Merethe Arntsen Strømberg

Sediment removal performance of a hydrodynamic vortex separator

Master's thesis in Civil and Environmental Engineering
Supervisor: Tone Merete Muthanna
June 2020

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Kunnskap for en bedre verden

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With increasing urbanization, the challenges connected to stormwater runoff are becoming more evident. Road runoff are carrying a high load of sediments, in addition to pollutants, that are released into the receiving waterbodies. Gully pots play an important part in reducing sediment load to the urban drainage network, with their main function to avoid sediment buildup and wear on the drainage system. Their capabilities to remove finer particles are not extensively documented in literature but there is a need for a similar space-efficient removal of fine particles.

A hydrodynamic vortex separator (HVS) was installed south of Trondheim, draining runoff from a high-traffic road. The HVS utilizes gravity separation enhanced by a vortex structure to remove sediments and are built as a space-efficient online treatment solution.
With the objective of improving water quality and protecting the recipient from the effects of the fine particles and pollutants in stormwater discharge, this thesis focused on assessing the performance of the HVS. The performance was determined in a field study with focus on removal of total suspended solids (TSS) and particle size distribution (PSD) to evaluate the ability of the HVS to capture fine particles.

The master thesis aims to answer the following research questions:

1) What is the sediment removal performance of the HVS in separating particles from road runoff in the case study setup?
2) How does the particle size distribution in the sediments from the HVS differ from sediments in standard gully pots?

Collaboration partners: Trondheim Municipality

Location: Department of Civil and Environmental Engineering

Preface

This report was submitted as the final product in the course *TVM4905 Water and wastewater engineering, Master's Thesis* at the Norwegian University of Science and Technology (NTNU), Department of Civil and Environmental Engineering. This thesis aimed to evaluate the sediment removal performance of a hydrodynamic vortex separator by collecting runoff and sediment samples. The study was conducted in the field, the analytical laboratory, and the hydraulic research hall at the Department of Civil and Environmental Engineering.

The thesis was written as a scientific paper, which is planned to be submitted to a suitable journal. The framework of this report is based on common guidelines for making a research paper, where the goal was to make a manuscript. Additional pictures, data, and results can be found in the appendix. Due to the COVID-19 pandemic, field and laboratory work was not authorized for 8 weeks. Some of the planned fieldwork had to be changed to adapt to these circumstances.

I would like to express my deepest gratitude to my supervisor Professor Tone Merete Muthanna for her advice and inspiration during this process of research and scientific writing. Thank you for teaching me that field studies are an emotional roaller coaster, hard work, and that something unexpected will always happen no matter how prepared you are. I would also like to thank Birgitte Gisvold Johannessen, Project leader at Trondheim Kommunalteknikk, for answering all my questions and enabling communication and help from Trondheim Bydrift. A special thank you to my boyfriend, Togeir Storflor Moen, for making the continuation of this field study possible by coming with me in the field during the COVID-19 pandemic.

In addition, I would like to thank:

- Bjørn Nordvik and Trondheim Bydrift for always helping me with whatever I needed in the field and for good problem-solving skills.
- Trine Hårberg Næss, Department of Civil and Environmental Engineering, NTNU, for arranging the laboratory opening after COVID-19 pandemic and for always guiding me in the lab.
- Nils Aaby, General manager at Miljø- of Fluidteknikk AS, for answering all my questions about the hydrodynamic vortex separator.
- Nadine Adler, former student at NTNU, for learning me the method of wet sieving developed in her master thesis.
- Gunnar Vistnes, Department of Geoscience and Petroleum, NTNU, for borrowing me a riffle splitter.
- Anna Teetzmann and Eline Klaastad, my friends, for coming out in the field with me occasionally and for great proofreading.

Trondheim, 29.06.2020

Merethe A. Strømberg

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Sammendrag

Avrenning fra veg representerer en betydelig kilde av partikler og forurensninger som slippes ut i elver og andre resipienter. Akkumulering av tungmetaller kan påvirke den økologiske tilstanden i vassdrag betydelig, men det er også sett at fine partikler dekker til bunnsubstratet i elver og dermed hindrer gyting. Tungmetaller er i tillegg ofte bundet til de fine partiklene. Det er derfor viktig å redusere mengden fine partikler i vegavrenning før det slippes ut i resipientene. Vanlige sandfang virker å gi god tilbakeholdelse på partikler større enn 2 mm, men det er lite forskning som sier noe om hvor godt de holder tilbake fine partikler.

En virvelseparator, også kalt supersandfang, ble derfor studert for å undersøke om den kan fjerne en større andel fine partikler. Vannet som kommer i en virvelseparator rettes tangentielt for å skape en virvelstrøm som brukes for å fremme sedimentasjonen av partikler. Det ble installert en virvelseparator i Trondheim som får avrenning fra et område på E6. 28 sandfang samler avrenning fra et område på 4.7 hektar betående av veg og gresskledte grøfter. Etter at avrenningen er samlet i overvannsystemet går det gjennom et fordrøyningsbasseng med utløp i ytterligere et sandfang, før det sendes gjennom virvelseparatoren. En mengderegulator er plassert i kummen rett oppstrøms for å hindre at vannføringen overstiger kapasiteten til virvelseparatoren på 192 L/s. Produsenten av virvelseparatoren tilbyr 80% tilbakeholdelse av partikler med partikkelstørrelse større enn eller lik 146 µm ved en vannføring under kapasiteten.

