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Storm water treatment in a multi-step system compared to a single-step system

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Storm water treatment in a multi-step system compared to a single-step system

Dagvattenrening i ett flerstegssystem jämfört med ett enstegssystem

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Abstract

Urban areas are expanding at an increasing pace around the world as well as surfaces with impervious layers, such as streets and rooftops. Precipitation, melt water and water from human activities, which temporarily flow on these surfaces are defined as storm water. As a result of replacing natural land with hard surfaces, a barrier for natural water infiltration is created and amplitude and volume of water runoff are increased. In addition, dissolved and particulate substances are transported with the water during the runoff on hard surfaces, with risk of contaminating the areas in its path. With concentrated and increased runoff, more particles are released and transported with the water. However, proper and sustainable management of storm water reduces the risk of flooding and contamination of water in urban and rural areas. The choice of storm water system, together with maintenance and monitoring, are of great importance for achieving the desired treatment and handling of storm water. In Sweden, dams are one of the most widely used storm water facility in storm water system. Dams function both as water reservoirs and as treatment facilities for removal of particles. In this study, a storm water system located in an expanding industrial area in Rosersberg was examined. The storm water system has the purpose to treat and delay storm water draining to the nearby valuable stream Verkaån. It is a multi-step system, consisting of a series of dams, which is commonly used in Sweden. However, studies on treatment in multi-step systems are scarce. Therefore, the aim of this study was to examine treatment of pollutants in a multi-step system compared to treatment in a single-step system. Monitoring data of pollutant loads from the multiple-dam storm water system in Rosersberg was compared with pollutant loads as generated from modelling of the system in the storm water software, StormTac. Monitored pollutant loads after treatment in multiple dams in the storm water system were lower than the modelled treatment of multiple dams for eleven out of thirteen substances, and lower than the modelled treatment of a single dam for twelve out of thirteen substances. Treatment effect of pollutants in the storm water system in Rosersberg was higher in multiple dams, than in a single dam, for all modelled pollutant loads except for nitrogen. It could therefore be concluded that a multi-step system treats storm water to a larger extent than a single-step system.

Keywords: Storm water, storm water management, storm water treatment, open storm water system, storm water dams, multi-step system, StormTac, pollutant load

Populärvetenskaplig sammanfattning

Urbana områden expanderar i allt högre takt runt om i världen och därmed även hårdgjorda ytor, såsom gator och hustak. Nederbörd, smältvatten och vatten som har använts vid mänskliga aktiviteter som tillfälligt rinner på dessa ytor definieras som dagvatten. Ett flertal problem är kopplat till dagvatten. Genom att man ersätter naturlig mark med hårdgjorda ytor, skapas en barriär för den naturliga vatteninfiltrationen i marken, vilket leder till ökad avrinning av vatten. Partiklar transporteras med vattnet under avrinningen på hårda ytor, vilket medför en risk att förorena de områden som vattnet passerar. Mer koncentrerad och ökad avrinning resulterar i att fler partiklar frigörs och transporteras med vattnet, men med hållbar hantering av dagvatten minskar risken för översvämningar och förorening av mark och vatten. Val av dagvattensystem och dagvattenanläggningar tillsammans med kontinuerlig skötsel och övervakning, är av stor betydelse för att uppnå önskad rening och hantering av dagvatten. I Sverige är dammar bland de mest populära dagvattenanläggningarna. De fungerar inte bara som vattenmagasin, där vattnet kan ansamlas och fördröjas för att förhindra översvämningar, utan renar även dagvattnet från föroreningar.

Inom och söder om ett ständigt expanderande industriområde i Rosersberg har man anlagt ett dagvattensystem med syfte att rena och fördröja dagvatten som dränerar till den närliggande och värdefulla ån, Verkaån. Verkaån anses vara värdefull eftersom att rödlistade arter såsom bäver, utter och asp förekommer i vattendraget. Dagvattensystemet är ett flerstegssystem bestående av flera dammar anlagda i en serie efter varandra, vilket inte är någon nymodighet i Sverige. Dock finns endast ett fåtal studier om hur effektiv reningen av dagvatten är i denna typ av system jämfört med reningen med en damm.

I den här studien har rening av dagvatten i ett system med flera steg jämförts med rening i ett system med ett steg. Föroreningsbelastning från industriområdet i Rosersberg har beräknats med uppmätt data från dagvattensystemet. Uppmätt föroreningsbelastning från industriområdet jämfördes med föroreningsbelastning genererade efter modellering i StormTac, en programvara för dagvattenmodellering. Uppmätta föroreningsmängder efter rening i en serie av dammar i dagvattensystemet var lägre än efter simulerad rening i flera dammar i modellen för elva av tretton ämnen, och lägre än efter simulerad rening i en damm i modellen för tolv av tretton ämnen. Reningseffekten av dagvatten i systemet i Rosersberg var högre i en serie av dammar, än i en damm, för alla modellerade föroreningar utom för kväve. Därmed drogs slutsatsen att ett system med flera steg renar dagvatten i större utsträckning än ett system med ett steg.

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Abbreviations

D0	A single dam
D1	Titandammen
D2	Järndammen
D3:1–3	Verkadammarna
DM	Dry Matter
DO	Dissolved Oxygen
PAH	Polycyclic Aromatic Hydrocarbons
PP	Polypropylene
SEPA	Swedish Environmental Protection Agency
SS	Suspended Solids
STA	Swedish Transport Administration
SWWA	Swedish Water and Wastewater Association
TOC	Total Organic Carbon
TSS	Total Suspended Solids
WFD	Water Framework Directive
WSP	Williams Sale Partnership Limited

1 Introduction

Storm water

Storm water is the water from precipitation, melt water and from human activities involving water that temporarily flows on hard surfaces (VA-guiden, 2016). Common hard surfaces are for example rooftops, streets, roads and car parks (VA-guiden, 2016). The awareness of storm water is connected to the continuous exploitation of urban areas around the world, which has an impact on the quality of water bodies. Since urban areas often consist of hard surfaces, natural land is replaced as well as areas where the water can infiltrate. This barrier of natural water infiltration results in increased volume and amplitude of storm water runoff. Consequently, there is an increased risk for flooding in urban areas. Another issue, highly connected to increased runoff of storm water in urban areas, is the pollution in storm water. Storm water carries particles, which derive from both natural and human sources in the urban area, during its transport on hard surfaces (Pettersson, 1999). Hence, increased storm water runoff enhances the wash out and transportation of particles within the storm water. Thus, there is a risk that the storm water reaches and contaminates adjacent water bodies (Brinkmann, 1985).

Studies have shown that proper and sustainable storm water management is required in order to reduce the risk of flooding in urban areas and contamination of water bodies (Stahre, 2004; SWWA, 2011). Here, the choice of storm water system and storm water facilities included in the system, together with maintenance and monitoring, are of great importance for achieving the desired treatment and handling of storm water. By involving storm water management in an early stage of the planning process, efficient storm water management is accomplished and therefore also efficient treatment of storm water (Stahre, 2004). Knowledge on hydro-meteorological variables, discharge patterns and physicochemical characteristics of the storm water, as well as presence and load of metals and other substances, are vital to consider in the management plan (Kaczala et al., 2012).

Sweden has an almost 40-year-old history of storm water management. Studies of particle transport in storm water, as well as management of storm water runoff, with the purpose to remove or reduce these particles and flooding, have been developed and implemented (Thornell, 2013). Commonly used storm water facilities in storm water systems are for example ditches, wetlands and dams. In Sweden, dams are one of the most widely used storm water facilities for treating storm water and extensive research is available in the subject (Blick et al., 2004; Persson and Pettersson, 2006; Pettersson, 1999; Stahre, 2004). Storm water dams do not only work as storm water reservoirs but also treat the water from pollutants as the water is delayed in the dams (Pettersson, 1999).

One way to predict and estimate discharge patterns and particle loads in a system is the use of models, and a commonly used software tool in Sweden is StormTac (Arnlund et al., 2014). Here, storm water quantity and quality, as well as separation in storm water facilities and interactions within a catchment area, can be estimated and used for planning and evaluating storm water systems in the storm water management (Larm and VBB VIAK, 2000; StormTac, 2016a).

The Rosersberg storm water study

In the area of Rosersberg, located north of Stockholm, an industrial area was implemented in the early 2000's and continuous exploitation has taken place in the area since then. South of the industrial area, the valuable stream Verkaån is located. The stream is valuable due to its presence of threated species like beaver, utter and asp. Since storm water from the area drains to Verkaån, measures are undertaken to make sure that the drained storm water has low impact on Verkaån (WSP Environment, 2009a). Consequently, a storm water system was implemented within and south of the industrial area during 2009. The storm water system is a multi-step system, consisting of a series of dams, which is designed to delay the discharge and thus minimizing flow peaks as well as treat the storm water (Lundkvist, 2017; WSP Environment, 2009a). A total of five dams are included in the system, where two large dams are located within and a bit south of the industrial area and connected by ditches in the street sections. After these dams, the storm water goes through a subsurface conduit before passing the last three dams and the outflow to stream Verkaån. Continuous monitoring of the system has been carried out since its implementation in order to monitor the treatment (Sigtuna Water and Sanitation, 2015a; WSP Environment, 2009a). The monitoring program started in 2009 and monitored surface water four times per year and sediment samples one time per year. Water samples were collected with random sampling upstream and downstream Verkaån and timed sampling were performed in the storm water system. Water discharge was also measured at these sites four times per year (WSP Environment, 2009a). Samples were analyzed for different parameters, both in the field and in a lab in order to determine impact on Verkaån and treatment effect of the storm water system.

The idea of constructing storm water systems with multiple dams is rather common in Sweden, however, studies on treatment in that kind of system compared to treatment in a single-dam system are scarce (Lundkvist, 2017).

1.1 Objectives

The purpose of this master thesis is to study the treatment of pollutants in a multi-step system compared to treatment in a single-step system. Furthermore, a literature review on storm water is performed with the aim to present a comprehensive description of the subject. The study assesses whether a storm water system with several dams has a significantly higher treatment effect of pollutants than a system with a single dam.

The study attempts to answer the following questions:

- Is storm water treated to a larger extent in a multi-step system compared to a single-step system?
- Is there any correlation between sediment samples from the storm water system and downstream Verkaån? Can any conclusions about treatment effect be drawn from these samples?
- Is there any correlation between pollutant concentrations in sediment and water in the retention dams?

The following hypotheses are investigated:

- Treatment of pollutants in storm water is higher in a multi-step system than in a single-step system.
- There is a correlation between pollutant concentrations in sediment and water in retention dams.

1.2 Limitations

This study focuses on treatment of pollutant loads for three out of five dams included in the storm water system in Rosersberg since water samples were collected at the outlet of the third dam.

Only the storm water system in Rosersberg is evaluated to determine whether the treatment in the multiple dams is higher than in a single dam.

The industrial area in Rosersberg has been expanding continuously since the implementation and monitoring of the storm water system, which is expected to have caused increased pollutant loads throughout the study period.

Generally, water samples are either sampled with random, timed or flow proportional sampling, where the latter is regarded as more reliable. Water samples in the monitoring program in Rosersberg were collected by either random or timed sampling, of which both sample methods are not considered as representative as a flow proportional method.

Maintenance practices of the storm water dams included in the storm water system are not taken into consideration in this study.

Treatment effect of the storm water system is estimated within a six-year span. Since monitoring data from the storm water system used in the calculation of pollutant loads were measured in 2010-2015.

2 Literature review

In this section, open storm water systems will be presented, with a focus on management, treatment and different storm water systems. Focus is particularly put on storm water dams, a commonly used facility in Sweden, their functions and how they are best designed, monitored and maintained to achieve an efficient treatment of storm water.

2.1 Storm water

Definition

Storm water is defined as the water runoff that temporarily flows on hard surfaces during or after precipitation, from meltwater, as well as from human activities involving water (VA-guiden, 2016). Several problems are related to storm water and are connected to the fact that urban areas are continuously expanding around the world. During its transport on hard surfaces the water carries dissolved and particulate substances, referred to as pollutants (Pettersson, 1999).

Pollution

There are several different sources from which pollution in urban areas derive, resulting in varying storm water characteristics among different areas (WRS AB and Naturvatten i Roslagen AB, 2013). Some examples of sources generated in urban areas are vehicular traffic, construction and wrecking of buildings, corrosion of various materials and waste (Brinkmann, 1985). Also, sources originating beyond the urban area contribute with pollutants to the storm water. Some examples are eroded upland areas, agricultural land and wet and dry deposition (Blick et al., 2004). Here, acid rain or aggressive gases increase the corrosion of various materials (Brinkmann, 1985). Of course, the degree of pollutant addition to the storm water varies widely depending on composition and concentrations of atmospherically deposited substances. From both atmospheric deposition and vehicular traffic, the pollutants are in solid, liquid and gaseous forms, resulting in a complex combination of compounds (Brinkmann, 1985).

Flooding

In addition to the problem with pollution of storm water in urban areas, there is an issue with large volumes of storm water. The barrier of water infiltration, created by the hard surfaces, increases the risk for ponding water and flooding. This is of particular concern during heavy rainfall events (Stahre, 2004). In Sweden, precipitation in urban areas are typically collected in closed conduits, also known as storm water sewers, with the purpose of rapid removal of water (Lee et al., 2012; Stahre, 2004). The risk for flooding during heavy rainfall events is increased as the water conduit capacity might be exceeded. Also, since high flow rates are created during heavy rainfall events, there is a risk of washout of pollutants deposited in the sewers during periods of low or no flow (Li et al., 2013; Verbanck et al., 1994).

Legislation

Consequently, managing storm water is important to consider when expanding urban areas. In Sweden, storm water management has received more attention since the 70's (Thornell, 2013). Still, the definition of storm water in Swedish legislation is non-existent, making it more vague and difficult to handle storm water in the exploitation process (VA-guiden, 2016). Luckily, in the almost 40 years of storm water management, studies of particles transported with storm water have been performed. A large number of storm water treatment facilities, with the purpose of removing or reduce these particles, have been developed and implemented in Sweden with an increasing trend during the last decade (Thornell, 2013). The positive trend is to a large extent associated with legislation including preservation of water bodies. This includes the Water Framework Directive (WFD) brought forth by the European Union (EU) in 2000, which states that all water bodies in Europe must maintain a certain water quality (Swedish Agency for Marine and Water Management, 2016). This also regards a majority of the environmental objectives stated by the Swedish Government, (SEPA, 2016).

2.2 Storm water quality and quantity

Impact of pollutants

Several substances that are referred to as pollutants in storm water are naturally occurring. The problem with these substances when they derive from urban areas, is the episodic and extreme concentrations that are transported by the storm water and to the recipients. Soluble substances in the urban runoff can reach very high concentrations during high flow events (Verbanck et al., 1994). They can give acute toxic effects due to the direct bioavailability of soluble substances (Pettersson, 1999). This is a so called short-term damage, which by the release of metals and other harmful substances affects water conditions such as pH, dissolved oxygen level (DO) and turbidity (Li et al., 2013; Pettersson, 1999). Also, long-term damage is a consequence of urban runoff, which is distinguished by particulate pollutants that have deposited on the bottom of the recipient. If these pollutants are released from the bottom sediments they can cause toxic effects on the sediment biota (Brinkmann, 1985). This also influence the sediment-water exchange, which is vital for uptake and release dynamics in the bottom area of water bodies (Brinkmann, 1985). Release of nutrients, such as nitrogen (N) and phosphorous (P), can result in eutrophication of water bodies, while heavy metals pose an ecotoxicological risk for organisms due to their bioavailability (Anderson et al., 2004). Heavy metals occurring in storm water are cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn) (Li et al., 2013). It is important to consider that also groundwater quality can be affected by the storm water if urban runoff is infiltrating to the soil and reaching the aquifer (Ellis, 2000).

Causes of flooding

In Sweden, flooding and high flows of water is naturally occurring, mainly during spring flood when the snowpack is melting (VA-Forsk et al., 2004). Flooding of land is a result of natural water storages, such as groundwater, streams and lakes, being filled entirely, or when precipitation exceeds the current infiltration capacity (STA, 2008a). Flooding and high flows can also occur as a result of replacing natural land with hard surfaces, creating an impervious layer where the water cannot infiltrate. This is the case in urban areas, which often consist of hard surfaces and a lack of areas capable of water infiltration or storage. The properties of the runoff system, such as flow rate and residence time, play an important role in both rural and urban areas to prevent flooding as well as contamination of recipients and adjacent areas in which the storm water drains. A number of factors affect the discharge pattern of storm water, such as frequency and volume of precipitation, topography, soil conditions, size of land use/s and structure of the catchment area (*Figure 1*) (SWWA, 2004).

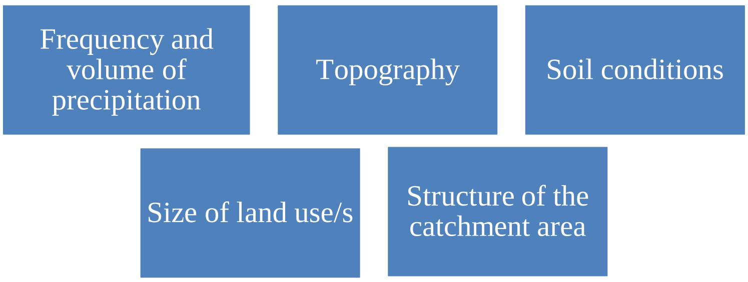

Figure 1. Factors affecting the discharge pattern of storm water.

Frequency and volume of precipitation

Since frequency and volume of precipitation affects discharge patterns of storm water, it is highly connected to storm water quality and quantity. Pollutants accumulate on the hard surfaces between precipitation events and are washed out by the runoff created by the precipitation. Of course, different precipitation intensities wash out different quantities of pollutants to the storm water. Consequently, there is a variation in pollutant concentrations and loads in storm water at different precipitation intensities and at different times of the precipitation event. For example, a very short intensive rainfall event can wash out large amounts of pollutants to the storm water system, which increases the risk of highly contaminated storm water (VA-Forsk et al., 2004). An extended still rainfall washes out only small parts of the accumulated pollutants. In addition, if two precipitation events come close to each other, independently on the precipitation intensity, it can be expected that the storm water that is created by the latter event will contain relatively small amounts of pollutants. This is due to the fact that a majority of the pollutants were washed out with the earlier precipitation event. Moreover, pollutants are much likely washed out in the beginning of a precipitation event, which results in lower pollutant concentrations in the storm water the longer the precipitation event continues.

The runoff coefficient

To reduce the risk of flooding in urban areas, design of storm water discharge should be assessed (STA, 2008a). In 2008, the Swedish Transport Administration (STA) presented equations for designing water discharge in urban land (STA, 2008a). Here, a runoff coefficient can be applied representing land use in the area. The runoff coefficient is defined as the share of precipitation that will be runoff into the storm water system after the rest of the water has infiltrated into the soil, or left through evapotranspiration by plants (STA, 2008a). Hence, a runoff coefficient of e.g. 0.85 states that 85% of the precipitation will be runoff, while the remaining 15% will be infiltrated to the soil or left through evapotranspiration. Larm et al. (2000) have defined a number of runoff coefficients for different land uses (*Table 1*). The factors mentioned in *Figure 1* highly affect the runoff coefficient and should all be considered in the design storm water treatment systems. For example, intensive rainfall events can create flooding even on green areas, areas usually considered to have good ability to infiltrate water. Further, high sloping areas causes higher runoff coefficient, independent on the land use. Also, compacted soils usually cause higher runoff than more porous soils (STA, 2008a).

