.

S. J. Nix. *Urban Stormwater Modeling and Simulation.* CRC Press, 1994.

Open SWMM. Functions in the node treatment editor. `https://www.openswmm.org/Topic/4517/functions-in-the-node-treatment-editor`, 2013. [Online; accessed 11.5.2022].

R. Pitt and R. Field. An evaluation of storm drainage inlet devices for stormwater quality treatment. *The University of Alabama at Birmingham, Department of Civil and Environmental Engineering, United States Environmental Protection Agency, Wet Weather Flow*, 1998.

R. Remley, R. A. Morgan, F. G. Edwards, K. R. Brye, and S. J. Burian. Pollutant removal capacity of stormwater catchbasin inserts. *World Water Congress 2005: Impacts of Global Climate Change - Proceedings of the 2005 World Water and Environmental Resources Congress*, page 217, 2005. doi: 10.1061/40792(173)217.

L. Rossman. *Storm Water Management Model User's Manual Version 5.1.* National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 2015. URL `https://www.epa.gov/water-research/storm-water-management-model-swmm`.

L. A. Rossman and W. C. Huber. *Storm Water Management Model Reference Manual Volume III-Water Quality.* National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 2016a. URL `https://www.epa.gov/water-research/storm-water-management-model-swmm`.

L. A. Rossman and W. C. Huber. *Storm Water Management Model Reference Manual Volume I-Hydrology (Revised).* National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 2016b. URL `https://www.epa.gov/water-research/storm-water-management-model-swmm`.

J. Sage, C. Bonhomme, S. Al Ali, and M. C. Gromaire. Performance assessment of a commonly used "accumulation and wash-off" model from long-term continuous road runoff turbidity measurements. *Water Research*, 78:47–59, 7 2015. ISSN 0043-1354. doi: 10.1016/J.WATRES.2015.03.030.

L. Sänkiaho, N. Sillanpää, and H. Setälä. Developing stormwater management through research and practice: experiences from a Finnish pilot programme. In *Proceedings of the Cities of the Future: Sustainable Urban Planning and Water Management, 22.-25.5.2011, Stockholm, Sweden*, 2011.

M. Suihko. Biofiltration for stormwater management in Finnish climate. Master's thesis, Aalto University. School of Engineering, 2016. URL `http://urn.fi/URN:NBN:fi:aalto-201612226246`.

M. C. Tu and P. Smith. Modeling Pollutant Buildup and Washoff Parameters for SWMM Based on Land Use in a Semiarid Urban Watershed. *Water, Air, and Soil Pollution*, 229(4):1–15, 4 2018. ISSN 15732932. doi: 10.1007/S11270-018-3777-2/TABLES/5.

C. Tuomela. Modelling source area contributions of stormwater pollutants for stormwater quality management. Master's thesis, Aalto University. School of Engineering, 2017. URL `http://urn.fi/URN:NBN:fi:aalto-201710307322`.

C. Tuomela. Setup of SWMM parameterisation for stormwater quality modelling, 2022. Unpublished work, Aalto University.

C. Tuomela, N. Sillanpää, and H. Koivusalo. Assessment of stormwater pollutant loads and source area contributions with storm water management model (SWMM). *Journal of Environmental Management*, 233:719–727, 3 2019. ISSN 0301-4797. doi: 10.1016/J.JENVMAN.2018.12.061.

U.S. EPA. Summary of the Clean Water Act. https://www.epa.gov/laws-regulations/summary-clean-water-act, 2022. [Online; accessed 14.7.2022].

M. Valtanen, N. Sillanpää, and H. Setälä. The effects of urbanization on runoff pollutant concentrations, loadings and their seasonal patterns under cold climate. *Water, Air, and Soil Pollution*, 225(6):1–16, 5 2014. ISSN 15732932. doi: 10.1007/S11270-014-1977-Y/TABLES/4.

S. Wang, Q. He, H. Ai, Z. Wang, and Q. Zhang. Pollutant concentrations and pollution loads in stormwater runoff from different land uses in Chongqing. *Journal of Environmental Sciences*, 25(3):502–510, 3 2013. ISSN 1001-0742. doi: 10.1016/S1001-0742(11)61032-2.