For å undersøke tilbakeholdelsen av partikler ble det installert automatiske prøvetakere i kummene oppstrøms og nedstrøms virvelseparatoren. Disse ble koblet sammen med en sensor som registrerte vannnivå, og prøvetakerne kunne forhåndsprogrammeres til å starte prøvetaking ved et bestemt nivå i kummen. Det ble tatt prøver fra i alt fem hendelser i april og mai 2020 som ble delt inn i regnhendelser og snøsmelting. Disse prøvene ble analysert for partikkelstørrelser med en partikkelteller, i tillegg til å undersøke totalt suspendert stoff. I slutten av mai 2020 ble det også tatt sedimentprøver fra virvelseparatoren og sandfanget som er tilknyttet fordrøyningsbassenget. Disse prøvene ble analysert for partikkelstørrelser ved våtsikting i størrelsene 50-2000 µm. Fraksjonen under 50 µm ble i tillegg analysert med partikkelteller.

Resultatet fra avrenningsprøvene før og etter virvelseparatoren viser liten forskjell i de mediane partikkelstørrelsene. Det var heller ingen statistisk signifikant forskjell mellom partikkelstørrelsene eller suspendert stoff før og etter. 99% av alle partiklene i antall var mindre enn 1 µm, og over 50% av alle partiklene i volum var under 35 µm. For regnhendelser var den gjennomsnittlige konsentrasjonen av suspendert stoff 71.0 mg/L inn i virvelseparatoren og 56.3 mg/L ut. Snøsmeltingen viste en konsentrasjon på 7.2 mg/L inn og 6.5 mg/L ut. Tilbakeholdelsen av partikler ble da 20.7% og 10.2% for henholdsvis regn- og snøsmeltehendelser.

Sedimentprøvene viser også et høyt finstoffinnhold, der både sedimentene fra virvelseparatoren og sandfanget oppstrøms viser at omtrent 90% av partiklene i massene er under 50 µm. Kornfordelingen i sedimentene mellom det vanlige sandfanget og virvelseparatoren viser ingen betydelig forskjell. Analysen av fraksjonene under 50 µm viser at de fleste partiklene i antall var rundt 0.09 µm, mens hvis analysert etter volum ligger de fleste partiklene mellom 7-11 µm.

Analysene som er utført tyder på at det både er svært fine partikler som går inn og ut av virvelseparatoren, men også som blir igjen i systemet. Forholdet mellom en volumbasert kornfordeling og en kornfordeling basert på antall partikler virker å være at noen partikler er større i volum, men det er svært få av disse partiklene. De fine partiklene som kommer inn kan til en viss grad forklare hvorfor tilbakeholdelsen av partikler er mye mindre enn det som virvelseparatoren skal ha kapasitet til ifølge produsenten. Det ble også gjort beregninger på vannføring for de hendelsene i denne studien, der gjennomsnittlig vannføring ligger på 10-30 L/s, med maksimum vannføring på 70 L/s. Dette er fortsatt godt under kapasiteten til virvelseparatoren.

Forskjellen mellom sedimentprøvene i sandfanget oppstrøms virvelseparatoren og selve virvelseparatoren er liten. Ytelsen til disse virker da å være ganske lik med tanke på hvilke partikkelstørrelser som fanges. Sedimentprøver av vanlige sandfang i litteraturen i geografisk nærhet og med tilsvarende arealbruk viser betydelig variasjon i kornfordeling, men gjennomgående grovere fraksjoner enn det som er funnet i denne studien. Det er vanskelig å avgjøre om større andel små partikler i sedimentene skyldes at vegavrenningen inneholder kun fine partiker, eller om alle større partikler blir avsatt i det første sandfangene som ligger på E6. Det var ikke mulig å ta prøve av disse sandfangene i studieperioden, men det ansees som viktig å også analysere disse sedimentene for å kunne vurdere overvannsanlegget i helhet.

Denne studien inneholder for få observasjoner til å kunne konkludere med hvor godt virvelseparatoren vil fungere på et generelt grunnlag. Flere avrenningsprøver er nødvendig for å vurdere separeringen av partikler over flere sesonger. Det kan tyde på at anlegget virvelseparatoren står i er overdimensjonert, der de to sandfangene oppstrøms tar ut de fleste partiklene før de kommer til virvelseparatoren. Det bør vurderes videre hvor man skal plassere slike renseløsninger for å utnytte potensialet på en bedre måte.

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Abbreviations

AV	Area velocity
AADT	Annual average daily traffic
DIS	Dispersed
GIS	Geographical information system
GP	Gully pot
HVS	Hydrodynamic vortex separator
NAT	Natural
NTNU	Norwegian University of Science and Technology
PIDS	Polarization intensity differential scattering
PSD	Particle size distribution
R	Rainfall
S	Snowmelt
SPD	Sodium pyrophosphate decahydrate
TSS	Total suspended solids
VSS	Volatile suspended solids

Sediment removal performance of a hydrodynamic vortex separator

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Abstract

Roads and their associated activities represent a significant source of sediments and pollutants supplied to the urban drainage system and subsequent recipients. Reduction of the sediment loads is an important measure to avoid the discharge of fine particles and particle-bound pollutants to receiving water bodies. Hydrodynamic vortex separators (HVS) are a stormwater treatment measure that utilizes vortex flow to remove particles by swirl-enhanced sedimentation.

A full-scale HVS was installed in the city of Trondheim, Norway to collect runoff from a high-traffic road. The current study has evaluated the performance of the HVS for capturing fine particles compared to standard gully pots. Flow-triggered automatic samplers were used to collect runoff from inflow and outflow manholes. The particles were characterized by total suspended solids (TSS) and particle size distribution (PSD). At the end of the sampling period a sediment sample was taken from the sump of the HVS to analyze the PSD.