Table 1. *Runoff coefficients presented as guideline values for a number of land uses, suggested by Larm in 2000. Layout modified and translated by the author (Larm and VBB VIAK, 2000)*

Land use	Runoff coefficient		
	Guideline value	Minimum	Maximum
Road	0.85	0.7	1.0
Parking	0.85	0.7	1.0
House	0.25	0.2	0.4
Terrace-house	0.32	0.3	0.5
Apartment building	0.45	0.35	0.6
Roof area	0.85	0.7	1.0
Allotment	0.2	0.1	0.5
Residence	0.35	0.3	0.5
Residence and city Centre	0.5	0.35	0.7
City Centre	0.7	0.4	0.9
Industry	0.6	0.5	0.8
Park	0.18	0	0.3
Golf course	0.18	0	0.3
Urban	0.5	0	1
Forest	0.1	0.05	0.4
Agriculture	0.11	0.1	0.3
Meadow	0.08	0	0.3
Wetland	0.2	0.1	0.4

2.3 Storm water management in the planning process

To reduce the risk of flooding in urban areas and contamination of water bodies, proper and sustainable storm water management is required. This can be accomplished most efficiently by involving storm water management in the early stage of the planning process when exploiting new areas (Stahre, 2004). A storm water management program is decided in the local plan made by municipalities (Stahre, 2004). Planning is often performed by the municipality’s management of water and sewage. The planning considers the diversion of storm water in a specific area. In Sweden, the Swedish Water & Wastewater Association (SWWA) provides guidelines and solutions for design of storm water systems for companies, governmental and nongovernmental agencies (SWWA, 2004). Discharge patterns of the storm water is a vital factor to take into account in the planning as well as the kind of exploitation that will be developed (Stahre, 2004). In the planning process, the whole runoff pattern has to be accounted for and the water should be led back to its natural flow path as soon as possible (Stahre, 2004). Here, knowledge about local hydro-meteorological variables plays an important role for the determination of e.g. frequency and amplitude of heavy rainfall (Kaczala et al., 2012). Another factor important for the implementation of a successful management program is the physicochemical characteristics of the storm water (*Figure 2*). The presence of metals and other substances should be detected and loads of respective metal and substance in the storm water runoff should be estimated (Kaczala et al., 2012).

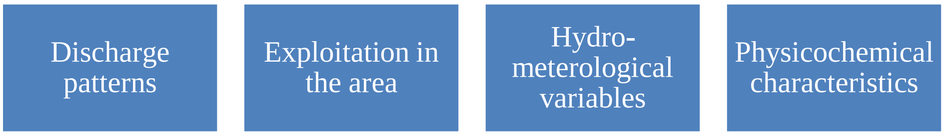

Figure 2. Factors to consider during the planning process and designing of storm water systems, in the storm water management.

Storm water modelling

Models can be used for predicting and estimating water discharge dynamics and particle loads in a storm water system (Pettersson, 1999). The complexity of a system is wide, due to large variations in climate, discharge and particle concentrations. Still, modelling conceptualizes the storm water properties and eventual environmental impacts (Kaczala et al., 2012).

StormTac is a modelling program, which can be used in the storm water management process. It is a software tool which provides information about water quantity and quality within a catchment area based on several area specific aspects adjusted in the software. Processes like water discharge, transport of particles, load, treatment and flow detention are all integrated in the model. A number of land use categories, based on scientific articles, with related runoff coefficients can be stated (StormTac, 2016a).

2.4 Storm water treatment

When reducing the amount of hard surfaces the storm water discharge is also reduced but this is often difficult to accomplish. Due to the difficulty in removing permanent hard surfaces, general guidelines for storm water management have been developed. These state that the water discharge should be handled as close to the source as possible. Further, the water that cannot infiltrate at the source should be diverted and, if transported downstream, delayed in a specially designed facility to minimize the amplitude of the storm water discharge (Stahre, 2004). Treatment takes place in every step of the storm water system. Particulate and dissolved substances are separated in different separation processes (Persson and Pettersson, 2006; Stahre, 2004). The major separation processes are particle sedimentation as well as uptake by plants (Persson and Pettersson, 2006). Sedimentation contributes with the most extensive separation of particulate compounds and is highly dependent on particle sizes, density and shape. P, in the form of different phosphates in water, forms compounds with cations and is separated from the storm water by sedimentation (Blick et al., 2004). This process also applies on heavy metals, suspended solids (SS) and organic compounds relating from vehicular traffic, such as PAHs (Polycyclic Aromatic Hydrocarbons) (Blick et al., 2004; Brinkmann, 1985). PAHs are strongly hydrophobic and therefore bound to particles (Persson and Pettersson, 2006). The degree of particle binding varies considerably among metals, where e.g. 80-90% of Pb in storm water is bound to particles while e.g. Cu can be strongly soluble (Pettersson, 1999).

The process of sedimentation in water bodies can be described by Stokes equation (*Equation 1*), which consider the force of gravity acting on particles in still waters. Here, separation, or settling velocity, is a function of the velocity of which the particles are settling as well as the residence time in water bodies (Persson and Pettersson, 2006).

$$V_S = \frac{g}{18}\left(\rho_p - \rho_w\right)\frac{d^2}{\eta} \qquad \textit{Equation 1}$$

where,
V_s = settling velocity (m/s)
g = gravity (m/s^2)
ρ_p = particle density (kg/m^3)
ρ_w = water density (kg/m^3)
d = particle diameter (m)
η = water dynamic viscosity (kg/m s)

N can be separated by sedimentation and also by denitrification. Denitrification is the process of soluble N being transformed to gaseous N and released to the atmosphere. The rate of denitrification varies in different storm water systems since it is highly connected to internal conditions in the water (Reisinger et al., 2016).

Additional separation techniques exist for remediating storm water runoff deriving from roads and industrial areas. Oil products are mostly separated from the storm water by placing oil screens at the outlet of the storm water facility (Persson and Pettersson, 2006). Filters can operate as a complement to sedimentation (Hallberg, 2008). Reactive filters can be used for separation of SS and also metals from the storm water, due to good correlation between metals and SS (Hallberg, 2008). Renman and Hallberg (2007) observed a removal of over 99% of SS when using reactive filters.

2.4.1 Storm water treatment in a series of storm water facilities

In order to achieve the required treatment capacity, it is sometimes necessary to arrange storm water systems in a series of facilities that together treat the water to the required reduction rate (Blick et al., 2004). The treatment effect of two storm water facilities in a series is considered to be higher than for a single facility with the same area or volume as the sum of two facilities (StormTac, 2016b). This relation can be explained by a simplified equation for the total suspended solids (TSS) removal rate for a pollutant after treatment in a series of two facilities, stated by Blick et.al (2004) (*Equation 2*).

$$R = A + B - [(A * B)/100] \qquad \textit{Equation 2}$$

where,
R = TSS removal rate (%)
A = TSS removal rate for the first or upstream facility (%)
B = TSS removal rate for the second or downstream facility (%)

In addition to the equation, higher treatment effect in a series of storm water facilities can be explained by good distribution of water in the entire water volume. This is of particular concern if using a dam or wetland as storm water facility, which results in more efficient sedimentation in the first dam and low outflow to the next dam. Further, low incoming water flow results in enhanced sedimentation, including sedimentation of small particles (StormTac, 2016b).

Blick et al., 2004, developed the following guidelines for arranging storm water facilities in series:

- Arrange the facilities so that the facility with the highest removal of TSS is located most downstream and the facility with the lowest removal rate of TSS is located most upstream.
- Arrange the facilities similar to the first guideline, but regarding nutrient removal, so the most downstream facility has the highest rate of nutrient removal.
- Arrange the facilities the same as the two above but for the facility's relative ease of sediment and debris removal. Here, the facility which most easy remove collected sediment and debris should be situated most upstream.

These guidelines are recommended to be applied in the above order, applying TSS removal for the facilities as the first consideration. Later on, the series of facilities is refined by the facilities' removal of nutrients and then their sediment and debris removal (Blick et al., 2004). Further, when arranging a series of storm water facilities, site conditions and the possibility for proper management and maintenance of the storm water system must be taken into account (Blick et al., 2004).

2.5 Open storm water systems

Storm water can be conducted either through closed water conduits or in open storm water systems, which basically means that the water can be observed visually (Stahre, 2004). An increase in constructing open storm water systems occurred in Sweden in the late 90’s and a need for proper design, adapted to Swedish climate, was emphasized (Larm and VBB VIAK, 2000). Knowledge about the design of a storm water system facilitates the choice of right type of system at the right place as well as the function of the system, which is beneficial for the treatment (Larm and VBB VIAK, 2000). In open storm water systems, the processes operating in separation of particles mimics natural water processes, such as infiltration, percolation and surface runoff (Larm and VBB VIAK, 2000; Stahre, 2004).

According to Stahre (2004), open storm water systems can be divided into four categories:

- Local disposal of storm water
- Slow diversion
- Delay close to the source
- Collected delay

Local disposal of storm water

Facilities that handle storm water at the source of runoff are referred to as “local disposal of storm water”, which have had an increasing trend lately (Thornell, 2013). This trend might have to do with the fact that these systems often contribute to biodiversity, by creating habitat for animals and plants. Also, there is growing awareness of the need for solving global environmental issues on a local scale (Thornell, 2013). According to SWWA (2004), storm water should be handled locally as much as possible and this should be accounted for in the exploitation process. Examples of these kinds of facilities are permeable coatings, stone fillings, grass areas, green roofs and dams (Stahre, 2004). Infiltration of storm water is the main purpose when using permeable coatings, stone fillings and grass areas. Even though this system removes redundant water, contaminants are filtered and fixed in the materials and plants which at some point have to be disposed, and proper maintenance of the treatment system is therefore required (Thornell, 2013). Rooftops can be used for handling storm water, either for water storage or uptake by plants. Water storage on roofs or in tanks have the purpose to collect water for household usage like irrigation or for flushing toilets (Stahre, 2004; Thornell, 2013). Roofs with plants, commonly called green roofs, delay the runoff through an increased infiltration of water to the vegetative layer, and is later released back to the atmosphere by evapotranspiration (Blick et al., 2004). Dams is another type of “local disposal of storm water”, often considered as an attractive element in urban areas (Stahre, 2004). Dams do not only give the adjacent area an appealing view and thus an esthetical value, but also function as a reservoir where storm water can be stored and treated at the same time (Thornell, 2013).

Slow diversion

Slow diversion of storm water in public areas consider and include meandering water such as channels, streams and ditches (Thornell, 2013). In urban areas, the facilities are often placed in street areas as ditches or channels (SWWA, 2004). These systems are characterized by functioning both as infiltration areas and transportation paths for the storm water and are of significant importance when replacing storm water conduits (Stahre, 2004; VISS, 2016). When designing the total capacity of slow diversion facilities, the area of hard surfaces contributing with storm water, maximum outflow from the facilities, as well as precipitation in the area, should be considered (SWWA, 2004).

Delay close to the source and collected delay

The two last categories of open storm water systems include “delay close to the source” and “collected delay”, and consider different types of water reservoirs. These two systems are comparable except that the “delay close to the source” system often concerns the upper parts of the catchment area while the “collected delay” systems are larger and situated at the lower part of the catchment area (Stahre, 2004). Commonly used facilities are flooding areas, grass areas, dams and wetlands (Stahre, 2004). Usually, these are two separate systems connected by a ditch or channel, which can receive water from the reservoirs when these are completely full. In these situations, the reservoirs must be provided with some kind of overflow regulation device, such as a conduit, that bypass excess water (SWWA, 2004). The reservoirs are drained either by differences in height within the dam inlet and outlet or by pumping of water (SWWA, 2004). Pumping of water is done in flat areas, and the reservoirs must be designed for the discharge that is determined for the catchment area. Also, when the flow exceeds the designed flow for the reservoir, a part of the flow has to pass the reservoir to a downstream conduit or ditch, available for receiving water, or to an adjacent recipient (SWWA, 2004). A summary of the storm water system categories, how they are related to each other and different storm water facilities within the systems are presented in *Figure 3*.

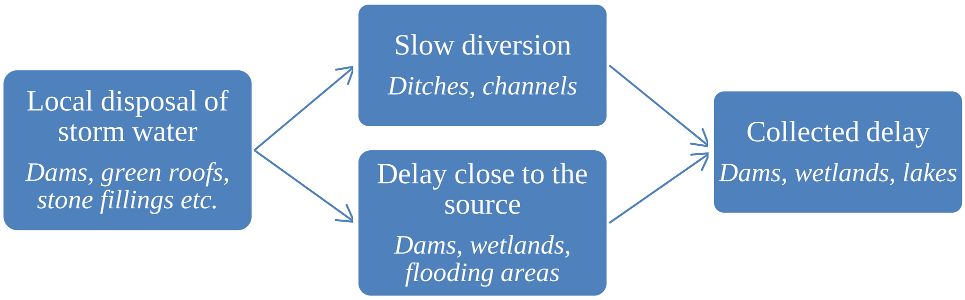

Figure 3. Open storm water systems, and respective storm water facilities for each system, and the distribution of the different systems.

2.6 Storm water dams

The interest in dams in Sweden started in the early 90's and nowadays dams are widely used for storm water treatment (Persson and Pettersson, 2006). The popularity of dams is connected to the fact that they not only work as storage of storm water but also decrease the concentration of pollutants and particles in the water. Storm water dams are considered a cost-effective method to treat contaminated storm water before reaching downstream water bodies (Pettersson, 1999). This section will discuss the treatment effect of storm water dams and factors affecting the treatment, such as design, maintenance and supervision.

2.6.1 Treatment in storm water dams

The reason for dams being efficient for storm water treatment is that the different pollutants are particulate-bound in varying degree and particles will settle to form sediment in the dam (Persson and Pettersson, 2006). For proper sedimentation of particles, low flow rates into the dam and appropriate residence time for the water in the dam are required. Here, the hydraulic efficiency is vital. The hydraulic efficiency of a dam describes its ability to distribute the water evenly, in order to use the entire volume of the dam (Pramsten, 2010). Consequently, a dam with high hydraulic efficiency evenly distributes the water over the dam, wherein treatment processes take place in the entire volume (Tonderski et al., 2002). Thus, the hydraulic efficiency of the dam strongly contributes to the treatment effect within the dam (*Figure 4*).

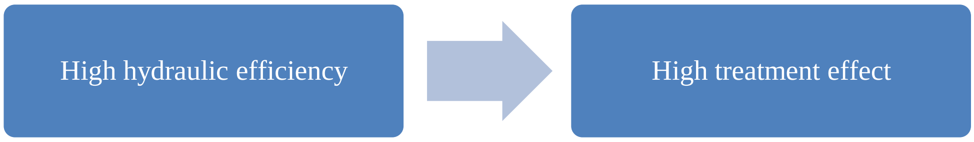

Figure 4. Relation between hydraulic efficiency and treatment effect.

A number of factors affect the hydraulic efficiency and have to be considered for an efficient treatment of storm water in dams. Factors constant over time like size of the dam in relation to its catchment area, dam location in the catchment area and design of the dam have to be considered. This also regards factors varying over time like pH, water discharge, DO-level and vegetation (*Figure 5*) (Li et al., 2013; Persson and Pettersson, 2006; Pramsten, 2010).

Factors varying over time	Factors constant over time
• pH • Water discharge • DO • Vegetation	• Size of the dam in relation to its catchment area • Dam location in the catchment area • Dam design

Figure 5. Factors, varying over time and constant over time, affecting the treatment effect in a storm water dam.

Factors varying over time

pH controls the solubility of many substances and influences many biochemical transformations, while DO is vital for growth of vegetation in the dam system (Kadlec and Knight, 1996; Li et al., 2013). Growth of vegetation is good for treatment in the dams since plant constituents reduce the water flow rate and thereby increase sedimentation of particles. An additional effect on the treatment in storm water dams is a cold climate, which contributes with annual changes in water discharge patterns. The spring flood contribute with large water volumes, partly washing out the sediments and particles, which is usually followed by long periods with dry conditions (VA-Forsk et al., 2004). Also, during winter when the dam surface is covered by ice, a reduction of aeration in the dams occurs since the mixing of surface water and deeper water columns is low.

DO, pH and release rates

Anaerobic conditions are required for denitrification to occur, where denitrifying bacteria transform N from dissolved to gaseous phase (WRS AB, 2013). Anaerobic conditions also cause P to be released from the bottom sediment to the water, and thus be resuspended in the water column. When it comes to metals, the release rates of Cr, Cu, Pb and Zn are enhanced during aerobic conditions (Li et al., 2013). Some heavy metals are highly mobile and bioavailable. This does not regard Cr and Pb, which can be described by their low presence in residual sediments (Wu et al., 2016).

The release rates of heavy metals are larger in low pH than in high pH conditions (Li et al., 2013). Heavy metal concentrations in storm water dams vary in different flow rates, due to the good correlation between metal release and pH-value. pH and flow rate covary due to the fact that a high flow rate dilutes the acidity in the water and thus increases the pH value (Li et al., 2013). The mean SS concentration is to a large extent coupled with removal of metals and nutrients as their particulate-bound parts attach to SS (Hallberg, 2008; Pramsten, 2010). Hence, the mean concentration of SS in the incoming flow to a dam is vital for sedimentation of particles (Pramsten, 2010).

Factors constant over time

The design of a storm water dam is critical for an efficient treatment of storm water. Several dam properties affect the sedimentation, and hence the hydraulic efficiency and treatment effect of a storm water dam. In the construction of storm water dams, dead zones or recirculation zones should be avoided. These zones decrease the area and volume for effective treatment (Pettersson, 1999). Since treatment occurs as water is delayed in a storm water dam between rainfall events, storm water dams should be constructed so that the dam can retain as large part of the rainfall water as possible (Pramsten, 2010). Also, the dam location in a catchment area is important for a reduced risk of flooding and to diminish high-peak flows from the area since dams have the capacity to retain water (Hagelin, 2015).

Dam design

When designing a storm water dam, vegetation, topography, placement of inlet and outlet, as well as depth of the dam and the relation between dam length and width should be considered. The layout of a dam inlet regulates the distribution of the incoming water to a dam, which affects erosion and resuspension of sediment in the dam. An inlet can consist of different types of conduit pipes, overflows, water courses or flooding surfaces (Tonderski et al., 2002). The dam outlet regulates the water level within the dam, the water outlet as well as the water storage capacity (Tonderski et al., 2002). An outlet can consist of the same types of conduit pipes and overflow etc. as an inlet. The dam outlet should be constructed to retain rainfall water between rainfall events (Persson, 1998). Further, both inlet and outlet of a dam can supply the water with oxygen (Tonderski et al., 2002). This is because the water surface layer, where absorption of oxygen occurs, is mixed with underlying water columns. A high hydraulic efficiency of a dam is achieved by constructing a long and narrow dam with inlet and outlet at each short side (VA-Forsk et al., 2004). Moreover, at the inlet of the dam, there should be a deep area going across the water flow for decreasing flow rate and favored conditions for sedimentation (Tonderski et al., 2002).

Specific dam area and effective dam volume

The specific dam area, defined as dam area (m^2) divided by reduced catchment area (ha_{red}) (Pettersson, 1999), affects the removal of pollutants. The reduced catchment area is the part of the catchment area that contribute with runoff. In a study by Persson and Pettersson (2006) the optimal specific dam area is approximately 200-250 m^2/ha_{red}. In specific dam areas larger than 250 m^2/ha_{red} the increased removal of pollutants is significant (Pettersson, 1999). The specific effective permanent dam volume (m^3/ha_{red}), principally follows the specific dam area and can also be used to determine the approximate pollutant removal efficiency of a dam (Pramsten, 2010; Tonderski et al., 2002). It is defined as permanent dam volume and average runoff volume, where the permanent dam volume is the total water volume that can be retained in a dam between precipitation events (Pramsten, 2010). It has been proved that the dam's ability to remove pollutants increases with increasing dam volume until a specific effective permanent dam volume of ca 50 m^3/ha_{red} is reached (Pramsten, 2010).

A summary of the factors affecting the treatment effect of storm water in storm water dams and their connection are in *Figure 6*.

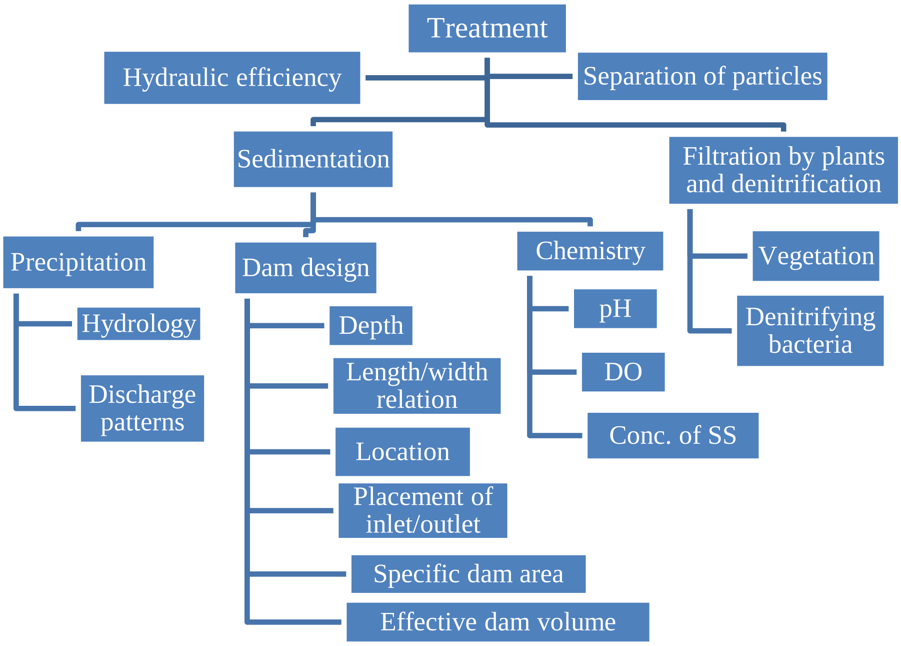

Figure 6. Summary of factors, and relation between them, that affects the treatment of storm water in a storm water dam.

2.6.2 Monitoring storm water dams

The efficiency of storm water treatment in dams can be investigated by monitoring. Monitoring should be performed after or during numerous successive rain events, and thus examining the dam's ability to separate particles from the storm water (Persson and Pettersson, 2006). More reliable results will be achieved the more continuous rain events that are included in the sampling. Monitoring of water in dams can be performed in different ways, and three common methods are:

- Random sampling
- Timed sampling
- Flow proportional sampling

Random and timed sampling

Random sampling is when samples are monitored randomly in the dam, without regard to any particular factor. Timed sampling is when samples are taken near the dam inlet and at the dam outlet after a specific set time. These methods are based on the assumption that there is a constant and continuous flow of storm water within the dam and that the separation of particles occurs during the residence time of storm water. The separation is calculated as the difference in particle concentration between the dam inflow and outlet (Persson and Pettersson, 2006). However, these methods are most suitable for facilities with constant and continuous flow, not very useful in common dams which usually have no or very low inflow (Persson and Pettersson, 2006). Also, lower concentrations are often observed with random and timed sampling due to the fact that large storm water flows, containing the highest pollutant concentrations, are easily missed[1].

Flow proportional sampling

The flow proportional sampling is when a certain volume of water is sampled when a certain amount of water has passed a certain point in the system (Andersson et al., 2012). Practically, the inlet and outlet are continuously sampled during a flow proportional sampling event, meaning that sampling frequency is proportional to flow volume (Arnlund et al., 2014). I.e. if the inflow increases, samples will be taken more frequently and vice versa. The results then represent the particle concentrations for the total water volume sampled during the set sampling period and is presented as flow based mean concentrations for the water that has passed the dam (Arnlund et al., 2014). Flow proportional sampling is rather time consuming and

[1] Telephone conversation with Thomas Larm, founder of the storm water software StormTac, February 8, 2017.

weather dependent, but highly recommended for determining the separation efficiency in storm water dams (Andersson et al., 2012; WRS AB and Naturvatten i Roslagen AB, 2013).

Comparison of the methods

Flow proportional sampling takes large water flows into account, and therefore also the variation of pollutant concentrations in the storm water. This is something that random and timed sampling might not detect. Since pollutant concentrations in storm water usually varies considerably over time, flow proportional sampling of storm water is favorable[1] (Pramsten, 2010). According to Persson and Pettersson (2006), random sampling in storm water dams is used to a large extent in Sweden, resulting in inadequate samplings, which should be improved.

Sediment sampling

Another type of sampling for estimating treatment effect in storm water dams is to take sediment samples. By analyzing dam sediments, the characterization of pollutant loads from a catchment area can be concluded (German and Svensson, 2002). Sediment samples can work as supplement to random and timed sampled water samples, and comparisons between pollution concentrations in the samples can be made (Andersson et al., 2012). Further, rough estimations of pollutant loads, treated in the dam, can be concluded. Sediment sampling require little work effort and costs, especially when comparing it with flow proportional sampling. Therefore, it is considered a sampling methodology that should be evaluated further (Andersson et al., 2012).

2.6.3 Maintaining storm water dams

Several components are necessary for an efficient storm water treatment in dams, and all should be included at the early stage of storm water management planning. A clearly defined description of to what extent a storm water dam should be maintained, and by whom, must be included in maintenance plans (SWWA, 2011). Also, proper and continuous maintenance must be taken into consideration. Maintenance activities include removal or addition of sediments and vegetation, repairing erosion damages and control of various facilities connected to the dams (*Figure 7*). By following these guidelines, management will efficiently keep costs to a minimum (Sustainable Stormwater Management, 2009).

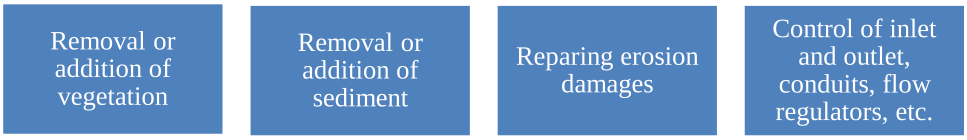

Figure 7. Basic maintenance practices for storm water dams.

The need for maintenance in storm water dams is low during winter and largest during the growing season, from March to October, which also is considered as the maintenance season (WRS AB, 2013). However, some kind of supervision during winter is of importance due to possible clogging of outlet conduits. It is particularly important to visit the dam at the beginning of the spring flood when high flows can worsen earlier damages in the system (WRS AB, 2013). It is common that municipalities, responsible for the maintenance, develop routine instructions for the supervision.

Removal or addition of vegetation

In 2013, WRS Uppsala AB released a manual for maintaining storm water dams and adjacent areas connected to the dams (WRS AB, 2013). Of course, the purpose of the dam is vital for what kind of maintenance that is required. In deep dams, deeper than 0.6 m, functioning as sedimentation dams, removal of vegetation is of importance (WRS AB, 2013). Too much vegetation increases the risk of flooding in adjacent areas and the formation of channels with increased water flow velocity within the dam (WRS AB, 2013). Still, the dam must contain vegetation for uptake of particles by plants and for reduction of water flow (WRS AB, 2013). For low impact on the fauna living in the dam, the removal of vegetation should not be performed earlier than late June. Also, it is recommended to use a method with low stirring of sediment particles so that the pollutants continue to stay trapped in the dam (WRS AB, 2013). Shallow areas (<0.6 m) in dams need intensive and continuous maintenance during the season due to the large growth of vegetation, especially occurring along the shore. Here, vegetation creating dense carpets functioning as filters, where the particles can filter and deposit, is desired (WRS AB, 2013). Vegetation should be harvested during autumn, before wilting and depositing on the dam bottom and supplying nutrients to the dam and downstream recipient (SWWA, 2011). Dams with continuous algae blooms can be handled by for example circulating the water using a pump or oxygenating the water by installing a fountain in the dam, preventing algae blooming (SWWA, 2011).

Removal or addition of sediment

Removal of sediment is also vital for proper treatment in dams functioning as sedimentation dams. STA brought forth a guide with recommendations for maintenance of storm water dams close to roads (STA, 2008b). Sediment removal in storm water dams is required when the sediment thickness exceeds 30 cm or when the primary water volume is half the amount (STA, 2008b). This thickness is considered to be reached after a five to ten-year interval, hence sediment removal should occur within that time span (WRS AB et al., 2016). However, the pollutant concentrations within the sediment decide time of sediment removal and monitoring and analysis is vital. The risk of inadequate sediment removal is that the sediment interferes with other functions in the dam and that pollutants are passing the dam outlet (STA, 2008b). In this process, stirring of sediments should be minimized to maintain low water turbidity (SWWA, 2011).

Other maintenance practices

Supervision of facilities connected to dams, such as pipes and manholes, is of great importance for an efficient function of a storm water dam. Control of conduit pipes, weirs and other facilities functioning as flow regulators, should be done for securing a permanent flow (SWWA, 2011). Gravel and sludge should be removed from manholes, conduits and grids, and the oil separator must be emptied several times per year. The dam walls should be controlled and repaired regarding possible erosion damages (SWWA, 2011). Areas adjacent to the storm water dam have different maintenance depending on the surroundings. Some areas are important for recreation while other function as habitat for animals and plants. In recreation areas, a clean and well-managed dam area is vital and the maintenance includes removal of garbage, grass cutting etc. continuously during the entire growing season (WRS AB, 2013).

2.7 The storm water model StormTac

StormTac is a commonly used software tool in Sweden for modelling of pollutant concentrations, loads and treatment in open storm water systems (*Figure 8*) (Arnlund et al., 2014). It was developed in Excel and Visual Basic by Thomas Larm at SWECO VIAK and is used for planning and evaluating storm water systems (Larm and VBB VIAK, 2000).

The model has been calibrated by data from Swedish storm water systems, and also from systems in other countries. It is based on the latest scientific findings within the research area and is updated regularly (StormTac, 2016c). Variables included in the updates are climate factors, rain intensity data, factors included in estimating treatment in storm water facilities and standard pollutant concentrations for different land uses (StormTac, 2016c). The model includes data bases with precipitation data, runoff coefficients, concentrations and treatment efficiencies (Larm and VBB VIAK, 2000).

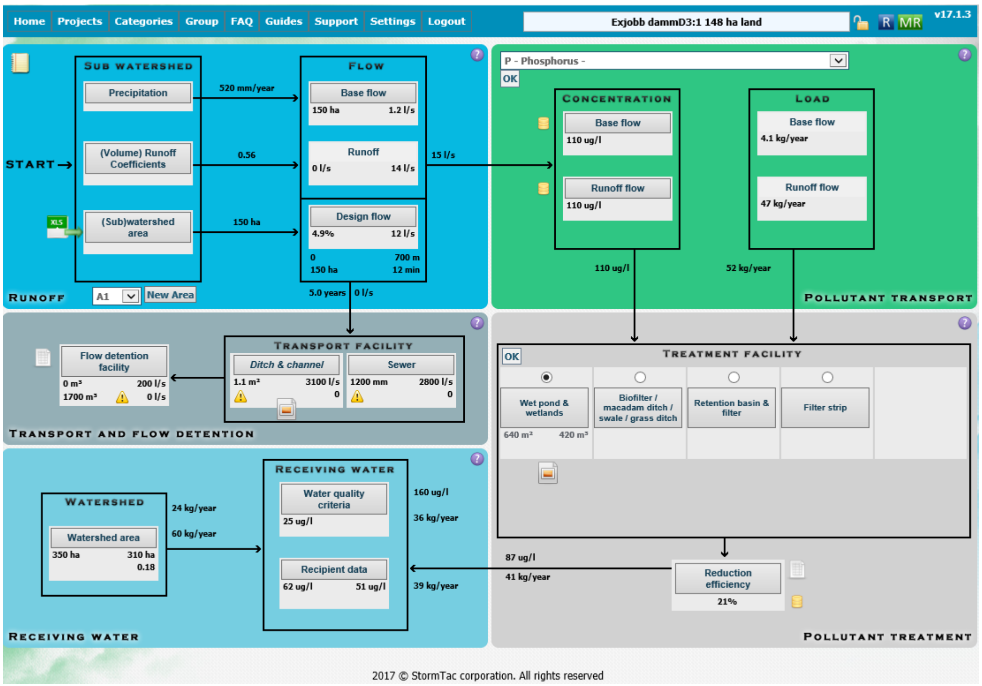

Figure 8. Print screen over the storm water software StormTac.

Input data required in the model is precipitation data and areas per land use within the total catchment area. Land uses consider both rural and urban land and around 80 land use templates are available (StormTac, 2016a). In addition, around 80 pollutants, with a majority originating from the WFD, are included in the model (StormTac, 2016a). Both the storm water and baseflow have standard concentrations for the different pollutants. These values have been estimated empirically from flow proportionally monitored sampling data (Larm and VBB VIAK, 2000; StormTac, 2016a). The model is especially well-suited for long-term predictions since it generates annual mean values of precipitation, water discharge, concentrations and loads (Larm and VBB VIAK, 2000). Monthly variations of substance concentrations in storm water are in the database, for spring, winter, summer and autumn.

Treatment in a storm water system, including different storm water facilities, can be generated in the model in order to monitor transportation of pollutants. A series of storm water facilities can be added in the model, for which treatment is calculated (StormTac, 2016b). This particularly concerns a series of facilities like dams and wetlands, where it is taken into account that the reduced pollutant concentration from the first dam/wetland decrease the treatment effect in the following dam/wetland (StormTac, 2016b). This is given by *Equation 3*, which describes the total treatment effect for two facilities in a series (StormTac, 2016b). It is based on equation from (Blick et al., 2004) (*Equation 2*).

$$RE=RE_1+RE_2-(RE_1*RE_2*0.01) \qquad \textit{Equation 3}$$

where,
RE = Total treatment effect for two facilities in a series (%)
RE_1 = Treatment in facility number 1; the first facility in the series (%)
RE_2 = Treatment in facility number 2; the second facility in the series (%)

The fact that treatment with two facilities in a series is higher than for only one facility, even though the total area or volume is the same for them, is also given by the empirical relation between the specific dam area or the specific effective dam volume and treatment effect (StormTac, 2016b). To calculate the treatment effect for three facilities, the above equation is repeated (StormTac, 2016b). Hence, the result from the first two facilities is "RE_1" and the third facility is "RE_2".

Earlier studies

In an earlier study, StormTac was evaluated with monitored data from flow proportional sampling in order to investigate if the results from the flow proportional sampled data were consistent and comparable (Arnlund et al., 2014). Here, the monitored data was consistent with the substances that had standard concentrations which were based on certain data, while the opposite was observed for substances with standard concentrations based on more uncertain data (Arnlund et al., 2014).

Further, other studies have used StormTac in order to evaluate presence of pollutants in a catchment area and possible impact on recipients (Feltelius, 2015; Lindqvist, 2011). One of these storm water investigations focused on providing better knowledge on pollutants in catchment areas and recipients in the municipality of Sundbyberg. Here, identification of major sources of pollution in the different catchment areas was performed in StormTac (Lindqvist, 2011). The study was based on the standard concentrations in StormTac and no monitored data was used. The other storm water investigation studied the treatment effect for a storm water dam was evaluated and measures for achieving the required treatment effect were suggested by using StormTac (Feltelius, 2015). Both investigations concluded that in order to obtain as correct pollution loads as possible from a catchment area and to use the modelled results as basis, it is recommended that monitored data is used with the standard concentrations in StormTac and that proper and more input data is required in the model (Feltelius, 2015; Lindqvist, 2011).

3 Material and methods

This section provides a description of the author's research. The first part describes the study area and the storm water system in Rosersberg together with its maintenance and monitoring programs. In the second part, the approach for calculations and modelling of loads as well as applications of sediment samples are presented.

3.1 Site description

The storm water system that has been the subject of this study is situated within and south of an industrial area in Rosersberg, Sigtuna municipality, Stockholm County (*Figure 9*).

Figure 9. Orthophoto showing the industrial area in Rosersberg situated within the red line. Modified by the author and derived from SLU:s Geodata Extraction Tool ©Lantmäteriet (Lantmäteriet, 2017).

The area has a mean annual temperature of 8°C, a mean annual precipitation of 525-600 mm and an annual runoff of 100-200 mm (SMHI, 2015a, 2015b, 2017). The area is characterized by presence of bedrock in the surface between soils like sandy moraine, postglacial clay and glacial clay (*Figure 10*).

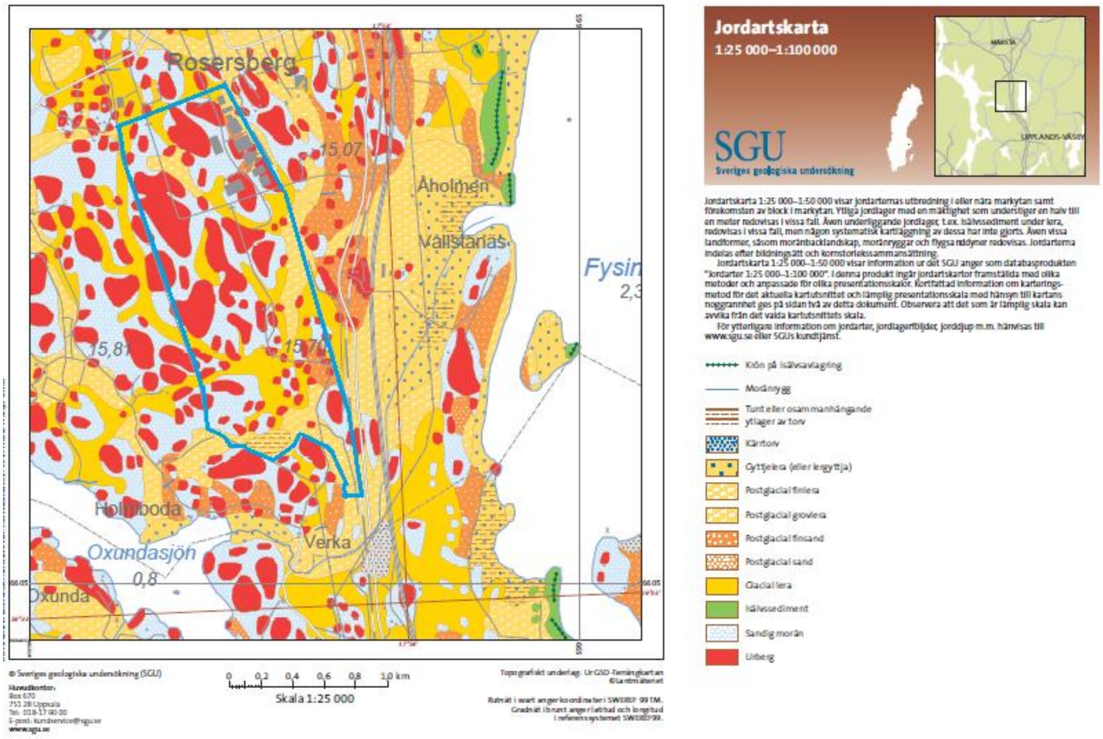

Figure 10. Soil map showing soils in or near the surface of the ground for the industrial area (located within the blue line) and surroundings. Red parts are bedrock, light blue areas are sandy moraine and yellow areas clay. Modified by the author and derived from SGU:s map generator ©SGU (SGU, 2017).

According to the local plan, the area is projected for exploitation by construction of buildings and industries, mainly for storage businesses (Sigtuna Municipality, 2007). The company Kilenkrysset AB started exploiting this area in the early 00's and has continued since then[2]. The industrial area is situated in the main runoff basin Norrström and sub-basin of stream Oxundaån and stream Verkaån (*Figure 11*).

[2] Meeting with Agneta Holm and Björn Johansson, Sigtuna Municipality, January 18, 2017.

Figure 11. Map showing Verkaån (red line), industrial area (within purple line), outlet of the storm water system to Verkaån (yellow dot) and the sub-basin of Verkaån situated within the blue line. Modified by the author (WRS AB and Naturvatten i Roslagen AB, 2013).

The storm water recipients of the area are stream Verkaån, lake Oxundasjön and stream Oxundaån, which flows into lake Mälaren (Sigtuna Municipality, 2012; VISS, 2017). The area is hilly with elevation differences from +4 m in the south close to Verkaån to +33 m on elevation tops (Sigtuna Municipality, 2012). The Verkaån sub-basin has a size of 492 ha and is highly affected by surrounding activities (WSP Environment, 2012a). Stream Verkaån has a length of 3.4 km and connects lake Fysingen with the downstream lake Oxundasjön (*Figure 9* and *Figure 11*) (VISS, 2017). The height difference between the lakes is 1 m (WRS AB and Naturvatten i Roslagen AB, 2013). Between the exploited area and stream Verkaån, the land is maintained and used for parts of the storm water system. In 2013, a compilation of the land use categories, impacting on the sub-basin of Verkaån in 2010, was listed by WRS Uppsala AB and Naturvatten i Roslagen AB (WRS AB and

Naturvatten i Roslagen AB, 2013). A total of fifteen land use categories were introduced together with their sizes, share of total area and runoff coefficient (*Table 2*). The dominating land uses were agricultural land and forests, representing 60% of the total area, while industry and streets represented approximately 20% of the area (WRS AB and Naturvatten i Roslagen AB, 2013).