For rainfall and snowmelt events, the HVS achieved a sediment removal efficiency of 10-20%. The difference between median particle sizes in inflow and outflow was not statistically significant. The sediments captured in the HVS were fine particles where 90% of the mass have a particle size below 50 µm. The PSD in standard gully pots in literature showed coarser particles than the sediments from the HVS.

The results indicated that the PSD consisted of fine particles and consequently affected the performance of the HVS. This could be caused by an over-dimensioned treatment train or a low supply of sediments from the catchment areas. The HVS did not perform optimally in this treatment train. However, more runoff sampling is necessary over a longer period, in addition to sediment samples in other gully pots to fully understand the performance of the HVS and the treatment train.

Keywords:

Hydrodynamic vortex separator, particle size distribution, road runoff, sediment removal performance

Introduction

Particles in road runoff are considered a major source of pollutants supplied to the urban drainage system and subsequent recipients (Brezonik and Stadelmann, 2002). Urbanization will affect the deposition of particles and associated pollutants on impervious surfaces. Climate change will increase both the annual precipitation volume and the occurrence of short-term heavy rain in Norway (Hanssen-Bauer et al., 2015), resulting in increased transportation of deposited particles on roads. Atmospheric deposition, surface structure and material, vehicular transport, and metallic building envelopes are among the major pollution sources in urban runoff (Müller et al., 2020). Thus, runoff represents a significant non-point source of pollution.

Deletic et al. (2000) pointed to reduced hydraulic capacity in the pipes and direct pollution of recipients as problems caused by sediments entering the drainage system. The former is caused by deposited coarser particles, whilst the latter problem is induced by finer sediments staying in suspension throughout the drainage system. Sediments deposited on road surfaces, such as heavy metals, are the main source of pollutants (Ma et al., 2018). Several studies have investigated the fractionation of heavy metals, among others Helmreich et al. (2010), Kayhanian et al. (2012), and Monrabal-Martinez et al. (2018). Results indicated that the majority of heavy metals being particle-bound, with the concentration of metals increasing with decreasing particle size in the suspended fraction. Discharge of particles and associated heavy metals are seen to cause a pattern of ecological decline in urban streams (Marshall et al., 2010). Consequently, reducing the sediment loads, especially finer particles, is an important measure to avoid the consequences of discharging pollutants to the recipients.

In dense urban areas, there is a need for sediment removal structures that are underground and online with a small footprint (Wilson et al., 2009). A variety of solutions for removing sediments from road runoff exists. Several of the most common technologies are based on sedimentation, this includes e.g. gully pots, detention basins, and to some extent hydrodynamic vortex separators (HVS). Determining the efficiency of these devices to remove particles from runoff is difficult due to variations in configuration, methods to determine efficiency, and drainage specific variations (Wilson et al., 2009). Treatment efficiency can be divided into two different categories; the ability of the device to capture particles from the influent, and the ability to retain particles once captured.

Gully pots are a common sedimentation-based solution for particles from impervious surfaces such as roads and parking lots. The existing research on gully pots is mainly related to characteristics of the sediment content, investigated by among others Bennerstedt (2005), Jartun et al. (2008), and Poleto et al. (2009). These studies are looking at the characterization of the sediments in the gully pots and can only be used to identify what particles were captured in the pot. Inflow and outflow samples taken at the same time over a rainfall-runoff event will give a better indication of the ability of the device to both capture and retain particles. Practical considerations in the configuration of the drainage system make it difficult to obtain inflow and outflow samples of gully pots in the field. Research on HVSs has included inflow and outflow samples in the field and laboratory, by among others Hilliges et al. (2013), Lee et al. (2014), and Tran and Kang (2013).

Particle removal efficiency in gully pots varies with inflow rate, particle size distribution (PSD), and particle density (Butler and Karunaratne, 1995, Ciccarello et al., 2012). A comparison of PSD between street sediments and gully pot sediments suggested that street sediments contain a higher fraction of finer particle sizes than the sediment mass in gully pots. Washout and lack of maintenance are some of the explanations that influence the capability of gully pots to retain particles (Poleto et al., 2009). Leikanger and Roseth (2016) characterized gully pot sediments where the results indicated a high concentration of oil compounds. Adler (2020) looked at differences in PSD and heavy metal concentration in gully pots located in traffic and no-traffic areas. The results suggested that no-traffic areas in the city center were more heavily polluted.

The inflow into the HVSs are usually directed tangentially into the device to create a rotary flow regime utilizing the hydraulic conditions to separate particles from the flow (Andoh and Saul, 2003). HVSs have been used to remove particles in wastewater, in combined sewer overflows to reduce particle discharge to recipients, and in fish farming to remove feces and excess feed (Andoh and Saul, 2003, Solbakken et al., 2008). Comparing previous studies on these devices are difficult, as there exist many proprietary devices with different configurations (Wilson et al., 2009). Nevertheless, several studies suggest that the performance of HVS varies widely with rainfall characteristics, flow, and PSD, among others Hilliges et al. (2013), Lee et al. (2014), and Tran and Kang (2013). Episodes of negative removal efficiencies were also reported from these studies, suggesting that washout is a problem. This was especially seen for smaller particles such as clay and silt (Andoh and Saul, 2003, Wilson et al., 2009). Curwell (2015) studied the same proprietary HVS as in this study by taking inflow and outflow samples from urban runoff. The results showed little difference in PSD and an average treatment removal of 21.1% total suspended solids (TSS).

Several of the rivers in Trondheim are exposed to the discharge of fine particles covering the natural spawning grounds for fish (Nøst, 2019). Retrofitting standard gully pots with HVS could be an important measure to remove finer particle size fractions in road runoff. In order to evaluate the sediment removal capacity of the HVS, the following research questions were proposed:

1) What is the sediment removal performance of the HVS in separating particles from road runoff in the case study setup?
2) How does the particle size distribution in the sediments from the HVS differ from sediments in standard gully pots?