Table 2. *Land use categories, with respective runoff coefficient, in the sub-basin of Verkaån in 2010. Layout modified and translated by the author (WRS AB and Naturvatten i Roslagen AB, 2013)*

Land use	Area (ha)	% of total area	Runoff coefficient
Road (max. 1,000 vehicles per day)	7.8	1.6	0.85
Road (~32,000 vehicles per day)	9.8	2.0	0.85
Private properties	5.8	1.2	0.2
Industrial area	72	14.5	0.6
Service area (gas station, restaurant, parking)	3.1	0.6	0.6
Water surfaces	4.6	0.9	1
Forest	162	33	0.05
Agriculture	149	30	0.26
Meadow	51	10	0.075
Railway	16	3.3	0.5
Horse farm	12	2.5	0.15
SUM	**492**	**100**	-

3.2 Stream Verkaån

Verkaån is highly-valued regarding nature conservation and is considered one of the three most valuable surface waters in Stockholm County (Sigtuna Municipality, 2007). The stream's presence of beaver, utter and asp, which all are included in the red list of threatened species, as well as benthos contribute to the river's signification (Sigtuna Municipality, 2007; WSP Environment, 2009a). In the local plan from 2007, it is stated that the flora and wildlife close to Verkaån should not be influenced by local disposal of storm water (Sigtuna Municipality, 2007). The stream has an annual average water flow of 0.7 m^3/s (WSP Environment, 2009a).

Ecological and chemical status

Since 2000, the EU decided that all water bodies in Europe must achieve good ecological and chemical status by year 2021 (Swedish Agency for Marine and Water Management, 2016). Of course, this also includes Verkaån and measurements on its status are pursued. In 2009, the starting year of the storm water system, the stream had good ecological and chemical status (WSP Environment, 2012a). When looking at the classification for 2016, the ecological status is moderate and the chemical status is not good (VISS, 2017). There is a risk for not achieving good ecological and chemical status until 2021 (VISS, 2017). The risk is connected to hydro-morphological quality elements, such as changes in continuity and habitat, and environmental toxins from point sources (VISS, 2017). It is also a result of upgraded classification standards to include more chemical compounds than previous years[3].

Impact from the industrial area

Due to an increasing exploitation in the industrial area, the replacement of bare land to hard surfaces influences the discharge pattern (Sigtuna Municipality, 2012). This has resulted in enhanced storm water runoff from the industrial area to Verkaån. Further, the runoff is contaminated by traffic and industry activities (Sigtuna Municipality, 2007). The risk for the industrial area contaminating Verkaån was already brought up in the local plan from 2007. Pollutions from chemical management and vehicles in the area were noted as severe threats against Verkaån ecological and chemical statuses (Sigtuna Municipality, 2007). In 2016, the industrial area's impact on Verkaån was evaluated. According to that evaluation, the low flow within the storm water system results in low addition of pollutants to Verkaån (WSP Environment, 2016a). However, the industrial area has been further exploited, which might have larger impact on Verkaån (WSP Environment, 2016a). Therefore, areas suitable for water reservoirs and other storm water systems need to be secured for possible future constructions within the catchment area (WRS AB and Naturvatten i Roslagen AB, 2013).

3.3 Storm water system Rosersberg

The storm water system in Rosersberg is located within two adjacent local plan areas which both require local disposal of storm water for each property in the area (Ramböll, 2011; Sigtuna Municipality, 2007). The system consists of pipes, ditches, dams and storage for detention. The storm water flow within the system is designed according to recommendations in publication P90 by SWWA in 2004, which was the contemporary guide for designing of storm water flow (Sigtuna Municipality, 2012). The construction of the system was funded by the developer, Rosersbergs Exploatering AB, while Sigtuna municipality is the owner of the storm water system and covers operation and maintenance costs (Dagvattenguiden, 2016). It is a multistep system built up by several dams with the purpose to treat and delay the storm water. The dams are also important for biodiversity as well as recreation (Sigtuna Municipality, 2012). No infiltration of storm water, deriving from hard surfaces in

[3] Meeting with Agneta Holm and Björn Johansson, Sigtuna Municipality, January 18, 2017.

the area, is allowed where the soil consists of sand and where there is a risk of polluting adjacent water bodies (WSP Environment, 2010a). Here, the soil should be covered with hard surfaces so that the storm water is drained from the area.

The storm water system is designed to manage storm water from an area of 124.2 ha (*Figure 12*) (Dagvattenguiden, 2016). Land use in the area is industrial area (Sigtuna Water and Sanitation, 2015a, 2015b, 2015c).

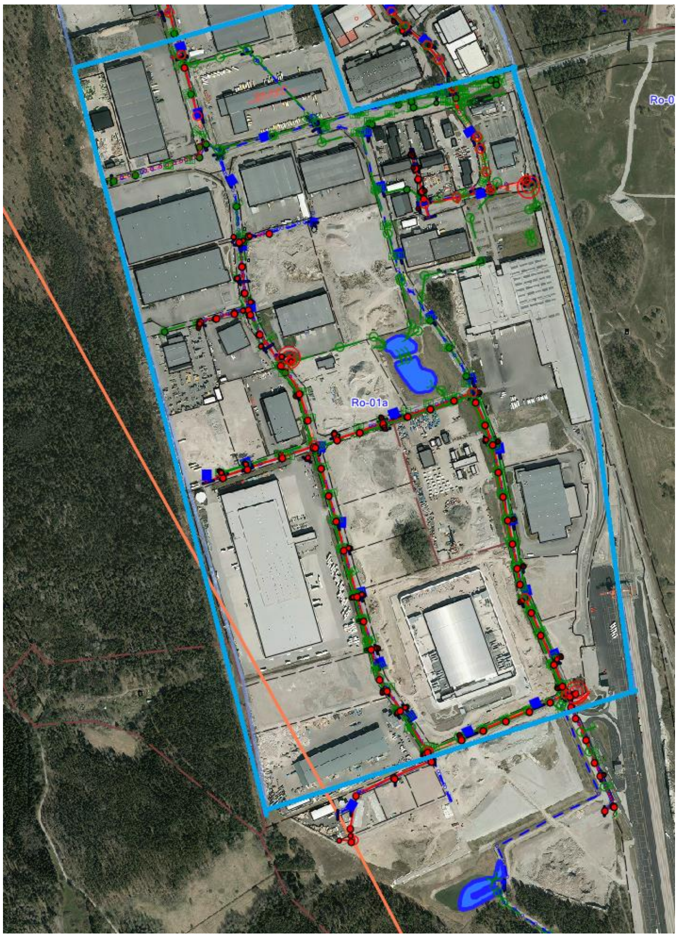

Figure 12. The catchment area for the storm water system with a size of 124.2 ha, located within the light blue line, and with water conduits (green and red lines) Modified by the author (Sigtuna Water and Sanitation, 2017).

The runoff coefficient has been limited to 0.6 per facility (Sigtuna Municipality, 2012, 2007). This means that a maximum of 60% of the precipitation within the area is allowed in the storm water system, while the remaining 40% must be infiltrated locally. The runoff coefficient was of great importance when designing the storm water system. Especially so that the increased storm water outflow to stream

Verkaån is managed in a way which reflects the natural runoff from the area (Sigtuna Municipality, 2007). Also, the runoff coefficient of 0.6 has to be followed in further exploitation within the area.

The system was constructed in 2008 to 2009 and it is characterized by a slow drainage pattern (Ramböll, 2011). It consists of two large dams within and a bit south of the industrial area, ditches with macadam in the street sections, a subsurface conduit, three small dams further south of the area and an outlet to Verkaån (*Figure 13*) (WSP Environment, 2009). The large dams are designed to delay, treat and receive the storm water and have a regulating height of 0.5 m (Dagvattenguiden, 2016). A total volume of 15,000 m^3 can be delayed in the system, where 13,500 m^3 is managed in the dams and 1,500 m^3 in the ditches (Dagvattenguiden, 2016). Excess storm water is led from the properties to the storm water dams through a conduit along the streets of the industrial area (Ramböll, 2011). The storm water passes two large dams in the industrial area and the subsurface conduit before going through the three small dams and finally reaching the outlet to Verkaån (WSP Environment, 2016a). In this area, delaying of water is very high in order to prevent a high flow to Verkaån causing turbidity and disturbing the spawning-ground for the asp.

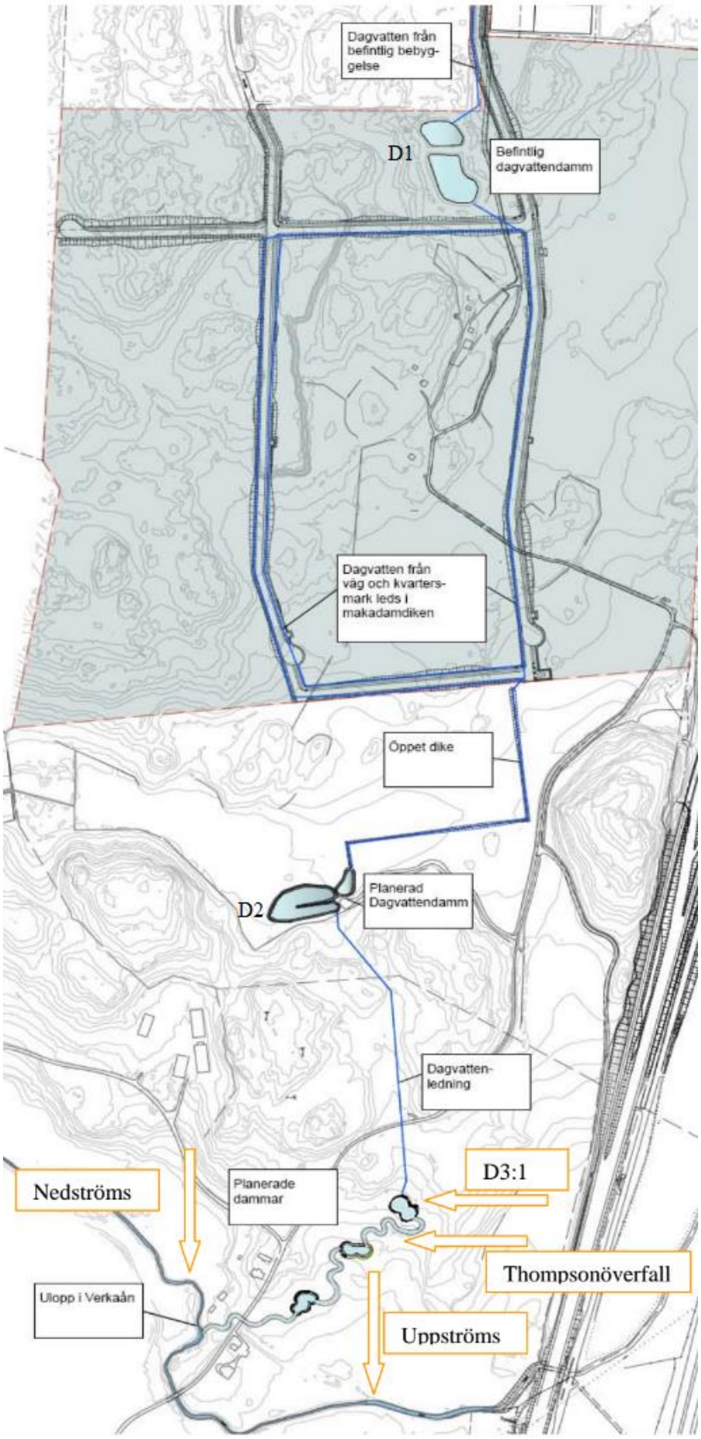

Figure 13. Design of the storm water system in Rosersberg with the different dams referred to as D1, D2 and D3 (1-3). The arrows point at locations for sampling, where the sampling point "Nedströms" is located downstream the outlet, "Uppströms" is located upstream the outlet and sampling points "Thompsonöverfall" and "D3:1" are located within the storm water system (WSP Environment, 2009a).

3.3.1 Storm water dams

Titandammen (D1) and Järndammen (D2) are the two large dams located within and south of the industrial area (*Figure 13*). Both have an installed oil separator and surrounding areas are slopes covered with vegetation for handling possible flooding (Dagvattenguiden, 2016). The three small dams, Verkadammarna (D3: 1-3), have the purpose to delay the water flow and thus minimize the flow peaks (*Figure 13*).

Dam D1

Dam D1 is designed to treat and delay the storm water within a 50.9 ha industrial area called Ro01a, which is a part of the total catchment area (*Figure 14*) (Sigtuna Water and Sanitation, 2015b). The dam has five inlets, consisting of concrete culverts with grids (WRS AB et al., 2016). It is divided into two parts by an oil separator and a dike shaped permeable wall consisting of macadam with submerged pipes to delay the flow (Dagvattenguiden, 2016). The pre-dam and following dam have an area of 2,006 m^2 and 3,746 m^2 respectively (Dagvattenguiden, 2016). Storm water treatment in the dam consists of separation of particles through sedimentation as well as oil uptake by the separator and uptake by plants within and in the surrounding area.

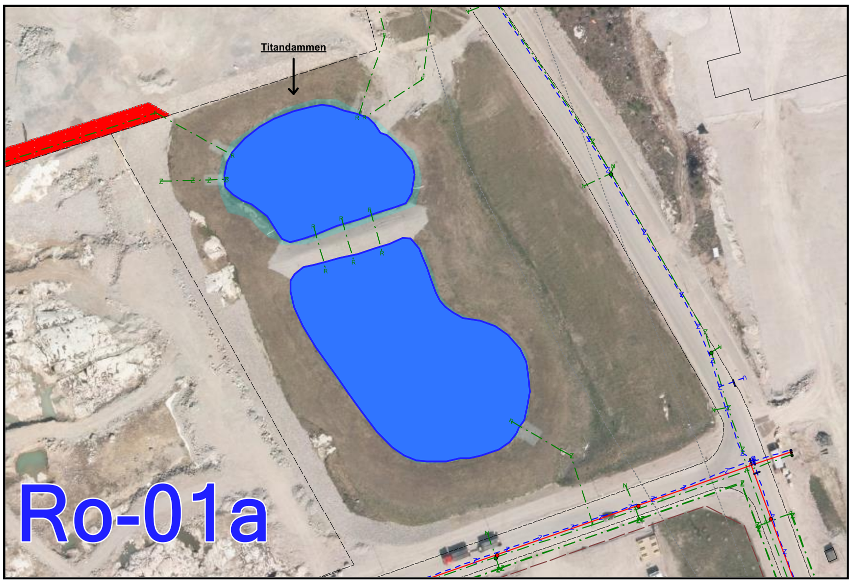

Figure 14. Dam D1 situated within the industrial area, with a wall of macadam separating the dam into two parts. The green dashed lines represent the storm water flow paths (Sigtuna Water and Sanitation, 2015b).

Dam D2

Dam D1 is connected to a downstream open ditch which leads storm water to dam D2. Dam D2 receives storm water from a catchment area, referred to as Ro01

(*Figure 15*). Ro01 is the total catchment area for the storm water system of 124.2 ha, in which the catchment area for dam D1 is included (Sigtuna Water and Sanitation, 2015c). Due to the slow drainage pattern in the catchment area, it takes time for the storm water to reach dam D2 (Ramböll, 2011). Dam D2 is divided into two parts by an oil separator and a macadam wall (*Figure 15*) (Dagvattenguiden, 2016). Macadam also covers the surrounding sloping surfaces of the dam for delaying storm water and prevent flooding. To increase distance between inlet and outlet a wall was constructed in the dam in order to guide the water through the entire dam area (Dagvattenguiden, 2016).

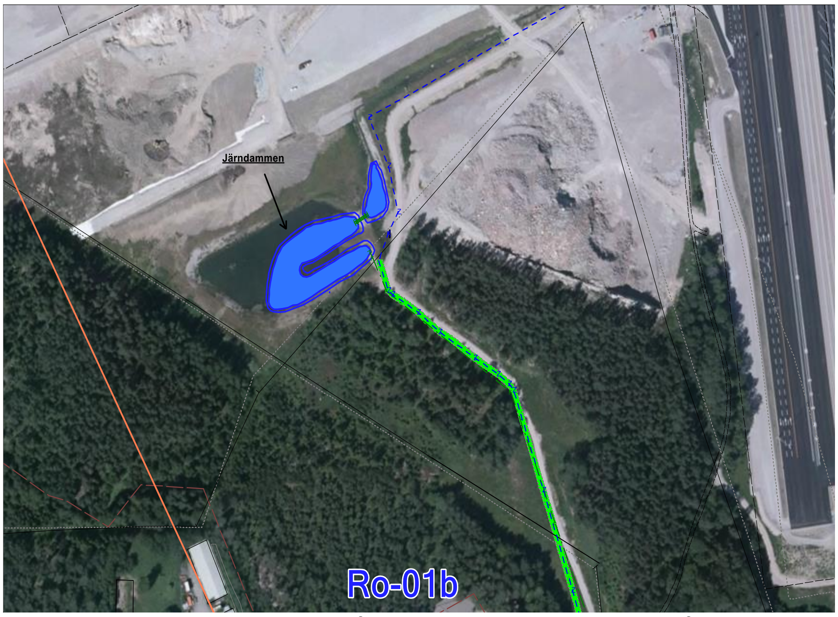

Figure 15. Dam D2 situated south of the industrial area, with a wall of macadam separating the dam into two parts. The blue dashed line represents the ditch transporting storm water from dam D1 to dam D2. The green dashed line represents the subsurface conduit leading the water to dam D3:1 (Sigtuna Water and Sanitation, 2015c).

After passing the outlet of dam D2, the storm water is lead to the D3 dams through a subsurface conduit. The polypropylene (PP) conduit has a diameter of 400 mm and it is going through bedrock at a depth of maximum 6-7 m. The maximum flow capacity of 225 l/s is considered low, due to the requirement of low inflows to Verkaån. However, high pressure has deformed the conduit and reinforcement by fiberglass plastic within the conduit is needed for proper functioning (Ramböll, 2011). The outlet from dam D2 is submerged and contains a spillway. The water level and normal outlet is regulated by a hole, with a diameter of 252 mm, inside the spillway (Ramböll, 2011).

The D3 dams

The D3 dams are located furthest downstream in the storm water system and are made up by three small dams (*Figure 16*). These dams were constructed to obtain as little and as clean water as possible reaching Verkaån (Lundkvist, 2017). The dams are connected by a meandering creek containing stone pebbles. The outflow from the entire storm water system to stream Verkaån is connected by a meandering ditch, which also includes stones for slowing down the water flow.

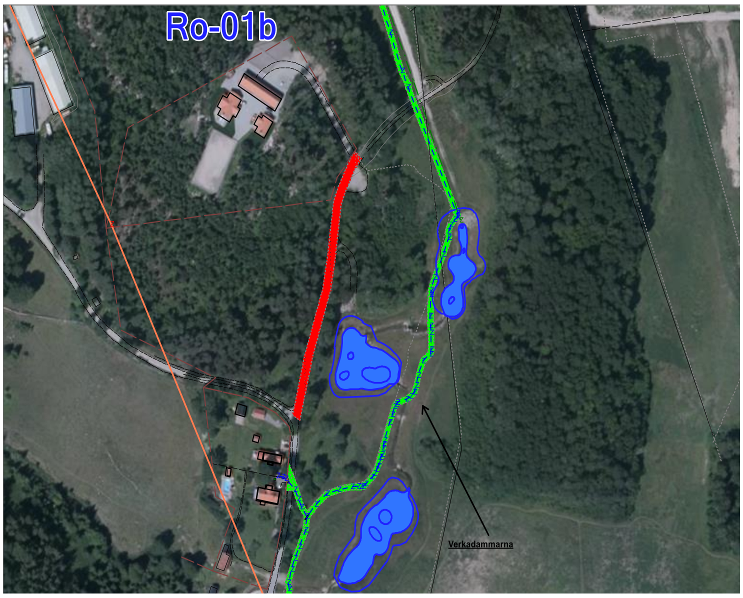

Figure 16. The D3 dams are situated south of dam D2 and connected by meandering ditches (blue/green dashed lines). The green dashed line represents the subsurface conduit leading the water from dam D2 to the D3 dams (Sigtuna Water and Sanitation, 2015a).

The outflow from the first dam (D3:1) passes a Thompson weir, which is a V-shaped concrete outlet used for simplified sampling and flow estimation (*Figure 17*) (Dagvattenguiden, 2016). Between the second (D3:2) and third (D3:3) dam, the outlet consists of a pave stone weir. The dams are constructed to handle storm water deriving from the same catchment area as for dam D2, the 124.2 ha industrial area (Sigtuna Water and Sanitation, 2015a).


Figure 17. Thompson weir and outlet of dam D3:1 to dam D3:2 (Picture taken 5th of April 2017).

Specific dam properties for each dam in the storm water system can be found in *Table 3*, where the reduced catchment area (ha_{red}) is defined as runoff coefficient multiplied by the catchment area (ha) for the dam.

Table 3. *Compilation of properties of dams included in the storm water system in Rosersberg (Dagvattenguiden, 2016; Ramböll, 2011)*

Dam	Area (m^2)	Depth (m)	Outflow (normal & max.) (l/s)	Catchment area	Catchment area (ha)	Reduced catchment area (ha_{red})	Land use in catchment area
D1	5,750	1.5	175 & 800	Ro01a	50.9	30.5	Industry
D2	3,170	1.5	70 & 225	Ro01	124.2	74.5	Industry
D3	3,330	Max. 1.5	-	Ro01	124.2	74.5	Industry
D3:1	630						
D3:2	1,200						
D3:3	1,500						

3.3.2 Maintenance

Proper and continuous maintenance of the dams, ditches, creeks, conduit and weirs is required for sustainable and long-lasting functioning and efficient storm water treatment. Sigtuna municipality has developed a maintenance plan for the dams included in the system and is responsible for following up on this plan (Sigtuna Water and Sanitation, 2015a). The dams should be inspected twice a year, one time in May to June and one time in August to September (Sigtuna Water and Sanitation, 2015c). A document has to be filled in during or after each inspection for proper management and follow ups. Inspection of dam slopes, vegetation, conduits, water levels and flow rates are some of the factors included in the maintenance plan (*Table 4*). A special management guideline by the municipality unit “VA & Avfall” should be followed during the control of dam slopes and garbage picking (Sigtuna Water and Sanitation, 2015c). If necessary, external maintenance of vegetation clearing, haymaking and reed cutting etc. is ordered by the municipality, in addition to the maintenance plan (Johansson, 2017). A summary of the different issues to be controlled can be viewed in *Table 4*.

Table 4. *Summary of maintenance plan for dam D1, D2 and D3 dams included in the storm water system of Rosersberg (Sigtuna Water and Sanitation, 2015a, 2015b, 2015c) as translated by the author*

To be controlled	Description
Garbage	Go through the dam and surroundings, gather litter and other materials that should not occur in the area. The control is performed according to the management plan issued by ”VA & Avfall”.
Dam slopes	Control regarding bushes, brushwood, grass and other vegetation. The control is performed according to the management plan issued by ”VA & Avfall”.
Vegetation	This concerns vegetation inside the dams which should be controlled and documented by noting type of vegetation in photographs and protocol.
Incoming and outgoing ditch	Control that the flow capacity is sufficient for preventing floods by ensuring free water flow.
Inlet and outlet culvert	Control the functioning by making sure that noting hinders the water flow. An extra control is required during heavy rainfall events.
Pumping plant	Control the functioning of the pumping plant in Steninge alley. NOTE: *only dam D2 and D3.*
Controllable well	Control of flow. Level before and after flow regulator should not vary between inlet and outlet at normal flow rate. NOTE: *only dam D1.*
Erosion protection	Control of possible supplementing of erosion protection along slopes, inlets and outlets of the dams.
Water levels and flows	Control water level against reference value at the inlet and outlet after normal rainfall events. Incorrect water flow must be noted by for example overgrowth in a ditch or around drains and conduits.

3.3.3 Monitoring

After the implementation of the storm water system in Rosersberg in 2009, monitoring has been executed for controlling the storm water system’s impact on recipient Verkaån. Samplings performed by the Swedish Environmental Protection Agency (SEPA) in December 2008 serve as reference values (WSP Environment, 2009a). On behalf of the developer Rosersberg Exploatering AB, WSP (Williams Sale Partnership Limited) developed a monitoring program for Verkaån, including a sampling scheme for 2009 to 2011 (WSP Environment, 2009a). The scheme stated that sampling of sediment, in dam D3:1, and surface water both upstream and downstream Verkaån as well as within the storm water system should be executed (*Figure 13*).

Monitoring program for 2009-2011

During the implementation of the storm water system in 2009, samples were collected at two occasions at the Thompson weir and upstream and downstream Verkaån. The collected sample values are considered reference values that can be used in addition to the values from SEPA (WSP Environment, 2009b). Water samples were taken by an ISCO automatic sampler at the Thompson weir. This sampler collected a few mm of water every hour and was installed for approximately five days resulting in a cluster sample. Upstream and downstream Verkaån, water samples were collected by random sampling. Water and sediment samples were taken at the same day at the different sampling points. The sediment was sampled with a Russian sampler (WSP Environment, 2009b). Samples were analyzed both in the field and in a lab. In 2009, water flow monitoring began at the Thomson weir. A timer sampler collected one sample per day during a week at four occasions per year in 2010 and 2011 (WSP Environment, 2010b).

Monitoring program for 2012-2017

However, due to lack of storm water flow during several sampling events in 2010 and 2011 water could not be sampled and flow could not be measured (WSP Environment, 2010b, 2011). This resulted in some changes that led to the current monitoring program for the period 2012-2017 (*Table 5*) (WSP Environment, 2012a). The water sampling frequency is set to four times per year and should be carried out during the growing season (March-April, May-June, July-August and September-October). Water samples are no longer taken upstream Verkaån since the storm water discharge was insignificant in the stream during three out of four sampling occasions (WSP Environment, 2012a). The water flow is reported as a daily average value calculated from the water level at the Thompson weir during the five days of sampling (WSP Environment, 2016b).

One sediment sample should consist of five subsamples, taken at 0-2 cm depth. Sampling of sediment should be done once a year in September-October in dam D2 (WSP Environment, 2012a). Hence, sediment sampling in dam D3:1 and in Verkaån were removed from the monitoring program. This was due to low sedimentation rate in dam D3:1 and due to large variations in sedimentation in Verkaån, making sampling uncertain and difficult (WSP Environment, 2012a).

Thirteen prioritized substances stated in the WFD (Report 5801), were added in the new monitoring program (*Table 5*). Here, PAH compounds are included and the following PAH's were considered: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, bens(a)anthracene, chrysene, bens(b)fluoranthene and bens(k)fluoranthene.

Table 5. *Monitoring program for the storm water system in Rosersberg between the years 2012 to 2017 (WSP Environment, 2012a)*

Sample	Sampling location	Sampling parameters		Samplings/year
		Field	Lab	
Water	Thomson weir	Flow rate, pH, temperature, conductivity	N, P, As, Cd, Cr, Co, Cu, Mo, Ni, Pb, Zn, V, oil index, SS, 13 prioritized substances	4
Water	Downstream Verkaån			4
Sediment	Dam D2	-	As, Cd, Cr, Co, Cu, Pb, Hg, Mo, Ni, P, Sr, Zn, V, oil index, TOC (Total Organic Carbon)	1

A yearly compilation of the lab results should be summarized in a memo (WSP Environment, 2015). Further, results from the samplings should be evaluated after two, four and six years to determine the impact on Verkaån (WSP Environment, 2012b). Sampling occasions for 2009 to 2015 can be viewed in *Table 6*.

Table 6. *Sampling occasions and periods for the storm water system, as well as upstream and downstream Verkaån in 2009-2011, between 2009-2015 (WSP Environment, 2009b, 2010b, 2011, 2015, 2016b)*

Year	Sampling 1	Sampling 2	Sampling 3	Sampling 4
2009	-	14 May	10 August	4 December
2010	9 February	9 April	(not possible)	25 October
2011	31 March	6 July	20 October	20 December
2012	25 April – 2 May	19 – 25 June	6 – 13 September	18 – 24 October
2013	16 – 22 April	19 – 25 June	2 – 8 October	28 Nov – 4 December
2014	13 – 18 March	5 – 9 June	19 – 24 August	6 – 11 November
2015	13 – 18 March	5 – 9 June	19 – 24 August	6 – 11 November

3.4 Attending sampling

While all data included in this study had been collected prior to this report, it was not possible for the author, Maria Schoeps to take part in the data collection. However, Maria got the opportunity to attend a sample collection session together with WSP. The first sampling occasion during 2017 was on the 5th of April. Monitoring was performed by WSP according to the monitoring program for 2012 to 2017. Water samples were taken at the Thompson weir and downstream Verkaån. Conductivity, pH and water flow were also measured at both locations. At the Thompson weir, water samples were taken with an ISCO automatic sampler which was installed to collect water samples (a few mm) every hour, automatically, into a ca fiveliter container, over a five-day period. The samples were collected by WSP and transferred to bottles for lab analysis (*Figure 18*). The height of the water level at the Thompson weir was measured with a ruler for calculation of discharge. The flow in Verkaån was unusually high and no water could be observed at the outlet of the storm water to Verkaån.

Figure 18. The ISCO water sampler and bottles for the collected water samples (Picture taken 5th of April 2017).

3.5 Defining catchment area

The storm water system is designed to manage storm water from an area of 124.2 ha, mainly consisting of hard surfaces in the industrial area, and to delay storm water episodes up to magnitudes of ten-year floods (Dagvattenguiden, 2016). However, due to further exploitation in the area during later years, the catchment area for the storm water system has increased[4] (Sigtuna Water and Sanitation, 2017). In order to refine the calculations and to get a better estimation of the treatment effect and pollutant loads, the catchment area for dam D1 and for the rest of the dam system, at the time of monitoring (2010 to 2015), were defined. The different land use categories within the catchment area were defined as well. The new catchment area was estimated using the scale tool in Google Earth, which calculates areas, with guidance from Sigtuna Water and Sanitation. Further, the land use categories in the catchment area were visually defined by studying the map from Sigtuna Water and Sanitation (*Figure 12*).

[4] Meeting with Agneta Holm and Björn Johansson, Sigtuna Municipality, January 18, 2017.

3.6 Data analysis

One of the main aims with this study was to compare storm water treatment in a multi-step system with a single-step system. Monitoring data of pollutant loads from the multiple-dam storm water system in Rosersberg was compared with pollutant loads as generated from modelling of the system in StormTac. This comparison aimed to verify the modelled data. Additionally, modelling of treatment in a multi-step system was compared with treatment in a single-step system, using input data from the Rosersberg area for both systems. Hence, pollutant loads after treatment in three different scenarios were investigated and compared (*Figure 19*).

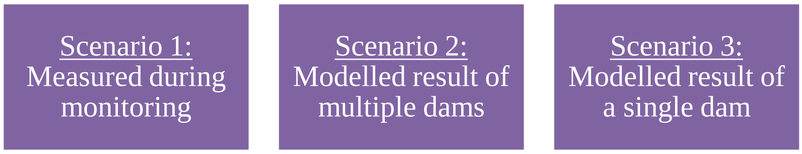

Figure 19. The different scenarios for determining treatment in a multi-step system and single-step system.

The data analysis consisted of evaluating received data from the monitoring occasions, in 2009 to 2015, in the storm water system to determine how the data could be used to achieve the aim. Choice of chemical substances, used in the data analysis, was based on presence in the monitoring program and in StormTac. Monitored pollutant concentrations from the storm water system were calculated to pollutant loads in order to compare and control pollutant loads from modelling in StormTac.

To get a picture of pollutant quantities within and from the storm water system, pollutant concentrations in sediment samples in dam D3:1 and upstream and downstream Verkaån were plotted for comparison. Further, sediment samples from dam D3:1 and D2 were calculated to be able to compare and verify the monitored water concentrations.

Annual mean concentrations and loads were used in all calculations and comparisons. Applications of monitoring data and purpose with each application in the data analysis are summarized in *Figure 20*.

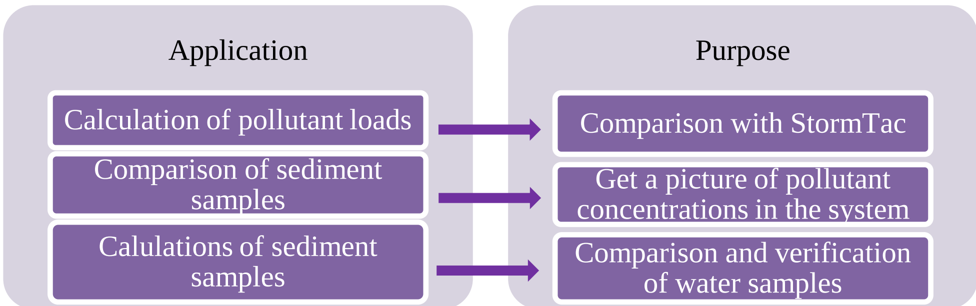

Figure 20. Summary of the applications of data and purpose with respective application.

3.6.1 Handling of basic data

Monitoring data from upstream and downstream Verkaån, from the Thompson weir, dam D2 and dam D3:1 was provided by WSP. The data consisted of substance concentrations in sediment and water samples as well as discharge data for 2009 to 2015 (Appendix 1 and Appendix 2). A majority of the monitored concentrations for Hg, oil, PAH and SS were below detection limit, while Cd and P were below detection limit only for a few times. Half the value of the detection limit was used in calculations of loads for these substances. For most constituents, this can be considered a conservative measure of the concentration. Since data from 2009 consisted of one monitoring occasion at the Thompson weir, this data was not further evaluated. Moreover, water discharge data monitored at the Thompson weir between the years 2012-2015, was absent during some monitoring occasions and therefore no discharge data was considered representative for estimation of pollutant loads.

Precipitation data was taken from SMHI's station "Sätra Gård", situated approximately four km south of the storm water system. Precipitation data for the monitoring years 2010 to 2015 was used (Appendix 3).

The concentrations, discharge and precipitation were plotted in Excel to get acquainted with the data and to visually detect possible trends and correlation between the different parameters. A summary of used data is found in *Figure 21*.

Water samples

- Thomspon weir for 2010 to 2015

Sediment samples

- Upstream and downstream Verkaån for 2010 and 2011
- Dam D3:1 for 2010 and 2011
- Dam D2 for 2012 to 2015

Precipitation data

- SMHI's station "Sätra Gård" for 2010 to 2015

Figure 21. Summary of data used in the data analysis.

3.6.2 Calculation of pollutant loads

Pollutant loads after treatment in the storm water system were calculated and compared with results from modelling in StormTac. Since pollutant loads are reported as annual mean values in StormTac, the monitored values were also summarized to annual loads. Monitored concentrations between 2010 and 2015 were used in the calculation together with calculated discharge for these years. Monitoring of pollutant concentrations was performed four times per year during 2011 to 2015. In

2010, sampling was performed three times. Since StormTac provides annual pollutant loads, each sampling year was divided into four periods where each sampling event represented one entire period (*Table 7*). The sum of pollutant loads for each period was assumed to represent the annual pollutant load.

Table 7. *Dates and number of days for the different periods in a year, where each period represents one monitoring occasion during the year*

Period 1	Period 2	Period 3	Period 4
1 Jan to 31 Mar	1 April to 31 June	1 July to 31 Sep	1 Oct to 31 Dec
90 days	91 days	92 days	92 days

Calculation of water discharge

Water discharge within the catchment area was calculated for every period (*Table 7*). This was done by multiplying precipitation (m), catchment area (m^2) and the weighted runoff coefficient for the area (no unit). Precipitation data was recorded at Sätra Gård for the years 2010 to 2015, where the total precipitation for each period and year was summarized (*Table 8*).

Table 8. *Precipitation data (mm) used to calculate water discharge in the area for the different periods and years*

Year	Total	Period 1	Period 2	Period 3	Period 4
2010	581.3	94.7	114.5	223.4	148.7
2011	510.2	96.2	84.0	199.9	130.1
2012	718.9	120.4	205.9	220.6	172.0
2013	449.2	59.0	97.8	133.0	159.4
2014	604.9	130.5	112.2	206.2	156.0
2015	696.2	154.3	157.6	279.5	104.8
Average	593.5	109.2	128.7	210.4	145.2

Calculation of runoff coefficient

The catchment area used in the calculation of water discharge was the defined catchment area. The weighted runoff coefficient was calculated by multiplying areas for the different land use categories in the area with respective runoff coefficient (*Equation 4*) (SWWA, 2004). The land uses, their area and runoff coefficient used in the calculation are in *Table 11* (section 4.1).

$$\varphi = (A_1 * \varphi_1 + A_2 * \varphi_2 \dots)/(A_1 + A_2 \dots) \qquad \textit{Equation 4}$$

where,

φ = Weighted runoff coefficient
A_1 = Size of subarea number 1 (ha)
φ_1 = Runoff coefficient for subarea 1
A_2 = Size of subarea number 2 (ha)
φ_2 = Runoff coefficient for subarea 2

Final calculation of pollutant loads

Water discharge was converted from m^3 to l. Pollutant concentrations, monitored at the Thompson weir, were converted from µg/l to kg/l and multiplied with the discharge for the same period (*Figure 22*). Pollutant loads (kg) for each period were given and summed up for every year for comparison with modelled loads in StormTac (Appendix 4).

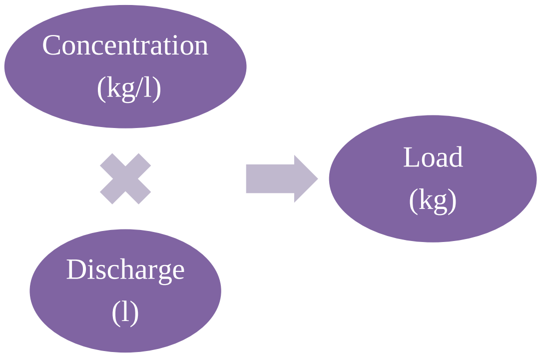

Figure 22. Calculation of pollutant loads for the monitoring years 2010-2015.

3.7 Modelling in StormTac

Modelling of the storm water system in Rosersberg was performed in the software tool StormTac in order to compare treatment in a single dam with treatment in multiple dams. StormTac was used in order to perform this comparison since it was available at Bjerking AB, the company at which this study was performed. Additionally, StormTac is commonly used in Sweden and considered user-friendly (Arnlund et al., 2014; Feltelius, 2015).

One limitation with modelling in StormTac was that simulated data for the modelled scenarios were not adjusted to the monitored data, since this was not within the frame of this study. This limitation is connected to too little basic data, resulting from the monitoring with timed sampling.

Modelling of discharge, pollutant concentrations and loads deriving from the catchment area was performed. Hence, treatment in dam D1, D2 and D3:1 were provided in the model. Standard substances were modelled in StormTac and monitored in the storm water system (StormTac, 2016d). To get a reliable assumption of discharge, pollutant concentrations and loads in the storm water in Rosersberg, for comparison with monitored values in the system, precipitation data and land uses were stated in the model (*Figure 23*). Precipitation data was taken from SMHI's station "Sätra Gård" and the different land uses included in the defined catchment area was modelled.

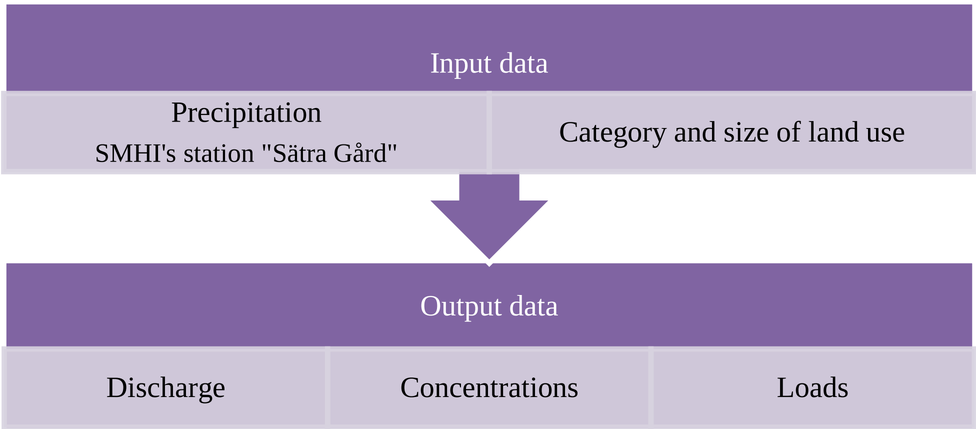

Figure 23. Input and output parameters in StormTac for modelling scenarios.

3.7.1 Modelling of treatment with multiple dams

Modelling of treatment in the catchment area in Rosersberg was done for scenario 2 in order to compare modelled pollutant loads with monitored data. When modelling treatment of dam D1, D2 and D3:1, the dams had to be added separately. The modelling procedure was done by following a guide provided by StormTac (StormTac, 2016b). Here comes a short summary of the performed steps, a simplified description is presented in *Figure 24*.