Materials and methods

Inflow and outflow samples were taken to analyze the particle sizes and loads before and after the HVS. The performance of an HVS was evaluated to see if the device was able to capture finer particles than a standard gully pot. The variations in treatment performance during, and over several rain events present uncertainty in the actual sediment removal efficiency.

Description of the study area

A full-scale hydrodynamic vortex separator (HVS) is located south of Trondheim, a coastal city in central Norway. The annual average precipitation is approximately 855 mm and the annual average minimum and maximum temperatures are -3.0 °C and 13.0 °C respectively (downloaded from www.eklima.no).

The HVS drains road runoff from a highway with an annual average daily traffic (AADT) of 24500 vehicles (Statens Vegvesen, 2020). Road runoff is collected in 28 roadside gully pots, with an estimated total catchment area of 47000 m^2. The study area is characterized by asphalt and grass-covered slopes alongside the road. Most of the gully pots have a dome grate inlet and are typically located at the end of swales connecting them to the HVS. The location of the HVS and a sketch of the drainage system is given in Figure 1.

Figure 1: The study area is located in Trondheim, Norway. The drainage area consists of 28 gully pots draining a high-traffic road (Kartverket, 2020b).

Road runoff could enter the drainage system in two ways: by infiltration in drainage swales alongside the road and collected in perforated sub-drains or collected as runoff in swales through the grate inlets. All runoff is diverted through gully pots before transported to the HVS. The gully pots in Trondheim, Norway normally have a diameter of 1000 mm, and the outlet is placed 1000 mm from the bottom (Trondheim Kommune, 2020b). This gives a sediment storage volume of approximately 0.8 m^3. Gully pots are typically designed for an inflow of 20-25 L/s. The longitudinal distance between each inlet on roads should be no more than 60-70 meters (Stiftelsen VA/Miljøblad, 2016).

The following detention basin has a volume of 88 m^3. The detention basin discharges into an additional gully pot with a diameter of 1600 mm, and a sediment storage volume of 2.0 m^3. Before runoff is entering the HVS, a flow regulator controls the flow to a maximum of 135 L/s, which is below the design flow of the HVS of 192 L/s (Hydro International, 2019). An overview of the treatment train with sampling locations are given in Figure 2.

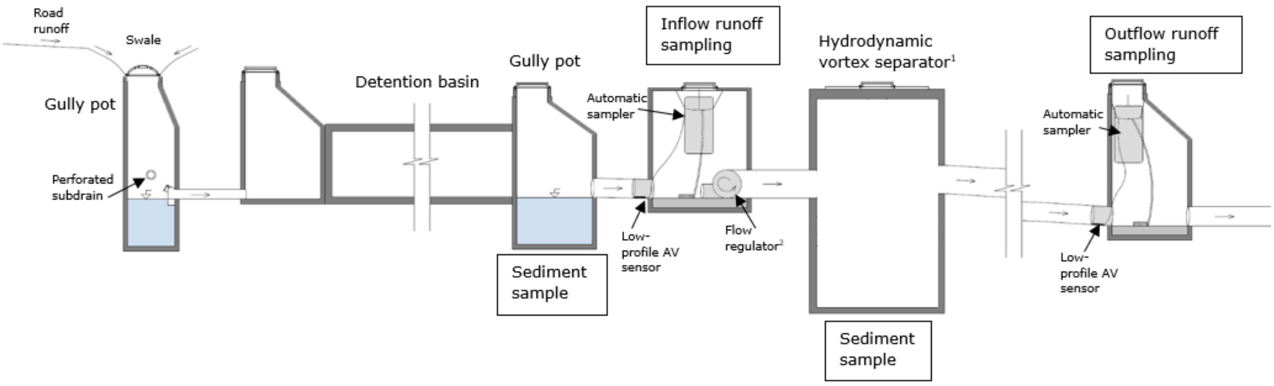

Figure 2: Schematic overview of the treatment train, sampling locations, and field set up.

[1]Downstream Defender D-2550.
[2]FluidCon Sun

The HVS consists of a submerged inlet, a cylindrical flow chamber, a collection zone for floatables, a sediment collection zone at the bottom, and an outlet (Hydro International, 2019). The HVS in this case study has an inner diameter of 2.55 m, an oil storage capacity of 2.5 m^3, and a sediment storage capacity of 3.8 m^3. A detail of the HVS showing the flow path of water and sediments with numbering are given in Figure 3. Runoff is directed tangentially through the submerged inlet into the flow chamber (1). Oil and floatables will rise to the surface and be captured in the upper zone (2). Water and sediments will be directed in a downward swirl (3), and when reaching the center cone, a zero-velocity flow zone will sweep sediments into an isolated sediment storage sump (4). The flow is then directed upwards around the center shaft and discharged through the effluent pipe (5) (Hydro International, 2007). Technical drawings from the manufacturer are given in Appendix A.

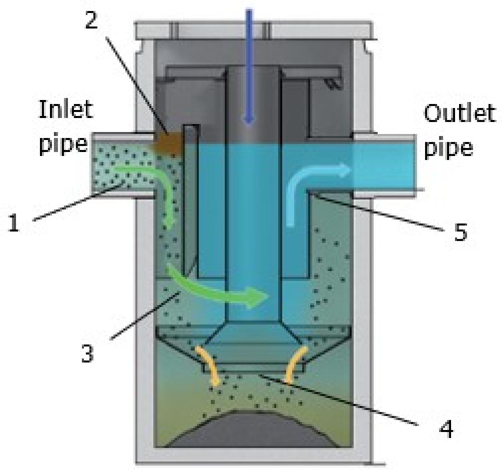

Figure 3: Detail of the HVS (Hydro International, 2019). The flow path numbering is described above.