Since dam D1 is situated upstream dam D2 and receives storm water from part of the catchment area, land use categories included in the catchment area for this dam was added first (*Table 9*). Dam D1 was added as a storm water treatment facility and the pollutant concentrations and loads after treatment in dam D1 were noted. Due to the fact that dam D2 receives storm water that have been treated in dam D1, plus storm water from the rest of the entire catchment area, the catchment area for dam D1 (with pollutant concentrations and loads) was selected together with the land use categories for dam D2 (*Table 9*). Dam D2 was added as a storm water facility and pollutant concentrations and loads after treatment in dam D2 were noted. These values reflected the concentrations and loads deriving from the entire storm water system's catchment area, after treatment in dam D1 and D2.

Table 9. *Land use categories with respective areas and runoff coefficient, used in the StormTac modelling with the defined storm water system catchment area*

Dam	Land use category	Area (ha)	Runoff coefficient
D1	Industrial area	43.9	0.6
	Forest	0.5	0.05
	Gravel surface	6.4	0.4
Sum	-	50.9	-
D2 and D3:1	Industrial area	57.2	0.6
	Forest	0.5	0.05
	Parking	7.5	0.85
	Gravel surface	32.7	0.4
Sum	-	97.5	-
Total		**148.4**	

Dam D3:1, located south of the catchment area, was added in the model and a series of dams, consisting of dam D1, D2 and D3:1, was composed. Hence, pollutant loads after treatment in multiple dams for comparison with monitored loads could be performed (*Figure 24*).

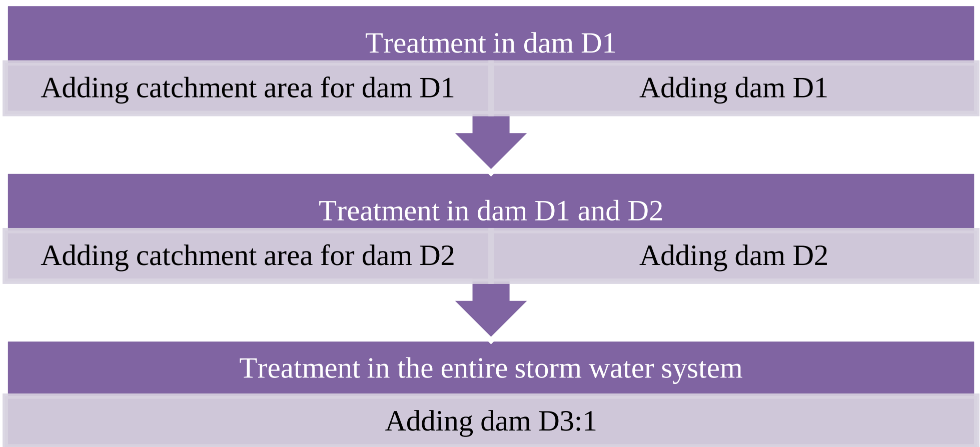

Figure 24. Steps in modelling of scenario 2, treatment in multiple dams, in the storm water system in Rosersberg.

When adding the dams in the model, specific dam area (m^2/ha_{red}), permanent water depth (m) and maximum outflow from each dam (l/s) were stated. Other parameters were automatically chosen in StormTac and used in the modelling. Since the catchment area has been expanded during recent years, the reduced catchment area (ha_{red}) and specific dam area for each dam were calculated using dam parameters in *Table 3*. The reduced catchment area was calculated by multiplying the runoff coefficient with the catchment area for the dam (ha). Specific dam area was calculated for all dams by dividing the dam area (m^2) with the reduced catchment area. More detailed data on input parameters for the dams is in Appendix 5.

3.7.2 Modelling of treatment with a single dam

As the purpose of this study is to compare the treatment of pollutants in a storm water system with one step and with multi-steps, modelling of treatment in the catchment area in Rosersberg was also done for a single dam. This single dam was referred to as D0 and modelling of dam D0 represented scenario 3. Treatment in dam D0 was modelled for the entire catchment area with the same land use categories as for the previous modelling with multiple dams (*Table 10*). The difference from the previous modelling was that the entire catchment area was used and not divided into two catchment areas.

Table 10. *Land use categories with respective area and runoff coefficient, used in the StormTac modelling of treatment in dam D0*

Land use category	Area (ha)	Runoff coefficient
Industrial area	101.2	0.6
Forest	1.0	0.05
Gravel surface	38.8	0.4
Parking	7.5	0.85
-	**148.4**	-

Dam D0 was added as a storm water facility situated at the same position as dam D3:1 in scenario 2 (*Figure 25*). The dam area was set to be the total area of dam D1, D2 and D3:1 and the water depth was assumed to be the same as for the dams. This was done since these dams are included in the comparison of monitored and modelled loads.

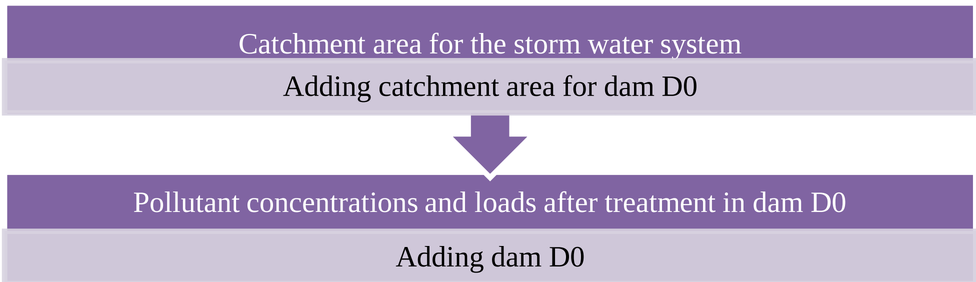

Figure 25. Steps in modelling of scenario 3, treatment in a single dam, in the storm water system in Rosersberg.

The reduced catchment area as well as the specific dam area were calculated as the above description (3.7.1). As for dam D3:1, the only known input parameters for dam D0 were the specific dam area and permanent water depth (*Table 3*). Other parameters were automatically chosen in StormTac and used in the modelling. More detailed data on input parameters for dam D0 is in Appendix 5.

3.8 Comparing sediment samples with water samples

Water samples give a momentary description of dissolved and suspended material at the sampling point. Sediment samples can be considered integrated measures over time of SS caught in the treatment process (German and Svensson, 2002). By comparing concentrations in sediment samples with concentrations in water samples it was possible to verify the water samples validity, and sediment samples were used together with water samples (Andersson et al., 2012). Substance concentrations in sediment samples in dam D3:1 and D2 were given in mg/kg DM (Dry Matter). In order to compare sediment samples with monitored concentrations in water samples, they were converted from mg/kg DM of sediment to average concentration in the water column in µg/l. Here, an empirical equation brought forth by German and Svensson was used (*Equation 5*) (German and Svensson, 2002):

$$C_V = 0.0001 \times C_S^2 + 0.11 \times C_S \qquad \textit{Equation 5}$$

where,
C_V = Expected yearly average concentration in inflowing storm water (µg/l)
C_S = Monitored average concentration (mg/kg DM)

This equation is only applicable on heavy metals as a correlation between heavy metal concentrations in sediment and event mean concentrations in incoming water were provided in that study. Further, the study was performed in storm water dams located in four urban catchment areas in Sweden (German and Svensson, 2002). In an evaluation of storm water dams by Andersson et. al. (2012), they used this equation for investigating sediment samples. The equation was considered quite unreliable as it had not been fully evaluated. However, in their evaluation they tested the equation and discovered that it can be an alternative to use in situations without or with insufficient data from water samples (Andersson et al., 2012).

After converting heavy metal concentrations in sediment samples in dam D2 and D3:1, the average concentrations for all monitoring years (2010-2015) were compared to annual mean concentrations in water (*Figure 26*). Heavy metal concentrations in water were monitored at the outflow of D3:1, for the same years.

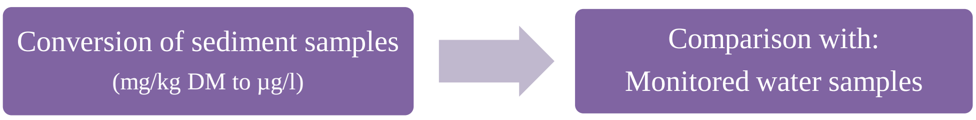

Figure 26. Summary of the performed steps for comparison of sediment samples with water samples.

4 Results

In this section, the defined catchment area will be introduced together with the results from the data analysis. The pollutant loads for the three different scenarios are compared as well as pollutants in sediment samples. A comparison of pollutant concentrations in sediment and water samples is also presented.

4.1 Definition of catchment area

By consulting Sigtuna Water and Sanitation for information about catchment boundaries and measuring areas in Google Earth, the catchment area for the entire storm water system was measured to 148.4 ha (*Figure 27*).

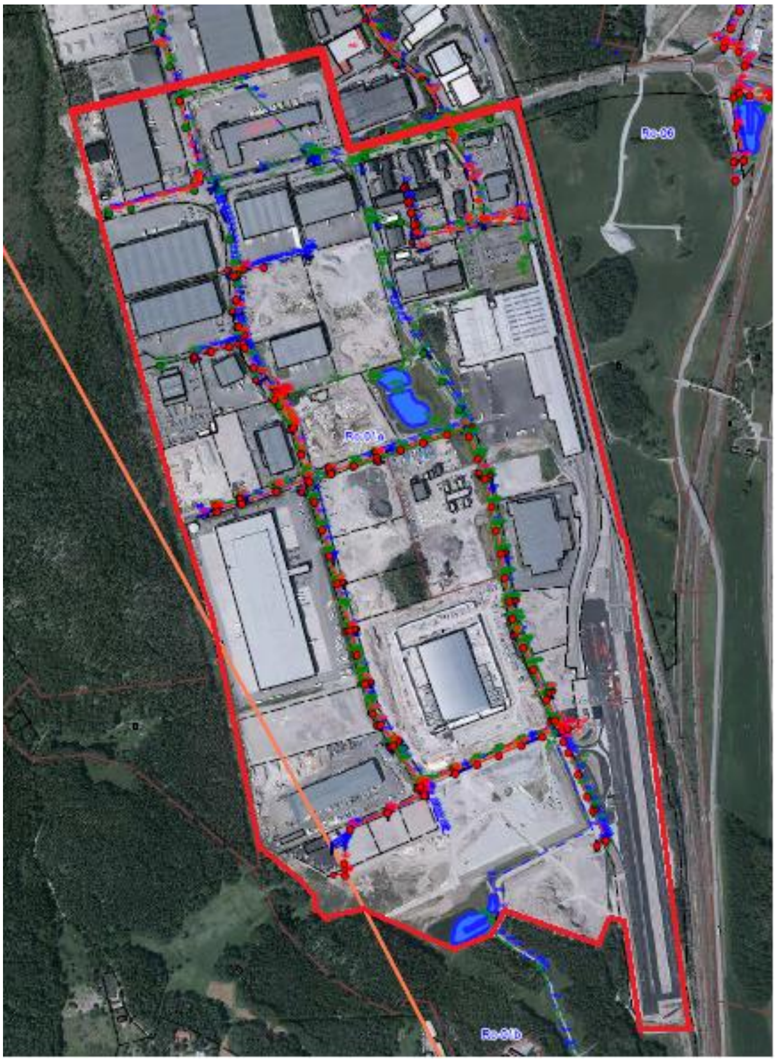

Figure 27. The catchment area for the storm water system situated within the thick red line representing an area of 148.4 ha. Modified by the author (Sigtuna Water and Sanitation, 2017).

The catchment area for dam D1 was also marked on the map (*Figure 28*), together with land uses in the area. Land use categories is mainly industrial area but also areas with piles of soil such as sand and gravel between the constructions, groves and an area for container cranes (*Figure 28* and *Table 11*).

Table 11. *Land uses and areas in the storm water system's catchment area, where the area for container cranes is referred to as parking*

Land use	Area (ha)	% of total area
Industrial area	101.2	68.3
Dams	0.9	0.6
Groves	1.0	0.7

Parking	7.5	5.1
Piles of soil	37.7	25.4
SUM	**148.4**	**100**

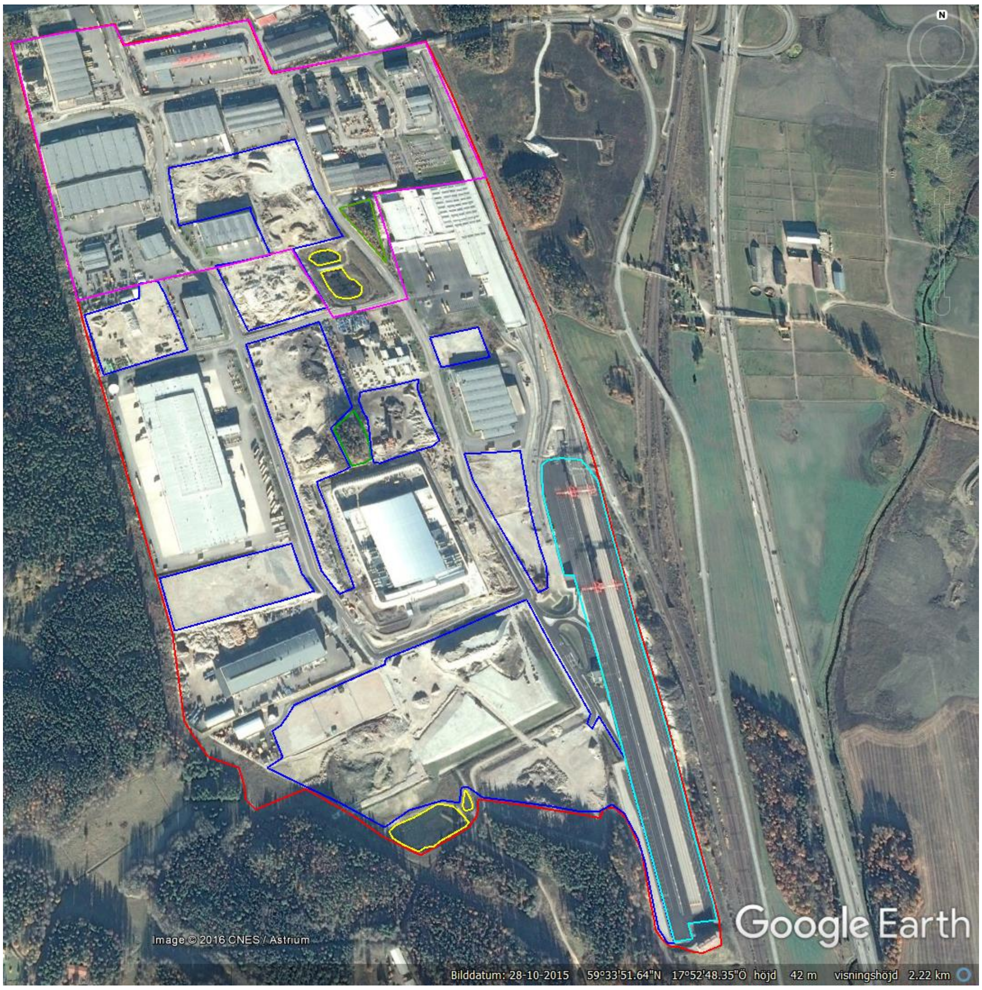

Figure 28. The total catchment area for the storm water system (to dam D2 and D3:1) is within the red line and the catchment area for dam D1 is situated within the purple line. Areas within the polygons represent different land use categories, where dark blue is piles of soil, yellow represents water surfaces (dam D1 and D2), green is grove and turquoise is an area for container cranes. The areas not included in the polygons are classified as industrial areas. Modified by the author ©Google Earth (Google Earth, 2015).

4.2 Comparison of the three scenarios

Monitored pollutant loads, representing the annual mean loads for 2010 to 2015, and modelled pollutant loads after treatment in multiple dams and in a single dam are shown in *Table 12*. Modelled pollutant loads after treatment in multiple dams are higher than monitored loads for eleven out of thirteen substances. Pollutant loads after treatment in a single dam are higher than monitored loads for twelve out of thirteen substances.

Table 12. *Annual loads (kg/year) as observed during monitoring as well as from modelling results in StormTac. Values highlighted in yellow represent the modelled pollutant loads that are higher than the monitored loads*

Scenario	As	Cd	Cr	Cu	Hg	N	Ni	Oil	P	PAH	Pb	SS	Zn
1 Monitored	0.7	0.006	0.9	1.4	0.0005	1,602	0.3	14.4	5.8	0.001	0.1	6,767	1.5
2 Multiple dams	0.6	0.22	1.2	6.0	0.02	541	2.2	47	41	0.11	2.4	8,892	26
3 A single dam	1.0	0.26	1.3	7.9	0.02	613	2.3	124	52	0.17	3.4	11,239	35

The runoff coefficient is the same for all three scenarios. Annual flow from the area for the monitored scenario is slightly higher than for modelled flow in StormTac (*Table 13*).

The calculated water runoff for the periods and years, and annual pollutant loads, based on monitored water flow for the entire area and measured concentrations at the Thompson weir, are presented in Appendices.

Table 13. *Calculated and modelled runoff coefficients and flow from the catchment areas for the three scenarios. Parameters are reported as annual averages*

Scenario	Runoff coefficient	Flow from the area (l/s)
1 Monitored	0.56	15.5
2 Multiple dams	0.56	15.2
3 A single dam	0.56	15.2

When comparing scenarios 2 and 3, multiple dams has a higher treatment effect than a single dam for all substances except for Hg (*Figure 29* and *Figure 30).*

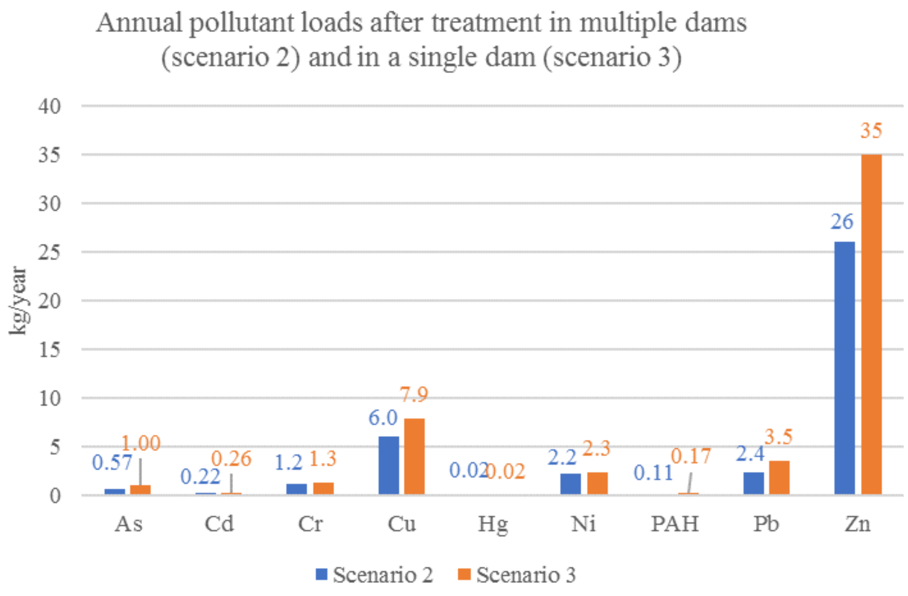

Figure 29. Modelled annual heavy metals and PAH loads from the storm water system after treatment in multiple dams (blue values) and in a single dam (orange values).

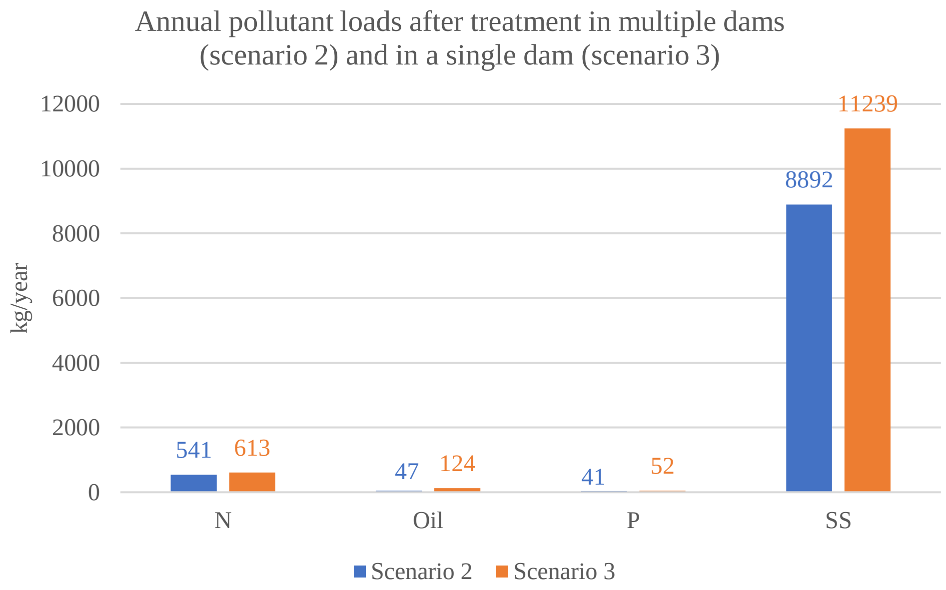

Figure 30. Modelled annual loads of N, oil, P and SS from the storm water system after treatment in multiple dams (blue values) and in a single dam (orange values).

4.3 Comparison of sediment samples

Average pollutant concentrations are higher in sediment upstream Verkaån than downstream Verkaån and dam D3:1 for seven out of nine substances (*Figure 31*). Only oil concentrations are higher downstream. Measured pH reflect basic conditions in the dam and stream.

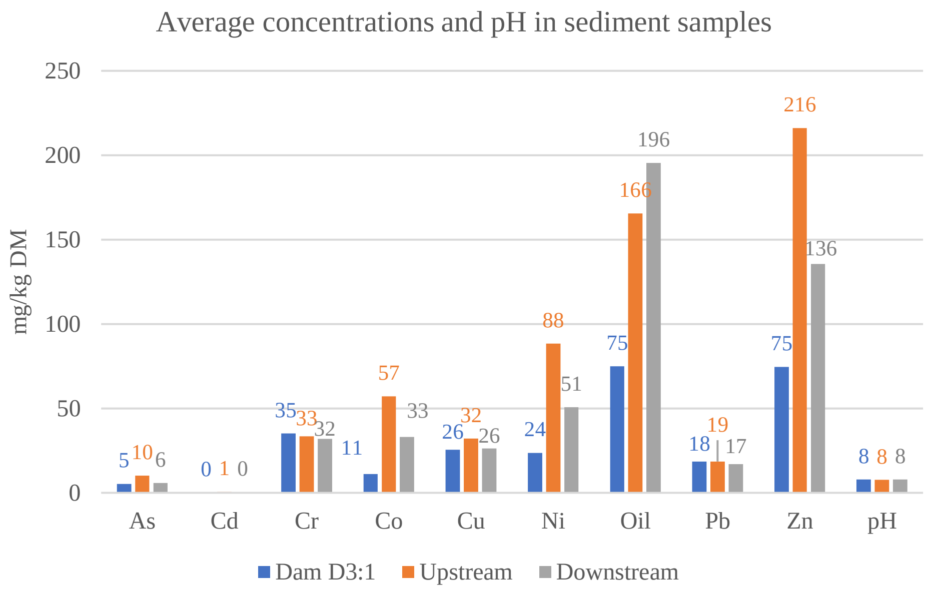

Figure 31. Annual average pollutant concentrations in two sediment samples from dam D3:1 (blue values), upstream (orange values) and downstream (grey values) Verkaån taken in 2010 and 2011.

4.4 Comparison of heavy metal concentrations in sediment and water samples

When comparing annual average heavy metal concentrations in sediment, in dam D3:1, with water samples from the Thompson weir, calculated concentrations in sediment are higher for five out of eight metals (*Figure 32*). All values represent annual averages for the years of 2010 to 2015.

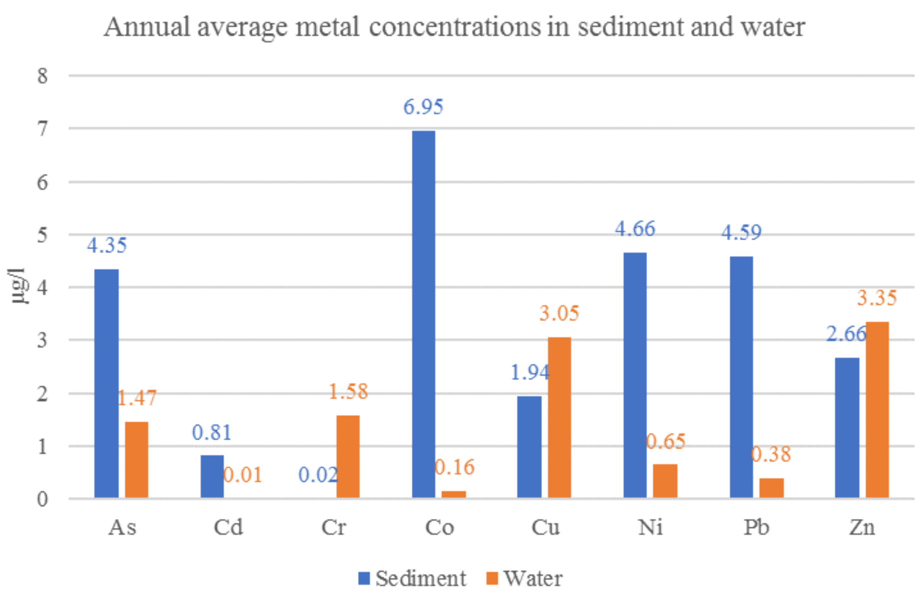

Figure 32. Annual averages of heavy metal concentrations in sediment (dam D3:1) (blue values) and water (Thompson weir) (orange values) for the years 2010 to 2015.

5 Discussion

This part discusses relations and reasons of the results with the stated questions and hypothesis. Connections to earlier studies and theory is also assessed.

5.1 Pollutant loads in the three scenarios

The main aim of this study was to assess if treatment effect in a storm water system with multiple dams is higher than in a system with a single dam. Hence, the first section of the discussion will focus on this question, which is particularly interesting as studies on treatment in a multi-step system compared to treatment in a single-step system are scarce. The second section focuses on discussing the approaches that were used to determine the pollutant loads for the different scenarios.

The fact that the weighted runoff coefficient, specific dam area and flow from the area are the same, or similar, for all three scenarios, shows that they have comparable background conditions. Further, the pollutant loads for the scenarios can be used for comparisons and for answering the main question and stated hypothesis.

Scenario 1 and 3

A higher pollution load can be observed for twelve out of thirteen pollutants after treatment in a single dam (scenario 3) compared to treatment in the monitored system (scenario 1). Even though the area for the single dam in scenario 3 is the sum of the areas for the dams in scenario 1, treatment is higher in scenario 1. This can be explained by the fact that it is more difficult for a large dam, than for several smaller dams, to distribute the water evenly in the entire water volume of the dam (StormTac, 2016b). Hence, larger dams usually have lower hydraulic efficiency and less efficient sedimentation of particles and removal of pollutants. Thus, less treatment occurs in the single dam in scenario 3.

Several factors in the dam design are connected to the hydraulic efficiency and treatment of pollutants in storm water dams. Since scenario 1 has multiple dams, it consists of several inlets and outlet, e.g. dam D1 has five inlets, where the distribution of the incoming water can be regulated and the water flow rate be reduced. Low water flow rate enhances the separation rate by increasing the sedimentation efficiency, thus more particles settle the lower the flow rate. This is of particular concern since intensive rainfall events wash out particles from a catchment area, which result in storm water containing extremely high concentrations of pollutants (VA-Forsk et al., 2004). Hence, it is vital for the dams to retain storm water between rainfall events (Persson, 1998; Pramsten, 2010). With several inlets and outlets there is a higher probability that the dams retain storm water since the incoming water flow can be regulated and reduced on several locations in the dam system. Additionally, the possibility for the storm water to be aerated increases with several outlets, which contribute with oxygen to the biotic and chemical processes in the dams (Tonderski et al., 2002).

Another factor highly connected to the hydraulic efficiency is the specific dam area. The optimal size of the specific dam area for most efficient treatment effect is 200-250 m^2/ha_{red} (Persson and Pettersson, 2006; Pramsten, 2010). In scenario 3, the single dam has a size of 114.9 m^2/ha_{red}, while dam D1 in scenario 1 has a size of 198.2 m^2/ha_{red} and the other two dams (D2 and D3:1) sizes are smaller than 40 m^2/ha_{red}. Based on the optimal size of the specific dam area, sufficient treatment of the storm water can occur in dam D1 before it drains to dam D2 and D3:1. The single dam can be assumed not to have enough treatment effect as the size is not as close to the optimal size of the dam in relation to its catchment area.

Further, the single dam in scenario 3 has to treat storm water from the entire catchment area, while in scenario 1, the catchment area is divided among the dams. Dam D1 (situated most upstream) treats storm water from a part of the total catchment area. The two dams, located further downstream in the catchment area, handle storm water from the rest of the total area and from dam D1, which on the other hand already has been treated. Additionally, two of the three dams in scenario 1 are connected by a ditch which also functions as a sedimentation area, where pollutants can be separated from the storm water (Stahre, 2004).

Still, a number of uncertainties occur for comparison of the scenarios. These are brought up in the calculation of pollutant loads for scenario 1 further down in the discussion.

The N load is considerably higher after treatment in multiple dams (1,602 vs 613 kg/year), which can attributed to the fact that N compounds behave rather differently than other substances and can undergo different processes depending on internal conditions in the dam (Persson and Pettersson, 2006). It can also be the internal conditions in dam D1 and/or dam D2 were changed so that the N was released from biota and sediment to its soluble form in the water. Further, in a study on treatment function of a storm water dam in Uppsala, N concentration was higher in flow proportionally monitored data than modelled data in StormTac (Arnlund et al., 2014).This can be connected to the fact that the estimated general treatment effect of N in storm water dams has a medium certainty in StormTac (Arnlund et al., 2014; StormTac, 2016d).

Scenario 2 and 3

As in the comparison between scenario 1 and 3, loads are higher for a majority of the pollutants after treatment in scenario 3 than in scenario 2. This is connected to the fact that scenario 2, just as scenario 1, consists of multiple dams. Here, the hydraulic efficiency is higher, due to the fact that several dams have several inlets and outlets, which reduce the water flow and aerate the water. Since the single dam only has one inlet and outlet, the hydraulic efficiency is lower. In scenario 2, dam D1 does not have five inlets and the ditch is not included as in scenario 1. Hence, scenario 2 has less inlets and treatment facilities than scenario 1. This might explain why the difference in pollutant loads between scenario 2 and 3 is smaller than for scenario 1 and 3. Still, scenario 2 matches the conditions in scenario 1, by having the same distribution and areas for the dams. Further, since both scenario 2 and 3 are modelled in StormTac with similar background conditions, which is proved not only by the same runoff coefficient and flow from the area, the difference in result is credible.

Another explanation for higher treatment effect in scenario 2 is that the equation for treatment in a series of storm water facilities in StormTac clearly states that treatment of storm water is higher in several facilities than in one facility (StormTac, 2016b).

Hg loads is the same for the modelled scenarios and can be explained by the fact that they might have reached the lowest limit for treatment in the dams, meaning that treatment of that low amounts is extremely unusual and does not affect downstream recipients.

5.1.1 Estimation of pollutant loads

Pollutant loads for the three different scenarios were estimated in different ways, where loads for scenario 1 were measured in the storm water system in Rosersberg and pollutant loads for scenario 2 and 3 were generated from modelling in StormTac. Hence, an interpretation of the different estimations is vital for understanding their connection and how the loads could be compared.

Calculation

As seen in the comparison of pollutant loads for the three scenarios, the pollutant loads for scenario 1 were lower than modelled scenarios for a majority of the pollutants. This can be explained by possible underestimation of pollutant loads for scenario 1 since several assumptions were made in the calculation. Since half of the detection limit was used for some of the monitored pollutants, pollutant concentrations might have been underestimated. Consequently, more uncertain loads were estimated for pollutants below detection limit. This was of particular concern for Hg, PAH, SS and oil, which were below detection limit during several monitoring occasions in 2010-2015. Also, this can explain the low loads for these substances compared to the loads in scenario 2 and 3.

Two other factors connected to possible underestimation of pollutant loads for scenario 1 is that pollutant concentrations were monitored using timed sampling, while the modelled scenarios are based on flow proportionally sampled data. With timed sampling, heavy rainfall events are easily missed, as well as high pollutant concentrations, since it is during these occasions that soluble substances in storm water runoff can reach very high concentrations (Verbanck et al., 1994). Hence, high pollutant concentrations are more easily missed in scenario 1. This might explain lower pollutants loads in scenario 1 than in the modelled scenarios. This is also connected to the assumption that one year was divided into four periods where pollutant concentrations for one period, approximately 91 days, represented one monitoring occasion of five days.

The assumption of dividing the year into four periods was also applied for the precipitation data in the calculation of water discharge, in order to be able to do the final calculation of load. However, daily values for all days included in every period were used, thus giving a more credible discharge. The calculated water discharge in the area is quite similar for the different periods, which indicate that precipitation distribution is similar for the years and that the average value for each period.

Another assumption made for estimating pollutant loads for scenario 1 was that precipitation data from station "Sätra Gård", situated approximately four km south of the storm water system, represented precipitation in the catchment area. It was the only close station with data for the required time, 2010 to 2015.

Modelling in StormTac

Simulated data for the modelled scenarios were not adjusted to the monitoring data, since this was not within the frame of this study. This limitation can result in that the model is not optimized for the storm water system in Rosersberg and there is a risk that the modelled scenarios do not represent the storm water system.

In order to get modelled pollutant loads for scenario 2 and 3, a number of assumptions were made. Just as in the calculation of pollutant loads, precipitation data from station “Sätra Gård” was used in the model as well as land categories and respective runoff coefficient. However, when adding land use categories, an area for container cranes was assumed as “parking”. Additionally, the piles of soil and the dam areas, situated within the catchment area, were assumed to be “gravel surface”. The dam areas were assumed to be “gravel surface” since part of their areas consist of macadam where infiltration of water occur. The annual average precipitation for 1961-2016 is used in the model where the water discharge is divided into baseflow and storm water. Since the annual average precipitation is used and time series of substance concentrations and loads are not given, seasonal variations in precipitation are not considered, nor are flow peaks and intensive rainfall events contributing with high pollutant concentrations (Verbanck et al., 1994).

Several standard properties for storm water dams were stated in the model and could be modified. Where data on dam properties was unknown, standard values were used for all modelled dams and as the same standard values were used it should show credible results on pollutant loads for scenario 2 and 3. One assumption for scenario 3 was that the dam area was assumed to be the sum of the areas of the dams in scenario 2 (dam D1, D2 and D3:1) and hence representing the same areas.

Still, some limitations exist in StormTac, just like with all models. Since the complexity of a storm water system is wide it is extremely difficult to describe natural biogeochemical and hydro-meteorological processes in a model (Feltelius, 2015; Kaczala et al., 2012). StormTac is considered to have a restricted range of uses, compared to other storm water models (Elliott and Trowsdale, 2007). Further, compared to other models, not as many pollutants and storm water facilities are included (Elliott and Trowsdale, 2007). However, the model is easy to use since little input data is required and it is still suitable for performing different simulations. Also, StormTac’s functionality is emphasizes by the fact that it is often used for modelling storm water, particularly by the Swedish consultancy businesses (Feltelius, 2015).

5.2 Applications of sediment samples

This section discusses whether there is any relation between sediment samples within the storm water system and upstream and downstream Verkaån. As sediment samples are good for estimating treatment of pollutants in storm water dams, the characterization of pollutant loads from a catchment area can be concluded (German and Svensson, 2002). Hence, the sediment samples can be used to verify the pollutant concentrations used for calculation of pollutant loads for scenario 1 and also treatment effect in the storm water system in Rosersberg.

5.2.1 Monitored sediment samples

A majority of pollutant concentrations in sediment samples upstream and downstream Verkaån and in dam D3:1 are highest upstream Verkaån. Further, a majority of the pollutant concentrations followed the pattern of highest to lowest: upstream Verkaån, downstream Verkaån, dam D3:1. The fact that pollutant concentrations were highest upstream Verkaån might be explained by a possible point source located upstream the sampling point, e.g. the airport Arlanda and/or the heavily trafficked road E4, which contribute with pollutants to the stream. Higher oil concentration was observed in the sediment downstream Verkaån than in the other two sampling locations. This is difficult to clarify since the morphology of the stream sediment is unknown, but one possible reason is that there might be an uncertainty in the sampling procedure. Without further studies these differences cannot be explained. Such a study could investigate the morphology of the stream sections, the chemistry of the contributing storm water and other aspects. Further, the differences in the results are difficult to interpret since the basic data covers a two-year period.

The fact that dam D3:1 has the lowest concentrations in sediment for a majority of pollutants might be connected to the fact that sampling was performed one year after the storm water system had been implemented. Hence, there is a risk that not enough particles had accumulated at the time of sampling and that monitored sediment samples consist of underlying material, which is interpreted as sediment that have been accumulated in the dam since the implementation of the storm water system. Additionally, the monitoring program in 2012 stated that the sedimentation rate at dam D3:1 is low and sampling is considered uncertain and difficult (WSP Environment, 2012a).

The low variation in pH reflects similar conditions for the three sampling points, just like the fact that heavy metals behave more or less the same in the different points. Basic conditions occur in the sediments and as release rates of heavy metals are smaller in high pH, the metals ought to stay in the sediments and not be released and transported downstream (Li et al., 2013).

5.2.2 Heavy metal concentrations in sediment and water samples

Sediment samples in dam D3:1, assumed to represent samples from both dam D2 and D3:1, and water samples from the Thompson weir show that a majority of the heavy metal concentrations are higher in sediment than in water. This can indicate that a majority of the heavy metals are removed from the storm water by treatment in the dams. However, it is difficult to evaluate the correlation between sediment and water samples in dam D3:1 due to little basic data. Further, the water samples were collected with timed sampling, where high flow peaks, often contributing with high pollutant load, are more easily missed. Therefore, a more suited monitoring program might discover a better correlation between sediment and water samples.

Also, the equation for converting sediment samples might not be suited for the storm water system in Rosersberg.

Concentrations for Co, Ni and Pb are considerably higher in the sediment. However, Cr, Cu and Zn concentrations are higher in water samples. This can be explained by the fact that release rate of these metals is enhanced during aerobic conditions (Wu et al., 2016). However, the oxygen conditions in the dams are unknown. The high concentration of Pb in sediment is however uncertain as this metal also has high release rate during aerobic conditions.

5.3 Uncertainties

A major uncertainty in this study is that the pollutant loads in scenario 1 are based on pollutant concentrations for timed sampling while the pollutant loads for the modelled scenarios are based on flow proportional sampled data. Hence, there is a risk that the high-flow peaks, contributing with high pollutant concentrations are more easily missed, which might result in an underestimation of pollutant loads in scenario 1.

In the estimation of pollutant loads for the three scenarios, several factors affecting the treatment effect in a storm water dam are unknown. Topography, relation of dam length and width and placement of inlet and outlet are some factors. In the two modelled scenarios, the only input data for the dams were dam depth, specific dam area and maximum outflow.

The distribution of the land use categories in the model are unknown, as well as how this influence treatment effect of storm water. Another uncertainty lies here as the runoff coefficient for the land use category "gravel surface" is less reliable than the other runoff coefficients in StormTac, due to the fact that it is not based on many studies (StormTac, 2016b). Further, the assumptions on land use categories in the model can affect the discharge patterns in the catchment area.

The division of discharge into baseflow and storm water is not considered in scenario 1. The baseflow can affect the pollutant loads as possible groundwater leaking into the storm water system in the area is included in the baseflow (Larm and VBB VIAK, 2000). Consequently, there is the uncertainty of how much of the water discharge in the catchment area that infiltrate into groundwater and never reaches the storm water dams or at least the recipient. It is stated that no infiltration of storm water is allowed where the soil consists of sand in the industrial area and that these areas should be covered with hard surfaces (WSP Environment, 2010a). However, as discovered on the defined catchment area for storm water system, areas with piles of soil exist (*Figure 28*). This is of great concern since piles of soil are areas where the water easily infiltrates.