Runoff samples

Several sampling strategies could be adopted in this case study. Flow-triggered automatic sampling was chosen as the sampling procedure as it is more practical, flexible, and effective compared to the alternative of manual sampling. Automatic samplers can be programmed to a certain frequency and volume. This makes it easier to obtain the first flush and maintains frequent sampling over the entire runoff event.

Both pre-defined flow levels and precipitation levels could be used to trigger the automatic samplers to start the sampling procedure. Flow-triggering was selected due to the direct relevance to the sampling location in the pipes. Precipitation triggering would need to consider a lag in the system from rainfall generates runoff at the sampling point.

The capabilities of automatic samplers to obtain a representative sample of the particles transported in runoff are questioned in the literature (Andral et al., 1999, Li et al., 2006, Sansalone et al., 1998, Selbig, 2013, Yun et al., 2010). Large and dense particles will be transported in the lowest position in the pipes as bed load. This is also where the intake of the automatic samplers is placed to sample during low flow conditions. The stratification of particles over the water column could result in a biased PSD towards larger particles (Selbig, 2013). However, automatic samplers were still chosen as the best alternative for the case setup to obtain runoff samples.

Automatic samplers were installed in the upstream and downstream manholes as shown in Figure 2, using steel chains and carabiners mounted to the concrete wall. The manholes immediately upstream and downstream of the HVS were chosen as sampling points to be able to evaluate the treatment efficiency of the HVS. Runoff samples were collected using two Teledyne ISCO 6712 Portable Samplers containing 24 polyethylene bottles of 500 mL. The samplers were connected to the Teledyne ISCO 750 area velocity (AV) modules that were continuously measuring water level, velocity, and discharge in the pipe (Teledyne ISCO, 2013).

Low-profile AV sensors were mounted in the invert position in the inlet pipes using stainless-steel spring rings. The low-profile AV sensors are connected to the automatic samplers causing them to start sampling at a set water level threshold. The measurement resolution of a low-profile AV sensor is 2.5 cm (Teledyne ISCO, 2013). Pictures of the equipment setup are given in Appendix B.

A perforated polypropylene strainer with a diameter of 3.3 cm and length 26.7 cm was placed downstream of the low-profile AV sensor to pump up water (Teledyne ISCO, 2016). The sampling routine was triggered by a pre-determined water level in the channel, set to 3.5 cm at the inflow sampling point, and 3.0 cm at the outflow sampling point, just above the diameter of the strainer. This is an optimization between capturing the first flush and at the same time ensuring sufficient water depth for pumping. Due to problems with lag and smoothing of flow in the downstream sample point, the trigger level was adjusted for the outflow from 3.5 to 3.0 cm as an attempt to minimize this problem. A time lag of approximately 20 minutes and generally lower flow levels were observed in the downstream sampling point.

When the low-profile AV sensor registered the specified depth of water, the samplers would collect 120 mL every 5 minutes for the duration of the pre-determined water level. This resulted in composite samples of 480 mL every 20 minutes in each bottle, and a potential of up to 8 hours of sampling for each event. When the water level dropped below the specified level, the samplers were disabled.

Rainfall was recorded using a 0.2 mm tipping bucket gauge, the ECH2O ECRN-100, located within 1.5 meters from the HVS, and within 100 meters of the drainage areas. The gauge was connected to a data logger, the EM50 Data collection system, providing a 5-minute resolution on rainfall data in the sampling period.

The sampling was conducted on one rainfall-runoff events, two snowmelt events, and two rainfall-induced event with some additional snowmelt in the end during the period from April 2020 to May 2020 given in Table 1. The last two events were characterized as rainfall. Due to the lag problem described above, it was often observed that the automatic samplers in the inflow manhole were triggered more frequently than the downstream. In total 81 inflow samples and 38 outflow samples were collected, however, only 30 inflow and outflow samples were paired to analyze the treatment performance of the HVS. Salt was used as a de-icing agent on the road over the sampling period.

Table 1: Overview of the sampling period. The events are divided into rainfall and snowmelt.

Event number	Date	Type of event	Rainfall [mm]	Antecedent dry period [min]	Rainfall duration [min]	Sampling duration [min]	Number of samples [n]
1*	14.04.2020	Rainfall	3.8	125	75	290	12
2*	15.04.2020	Rainfall	11.6	540	400	184	18
3*	20.04.2020	Snowmelt	-	-	-	123	12
4*	21.04.2020	Snowmelt	-	-	-	140	16
5	06.05.2020	Rainfall	4.8	865	115	83	2

*stored for two weeks outdoors due to COVID-19 lab access restrictions

Hydrograph

The time-area method was used to get an indication of the flow into the HVS from the catchment areas to better assess the sediment removal performance (Butler and Davies, 2017). A map of the designed drainage network was supplied from Trondheim Municipality. The map included gully pot inlets, stormwater manholes, pipes, and field drains. Coordinates for gully pot inlets were estimated from the map and used to draw the catchment areas to each inlet. The catchment areas were mapped out manually using ArcMap 10.7.1, geographical information system (GIS) program. The estimation of the areas was based on field observations. Vector data of the road surface were downloaded to calculate the land use categories using ArcMap (Kartverket, 2020a). A map of the estimated catchment areas is given in Appendix C.