One of the largest uncertainties is the equation used for comparing sediment samples with water samples since this equation has not been fully evaluated (Andersson et al., 2012). However, in the study where the equation was developed, a relation was found between event mean concentrations and sediment concentrations of heavy metals, which is corresponding to this study since a majority of the concentrations used in calculations are annual means (German and Svensson, 2002). The equation is based on storm water dams in four urban catchment areas in Sweden, but it is still uncertain how representative the storm water system in Rosersberg is for the use of the equation.

Since maintenance practices of the storm water dams included in the storm water system has not been taken into consideration, it is uncertain whether sediment has been removed from or added to the dams during the monitoring years. Hence, there is a risk that collected sediment samples contain underlying material, which are misinterpreted as sediment.

When defining the catchment area for the storm water system, land use categories and respective areas were estimated using a map from Google Earth from 2015. Since the monitoring data, used for calculations and comparisons, were taken in 2010 to 2015, the map should reflect the monitoring dates and the conditions in the area. Still, continuous exploitation has occurred in the area during all years which means that the distribution of land use categories might have been different in earlier years (Sigtuna Water and Sanitation, 2017).

5.4 Comments on the monitoring program

Due to the fact that a proper management is vital for an efficient treatment of storm water, it is important that the management plan, containing both maintenance and monitoring programs, is continuously updated and evaluated (Stahre, 2004; SWWA, 2011). In the monitoring program for the storm water system in Rosersberg, there are several parts that are suitable for estimating treatment in the system. Many different pollutants are monitored and analyzed, and monitoring of sediment samples are performed once a year downstream Verkaån and in dam D2. These procedures are recommended to continue in the future. However, sediment sampling upstream Verkaån could be implemented in the monitoring program again as sediment samples can work as supplement to timed water sampling (Andersson et al., 2012). Sediment samples upstream Verkaån provides more data to evaluate pollutant loads from the storm water system. Further, sediment samples require relatively little work and costs (Andersson et al., 2012).

At the moment, water samples are monitored during approximately five days which is more representative than a random sample. Unfortunately, some uncertainties occur since rain intensities, which affect variation in pollutant concentrations, are not taken into consideration. In order to get even more reliable data from water samples and monitoring of discharge, suggestions on improvements in the monitoring program are to:

- Monitor water samples using flow proportional sampling
- Monitor water discharge continuously using a logger with a pressure sensor
- Follow weather forecasts and try to monitor in connection with precipitation events

Flow proportional sampling should be used since it takes large water flows into account and therefore also varying pollutant concentrations in storm water, which is more difficult to detect with timed sampling (Pramsten, 2010). Further, flow proportional sampling should be considered for future comparisons of treatment of pollutants in the storm water with modelled values in StormTac. This is due to the fact that other studies using StormTac to compare flow proportional monitored data with modelled data, show that the data is consistent (Arnlund et al., 2014; Feltelius, 2015). However, flow proportional sampling is time consuming and weather dependent, and thus also more expensive (Andersson et al., 2012; WRS AB and Naturvatten i Roslagen AB, 2013).

6 Conclusions and recommendations

Based on the results and discussion it could be concluded that:

- Multiple dams have higher treatment effect than a single dam since multiple dams have several inlets and outlets where the water is aerated and where the water flow rate is reduced. This results in a higher hydraulic efficiency and thus a more uniformly distribution of the water over the entire dam volume.
- There is a correlation between sediment samples in the storm water system and in Verkaån, which shows that the industrial area does not seem to have contributed with pollutants in any visible way to the sediment downstream Verkaån. Hence, the retention dams included in the storm water system seem to have enough treatment of pollutants.
- There is a correlation between sediment samples and water samples in the storm water system, which seems to indicate that heavy metals are trapped in the retention dams, by being removed from the storm water and accumulated in the sediment. Hence, the retention dams included in the storm water system tend to have sufficient retention of heavy metals.

Recommendations for further research include:

- Simulated data from the storm water software StormTac should be adjusted with monitored data, and parameters included in the model should be further evaluated in order to achieve more credible results from modelling and for comparisons of data.
- More studies should further evaluate if several dams treat storm more efficiently than a single dam, but with data from more different storm water systems for a more credible result. Further research should focus on investigating the design of storm water dams and its treatment effect.
- A monitoring program for storm water dams should use flow proportional sampling in order to detect varying pollutant concentrations in storm water and also to estimate treatment effect in the dams. However, if time or costs stand as obstacles, sediment sampling is preferable as it is inexpensive and more easily executed.

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Appendices

Appendix 1.

Basic data in form of monitored concentrations of substances (µg/l) in water at the Thompson weir in 2010 to 2015 and annual average concentrations for all years.

Date	As	Cd	Cr	Cu	Hg	N	Ni	Oil	P	PAH	Pb	SS	Zn
2010-04-09	1.31	0.01	0.57	4.5	-	7,590	0.76	25	20	-	1.42	4,700	2.1
2010-08-20	1.43	0.00	1.75	3.7	-	3,810	0.55	25	5	-	0.17	1,000	0.9
2010-10-25	0.97	0.00	0.62	3.1	-	1,150	0.70	25	5	-	0.25	2,500	1.0
Average 2010	1.24	0.00	0.98	3.8	-	4,183	0.67	25	10	-	0.61	2,733	1.3
2011-03-31	1.53	0.01	0.84	4.4	-	2,000	0.98	195	23	-	1.74	8,500	5.7
2011-07-06	2.31	0.00	0.46	2.1	-	600	0.46	25	5	-	0.14	2,500	0.8
2011-10-20	2.43	0.04	1.33	4.5	-	2,200	0.76	25	19	-	0.54	4,400	4.5
2011-12-20	2.00	0.02	0.76	3.9	-	3,500	0.90	25	13	-	1.60	1,150	6.0
Average 2011	2.07	0.02	0.85	3.7	-	2,075	0.77	68	20	-	1.00	4,138	4.2
2012-05-02	1.59	0.01	0.14	4.1	0.001	4,540	0.52	25	23	0.003	0.08	10,600	3.5
2012-06-25	1.86	0.01	0.09	3.2	0.001	8,290	0.52	25	5	0.003	0.09	170,000	1.7
2012-09-13	1.50	0.01	7.74	3.1	0.001	8,490	0.47	25	5	0.003	0.03	1,000	1.2
2012-10-24	1.53	0.01	0.58	3.4	0.001	3,980	0.47	25	17	0.003	0.02	8,000	3.1
Average 2012	1.62	0.01	2.14	3.5	0.001	6,325	0.50	25	10	0.003	0.06	47,400	2.4
2013-04-22	1.08	0.02	1.38	4.0	0.004	2,640	1.25	25	21	0.003	1.54	18,000	7.1
2013-06-25	1.78	0.01	0.27	2.2	0.001	180	0.46	25	5	0.003	0.17	2,500	0.7
2013-10-08	1.07	0.02	0.13	2.6	0.001	1,490	0.52	25	5	0.003	0.04	2,500	3.2
2013-12-04	1.09	0.01	0.25	2.2	0.001	3,070	0.60	25	5	0.003	0.19	2,800	2.1
Average 2013	1.26	0.01	0.51	2.78	0.002	1,845	0.70	25	10	0.003	0.49	6,450	3.5
2014-04-10	1.06	0.01	6.03	1.9	0.001	2,950	0.44	38	14	0.003	0.03	5,700	0.8
2014-06-09	1.14	0.01	0.08	1.7	0.001	1,090	0.43	25	15	0.003	0.05	2,500	3.2
2014-08-25	1.36	0.01	6.43	2.8	0.001	3,840	0.75	25	5	0.003	0.09	4,300	3.6
2014-11-17	1.45	0.02	6.81	2.0	0.001	3,830	0.49	25	11	0.003	0.12	4,800	4.1
Average 2014	1.25	0.01	4.84	2.1	0.001	2,928	0.53	28	10	0.003	0.07	4,325	2.9
2015-03-18	1.04	0.02	0.11	2.3	0.001	3,800	0.63	25	5	0.001	0.07	6,100	4.8
2015-06-09	1.36	0.02	0.24	3.6	0.001	1,620	0.68	25	16	0.003	0.12	4,600	4.0
2015-08-24	1.58	0.01	0.09	1.7	0.001	220	0.67	25	25	0.003	0.01	1,000	3.0
2015-11-11	1.49	0.01	0.24	2.5	0.001	1,240	0.81	25	24	0.003	0.08	13,000	12.1
Average 2015	1.37	0.01	0.17	2.5	0.001	1,720	0.70	25	20	0.002	0.07	6,175	6.0
Annual mean	1.47	0.01	1.58	3.1	0.001	3,179	0.65	33	10	0.002	0.38	11,870	3.4

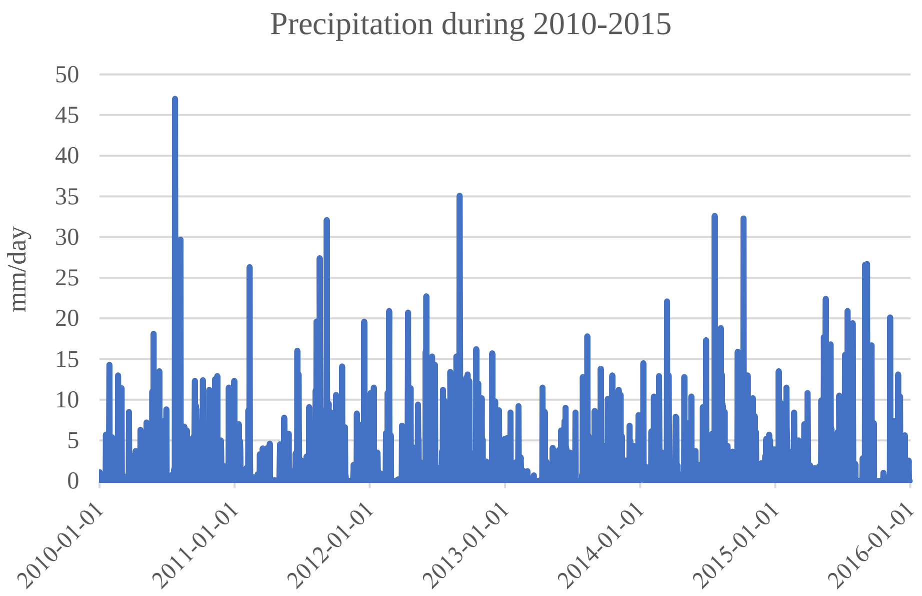
Appendix 2.

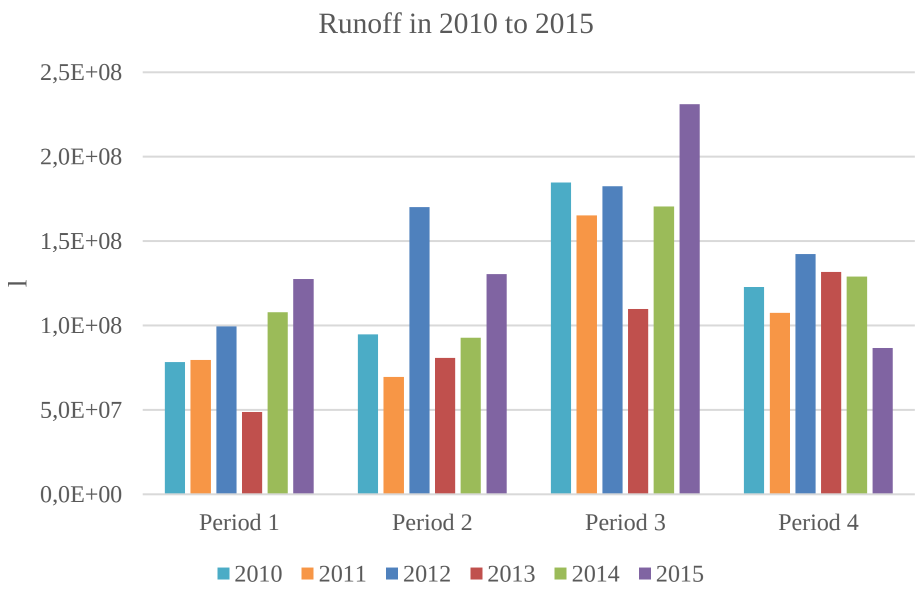
Basic data on monitored concentrations (mg/kg DM) and pH in sediment in dam D3:1 and upstream and downstream Verkaån for 2010 and 2011, as well as in dam D2 for 2012 to 2015.

		As	Cd	Co	Cr	Cu	Hg	Ni	Oil	Pb	Zn	pH
Dam D3:1	2010	6.1	0.2	12.1	43.3	27.9	0.02	26.1	10	20.0	81.9	7.7
	2011	4.6	0.1	10.3	26.9	23.1	0.5	21.3	140	16.9	67.4	8.0
Upstream	2010	15.0	0.5	63.1	38.2	35.4	0.5	91.5	211	19.2	236	7.7
	2011	5.3	0.7	51.2	28.7	28.9	0.5	85.3	120	17.9	196	7.6
Downstream	2010	6.5	0.3	35.7	23.9	20.4	0.5	50.2	121	14.9	136	7.9
	2011	5.2	0.3	30.4	40.0	32.2	0.5	51.3	270	19.0	135	7.8
Dam D2	2012	8.0	0.1	16.9	64.7	39.8	0.02	40.4	10	23.9	117	-
	2013	7.0	0.2	16.0	49.4	43.8	0.02	35.9	47	26.0	122	-
	2014	8.6	0.2	21.9	76.3	45.5	0.02	47.7	N/A	23.3	119	-
	2015	9.9	0.1	26.8	96.6	63.9	0.02	68.9	10	32.0	150	-

Appendix 3.

Precipitation data (mm/day) for the monitoring period and runoff (l/period) for the four different periods. Precipitation data from Sätra Gård station (97320) can be found at SMHI's website: http://opendata-download-metobs.smhi.se/explore/#





Appendix 4.

Pollutant loads (kg/year) for every monitoring occasion calculated by sampled water concentrations (Appendix 1), and annual pollutant loads for all monitoring years and annual mean for all years.

Date	As	Cd	Cr	Cu	Hg	N	Ni	Oil	P	PAH	Pb	SS	Zn
2010-04-09	0.12	0.001	0.05	0.42	-	718	0.07	2.4	1.89	-	0.13	445	0.20
2010-08-20	0.26	0.000	0.32	0.68	-	704	0.10	4.6	0.92	-	0.03	185	0.17
2010-10-25	0.12	0.000	0.08	0.38	-	141	0.09	3.1	0.61	-	0.03	307	0.12
Total 2010	0.5	0.001	0.5	1.5	-	1,563	0.3	10.1	3.4	-	0.2	937	0.5
2011-03-31	0.12	0.001	0.07	0.35	-	159	0.08	15.5	1.83	-	0.14	676	0.45
2011-07-06	0.16	0.000	0.03	0.14	-	42	0.03	1.7	0.35	-	0.01	174	0.05
2011-10-20	0.40	0.007	0.22	0.75	-	364	0.12	4.1	3.14	-	0.09	727	0.74
2011-12-20	0.22	0.002	0.08	0.42	-	376	0.10	2.7	1.40	-	0.17	124	0.65
Total 2011	0.9	0.010	0.4	1.7	-	941	0.3	24.1	6.7	-	0.4	1,700	1.9
2012-05-02	0.16	0.001	0.01	0.41	0.0001	452	0.05	2.5	2.29	0.0002	0.01	1,055	0.35
2012-06-25	0.32	0.002	0.02	0.54	0.0002	1,411	0.09	4.3	0.85	0.0004	0.02	28,933	0.29
2012-09-13	0.27	0.002	1.41	0.57	0.0002	1,548	0.09	4.6	0.91	0.0005	0.01	182	0.22
2012-10-24	0.22	0.001	0.08	0.49	0.0001	566	0.07	3.6	2.42	0.0004	0.00	1,137	0.44
Total 2012	1.0	0.006	1.5	2.0	0.0006	3,969	0.3	14.8	6.5	0.002	0.03	31,252	1.3
2013-04-22	0.05	0.001	0.07	0.20	0.0002	129	0.06	1.2	1.02	0.0001	0.08	878	0.34
2013-06-25	0.14	0.000	0.02	0.18	0.0001	15	0.04	2.0	0.40	0.0002	0.01	202	0.06
2013-10-08	0.12	0.002	0.01	0.29	0.0001	164	0.06	2.8	0.55	0.0003	0.00	275	0.35
2013-12-04	0.14	0.001	0.03	0.29	0.0001	405	0.08	3.3	0.66	0.0003	0.03	369	0.27
Total 2013	0.5	0.005	0.1	1.0	0.0005	710	0.2	9.3	2.6	0.001	0.12	1,721	1.0
2014-04-10	0.11	0.001	0.65	0.21	0.0001	318	0.05	4.1	1.51	0.0003	0.00	615	0.08
2014-06-09	0.11	0.001	0.01	0.16	0.0001	101	0.04	2.32	1.4	0.0002	0.00	232	0.30
2014-08-25	0.23	0.002	1.10	0.48	0.0002	655	0.13	4.26	0.9	0.0004	0.02	733	0.62
2014-11-17	0.19	0.003	0.88	0.26	0.0001	494	0.06	3.22	1.4	0.0003	0.02	619	0.53
Total 2014	0.6	0.007	2.6	1.1	0.0005	1,565	0.3	13.8	5.2	0.001	0.04	2,195	1.5
2015-03-18	0.13	0.002	0.01	0.30	0.0001	485	0.08	3.19	0.6	0.0001	0.01	778	0.61
2015-06-09	0.18	0.002	0.03	0.47	0.0001	211	0.09	3.26	2.1	0.0003	0.02	599	0.52
2015-08-24	0.37	0.002	0.02	0.39	0.0002	51	0.16	5.78	5.8	0.0006	0.00	231	0.70
2015-11-11	0.13	0.001	0.02	0.21	0.0001	107	0.07	2.17	2.1	0.0002	0.01	1,126	1.05
Total 2015	0.8	0.007	0.1	1.4	0.0006	852	0.4	14.4	10.6	0.001	0.03	2,729	2.9
Annual mean	0.7	0.006	0.9	1.4	0.0005	1,602	0.3	14.4	5.8	0.001	0.1	6,767	1.5

Appendix 5.

Dam properties for every dam used in StormTac and input parameters in the software for simulation treatment with multiple dams (D1, D2 and D3:1) and a single dam (D0).

Dam	Area (m^2)	Permanent water depth (m)	Outflow max. (l/s)	Runoff coefficient	Catchment area (ha)	Permanent water depth (m)	Reduced catchment area (ha_{red})	Part of reduced catchment area (m^2/ha_{red})
D1	5,750	1.5	800	0.57	50.9	1.5	29.0	198.2
D2	3,170	1.5	225	0.56	148.4	1.5	83.1	38.1
D3:1	630	1.5	200	0.56	148.4	1.5	83.1	7.6
D0	9,550	1.5	200	0.56	148.4	1.5	83.1	114.9

Appendix 6.

Calculated heavy metal concentrations (µg/l) in sediment in dam D2 and D3:1 for 2010 to 2015, and annual mean concentrations.

	2010	2011	2012	2013	2014	2015	Average
As	1.11	17.36	1.11	5.39	0.00	1.11	4.35
Cd	0.67	0.51	0.88	0.77	0.95	1.10	0.81
Co	0.02	0.02	0.01	0.02	0.02	0.01	0.02
Cr	4.95	3.03	7.54	5.68	8.98	11.56	6.95
Cu	1.35	1.14	1.89	1.79	2.46	3.02	1.94
Ni	3.15	2.59	4.54	5.01	5.21	7.44	4.66
Pb	2.94	2.39	4.61	4.08	5.48	8.05	4.59
Zn	2.24	1.89	2.69	2.93	2.62	3.62	2.66

Appendix 7.

Modelled metal concentrations (µg/l) and loads (kg/year) at the inflow to dam D2, outflow of dam D3:1 and the difference between them, reflecting the metal concentrations and loads that is treated in the dams.

	Inflow D2		Outflow D3:1		Difference	
	Conc.	Load	Conc.	Load	Conc.	Load
As	3.2	1.50	1.2	0.57	2.0	0.93
Cd	0.83	0.39	0.46	0.22	0.37	0.17
Cr	7.4	3.4	2.5	1.2	4.9	2.2
Cu	28	13	13	6	15	7
Hg	0.94	0.44	0.74	0.35	0.2	0.09
Ni	8.4	3.9	4.8	2.2	3.6	1.7
Pb	16	7.7	5.2	2.4	10.8	5.3
Zn	150	69	55	26	95	43