The surface consists of two land use categories: asphalt, and grass-covered slopes and swales. The fraction of each land use category was found using the Analysis-toolbox in ArcMap to obtain the road surface in each catchment area. The runoff coefficient, also called the C-value, was set to 0.95 for the asphalt areas, and 0.6 for the grass-covered areas. This is based on the area being newly constructed, new asphalt will have little storage space for water in pores and recessions on the road. In addition, the underlying soil in the catchment area is marine clay (Norges geologiske undersøkelse, 2020). Assuming little of the water will infiltrate, a high runoff coefficient for the grass-covered areas was chosen.

Time of concentration (T_c) is defined as the time required for runoff to flow from the farthest part of the catchment area to the point of interest (Butler and Davies, 2017). T_c is divided into time of entry, also called overland flow, and time of flow in pipes. The overland flow was obtained by using a nomograph from the stormwater calculation guidelines from Trondheim Municipality (Trondheim Kommune, 2020a). The nomograph is based on the slope, length, and runoff coefficient of the catchment area. Time of flow is calculated using the approximation of pipe-full velocity from Manning's formula (Butler and Davies, 2017). Since the slope of pipes is unknown it is estimated to follow the slope of surface. A Manning's roughness coefficient of 0.015 was used (Ødegaard et al., 2014). The nomograph and formulas for calculating T_c are given in Appendix D.

The information presented above was used to create a time-area diagram for each of the 28 catchment areas. The time-area diagram is used to produce a flow hydrograph from time-varying rainfalls for each rainfall event. The flow was calculated under the assumption that the soil was not saturated from previous rainfall events. The time-area diagrams are given in Appendix E together with the formula for calculating the runoff. Rainfall events used to calculate the hydrographs are given in Appendix F.

Due to the lack of information about the catchment area and no real hydrographs to validate the calculated hydrographs from the time-area method, the hydrographs will only indicate the flow at the HVS. A calibration procedure of the three rainfall-runoff events was conducted. The calibration was based on the information about the length of the sampling periods.

Lab analysis

PSD determines many sediment properties and influences the treatment efficiency in sedimentation-based processes (Charters et al., 2015). Traditionally, TSS is used as a parameter for evaluating particle removal in treatment processes. However, Ferreira and Stenstrom (2013) suggested that using PSD in evaluating treatment performance in sedimentation-based units gave more accurate removal rates. In the following sections, the methods for the determination of PSD and TSS in runoff samples are explained.

Particle size distribution

PSD was analyzed using a Beckman Coulter LS230 for particle sizes ranging from 0.04 µm to 2000 µm. The use of a laser diffraction particle size analyzer was chosen to analyze the PSD due to the possibility of measuring particle sizes over a wide size range and with low solids concentration in the sample. Mass-based PSD obtained by wet or dry sieving is another common method for particle sizes above 45 µm (Li et al., 2005). Due to the low concentration of solids and interest in finer particles, this method was found unsuitable for this purpose. Based on the Fraunhofer model, the Coulter LS230 computes the pattern of light scattering as a function of scattering angle for each size classification. For particles between 0.04 µm and 0.4 µm, polarization intensity differential scattering (PIDS) was used. Distributions could be represented as volume-, number, or surface-based (Beckman Coulter, 2011).

Runoff samples should ideally be stored at 4 °C and analyzed for particle sizes within 6 hours to minimize the effects of particle aggregation (Li et al., 2005). Due to the closing of the university and laboratory during the COVID-19 pandemic, samples 1, 2, 3, and 4 were stored for two weeks outdoors. The storage temperature was below 10 °C and direct sunlight was avoided. Samples from event 5 were analyzed within 24 hours.

De-ionized water was used as background liquid and de-bubbled before adding the sample to minimize air bubbles affecting the measurements. Between 5 and 140 mL of sample was inserted using a pipette with a truncated tip or by pouring directly from the sample bottle to obtain a PIDS between 45-55% and obscuration of 8-12% (Beckman Coulter, 2011). The extracted amount was dependent on the concentration of particles in each sample. The sample was inserted gently to avoid bubbles and the bottle was inverted between each extraction. Due to the low concentration of solids in some samples, the target range of PIDS and obstruction were not always possible to attain. The Coulter LS230 has the target range of solid concentration to be able to measure the finest particles, and this could lead to a shift towards larger size fractions in the PSD. When the Coulter had registered sufficient concentration or the maximum sample volume was inserted, three runs with a duration of 90 seconds were conducted consecutively. Ideally, the variation of the three resulting PSDs should be less than 1%. The pumping speed was adjusted experimentally to obtain as stable sample as possible but was kept constant when first determined. Between each sample, the device was flushed three times with de-ionized water.

Total suspended solids

TSS were determined by filtration of the sample through 0.45 µm cellulose nitrate filter with a basis in the standard NS-EN 872 (Standard Norge, 2005). The standard is valid for glass fiber filters, but the same procedure was followed in this study. The determination of TSS was carried out using vacuum filtration. The low concentration in some samples made it difficult to obtain the optimum range of 5 to 50 mg dry residue on each filter. All samples were however above the limit of detection of 2 mg/L.

Due to the organic nature of the filter with pore size 0.45 μm, the volatile fraction was obtained by filtering excess samples through glass microfiber filters with pore size 1.2 μm. This was only done with the samples that had above 40% of the sample left after PSD and TSS analysis. The samples were vacuum filtrated and the organic fraction was determined according to the standard NS-EN 872 (Standard Norge, 2005).

The removal efficiency of the HVS was calculated based in the average TSS concentrations in the inflow and outflow for the event categories. The percentage removal was calculated from Equation 1.

$$\text{Removal efficiency [\%]} = \frac{Inflow\ TSS - Outflow\ TSS}{Inflow\ TSS} \times 100 \qquad \text{Equation 1}$$

Sediment samples

To evaluate the treatment train in this field study, the sediments captured within the system were collected and analyzed. Initially, the two gully pots and the sump of the HVS were to be sampled. Because of safety and time considerations, the gully pots at the road were not attainable due to high traffic and no scheduled maintenance from the municipality in the study period.

Two sediment samples were therefore taken from the gully pot right upstream of the HVS (subsequently called upstream GP) and from the sump of the HVS as shown in Figure 2. A soil gripper of stainless steel was used to take composite grab samples of one liter. The upstream gully pot and HVS were both emptied approximately 11 months prior to the collection of sediment samples. The sediment depth was so low that samples from several layers were not possible. A suction vehicle provided by Trondheim Municipality suctioned up the top-water to examine the sediment depths before sampling.

Lab analysis

PSDs in the sediment samples were determined by manual wet sieving for particles between 50 and 2000 µm and a laser diffraction particle size analyzer for particles below 50 µm. The fraction of volatile solids was also evaluated for every size fraction.

Particle size distribution

The determination of the PSD in gully pot sediments was based on the adaption of the method developed by Adler (2020) and is described in the following section. The PSD was obtained by manual wet sieving of particles between 50 – 2000 µm. Additionally, particles below 50 µm were analyzed using the Beckman Coulter LS230. Wet sieving resulted in a mass-based PSD, whilst the Coulter LS230 gave a volume- and number-based PSD.

Sediments found in the urban environment consist of a mixture of individual particles and aggregates (Roberts et al., 1988). To evaluate the effect of particle aggregation on the PSD a gentle dispersant was used to separate particles. 3 g/L sodium pyrophosphate decahydrate (SPD), or $Na_4P_2O_7*10H_2O$, was chosen as a dispersant. SPD was used in crystal form as an optimization between separating the aggregations and destroying or changing the particles (Adler, 2020, Konert and Vandenberghe, 1997).

As the samples were collected in 1 liter-bottles, a riffle splitter was used to create two equal subsamples to compare the sample with and without dispersant. To prevent overloading of the smaller mesh-sizes or underloading of the bigger sieve sizes, a dry mass of 100 g was intended according to the NS-EN ISO 17892-4 (Standard Norge, 2016). This was obtained by an initial weight of approximately 300 g of wet samples depending on the size distribution in the sample.

Eight stainless steel sieves with diameter 200 mm and mesh sizes 50, 75, 100, 150, 250, 500, 1000, 2000 µm were used to determine the PSD. This was adapted for comparison with the Hydro International (2015) technology verification report for the HVS in this study. The sample was diluted to approximately four liters using distilled water before it was poured over the sieve stack. Particles with size below 50 µm were collected in a tray. Each sieve was flushed with 0.5 liters distilled water where the flush water was collected and poured over the remaining sieves standing over a new tray. The flushing was repeated over a third tray. The remaining particles on each sieve were transported carefully into beakers using distilled water. Samples were dried at 105 °C for at approximately 72 hours according to the standard NS 4764 (Standard Norge, 1980). The dried samples were cooled in a desiccator, weighted, dried again for one hour and weighted again to ensure a completely dry sample. Particles above 2000 µm were not included in the PSD calculations to avoid underestimating the smaller fractions.

For the particles below 50 µm, a sample of 100 mL was subtracted from the first tray after gently stirring the tray by hand. 20 mL was subtracted with a pipette and diluted with 30 mL of distilled water. Then 5 mL of the diluted sample was added to the Coulter LS230 to obtain the necessary PIDS and obscuration as described in above for the runoff samples. Due to a higher concentration of particles in the sediments compared to the runoff samples, the pumping speed was adjusted to a slightly higher level. The device was flushed three times between each sample. Distilled water was used as background liquid.

The procedure described above was repeated for the second subsample after adding 3 g/L of SPD. The sample was soaked overnight for at least 12 hours (Statens Vegvesen, 1997). The added weight of dispersant was subtracted from the fraction mass of particles below 50 µm which are flushed into the tray with the small particles. 3 g/L SPD was also used as background liquid in the Coulter LS230.

Ignition loss
The fraction of organic matter in the collected sediments was determined according to the standard NS 4764:1980 (Standard Norge, 1980). The samples without dispersant were chosen to analyze organic matter in each size range from the sieves.

Statistical analysis

Statistical analysis was conducted using the statistical computing program RStudio. The inflow and outflow samples taken before and after the HVS were divided into two categories based on the type of event: rainfall (n=16) and snowmelt (n=14) events. The Shapiro-Wilk test was used to test for normality. Due to non-normality in most of the data, the Wilcoxon sign rank test was used to evaluate statistically significant differences with a p-value of 5%. D_{50} (i.e. the particle size at which 50% of the particles pass) and TSS were used in the statistical analysis. To evaluate the statistical difference between inflow and outflow samples in each category, a paired two-sample Wilcoxon test was used. An unpaired two-sample Wilcoxon test was used to study the difference between rainfall and snowmelt events.

Results

Characterization of runoff

Runoff samples were divided into rainfall and snowmelt events. There was a statistically significant difference both for the observed PSDs and for the TSS between these two categories. The sediment removal performance was evaluated by analyzing PSD and TSS in runoff samples before and after the HVS.

D_{50}, or the median particle size, is used as a representation of the PSD in Figure 4. It represents the particle size where 50% of the particles are smaller than this size. The PSD was analyzed based on volume, and number distributions. These PSDs express the percentage that each size class takes up of the overall distribution calculated as a percentage of the total volume or number of the particles. For the volume-based PSD in Figure 4 A) the median D_{50} for the inflow and outflow was 9.16 µm and 9.95 µm for rainfall events and 35.34 µm and 35.79 µm for snowmelt events, respectively. The number-based median D_{50} Figure 4 B) was 0.10 µm for inflow and outflow at rainfall events. For snowmelt events, the median D_{50} for inflow and outflow were 0.17 µm and 0.13 µm. Outliers were found in both categories.

A) **B)**

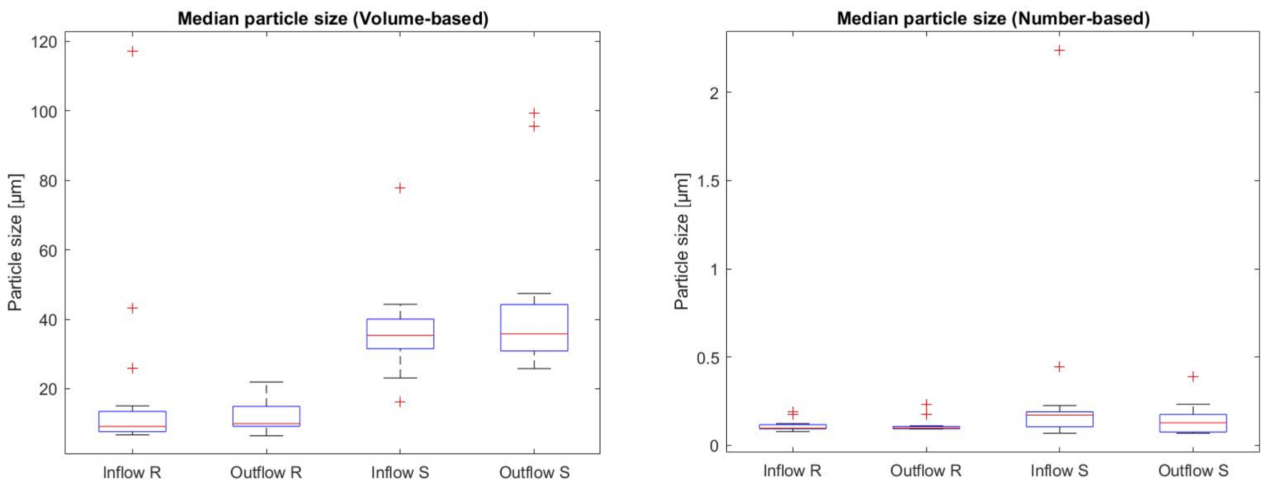

Figure 4: Box-and-whisker plot for median particle size (D_{50}) from the runoff samples analyzed by the Coulter LS230. Upper and lower bounds of the boxes refer to the 25th and 75th percentiles and the difference represents the interquartile range. The line in the middle of the boxes is the median of the sample. Whiskers represent the observations within the interquartile ranges. Outliers are values more than 1.5 times the interquartile range from the upper or lower bounds. **A)** The median particle sizes from a volume-based PSD, **B)** The median particle sizes from a number-based PSD. R stands for rainfall events and S for snowmelt events.

The Shapiro-Wilk test indicated non-normality in the median particle sizes from the inflow and outflow samples with a 95% confidence interval. The Wilcoxon sign rank test showed no evidence for a statistically significant difference in the inflow and outflow samples. The volume-based D_{50} had a p-value of 0.528 and 0.241 for rainfall and snowmelt events, whilst the number-based showed a p-value of 0.501 for rainfall events and 0.358 for snowmelt events. This means the null hypothesis was not rejected for the D_{50} particle size in these samples. Appendix G contains cumulative summary statistics for D_{10}, D_{50}, D_{90} characterizing the PSD.

The concentration of TSS, determined by filtration through a 0.45 µm filter, is shown in Figure 5. The inflow and outflow of the rainfall events had a median concentration of 40.6 and 46.0 mg/L, respectively. For snowmelt events, the median inflow concentration was 6.4 mg/L and the median outflow concentration was 5.8 mg/L.

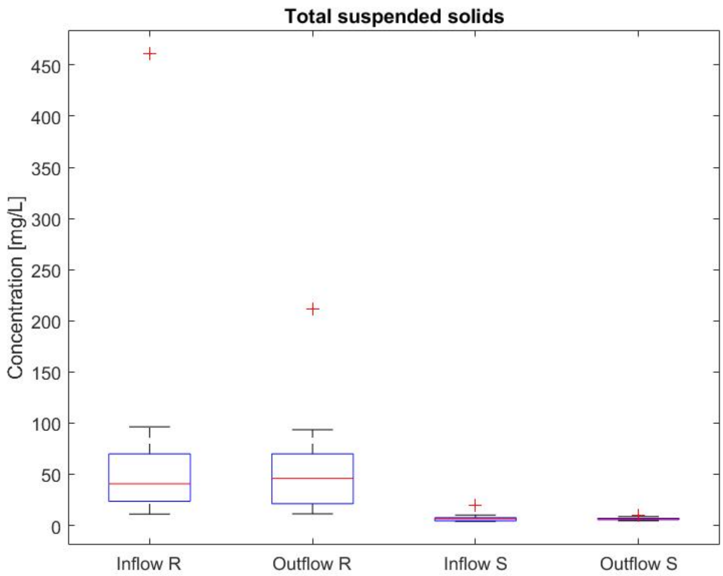

Figure 5: Box-and-whisker plot for TSS concentration in mg/L from the runoff samples. Upper and lower bounds of the box refer to the 25th and 75th percentiles and the difference represent the interquartile range. The line in the middle of the box is the median of the sample. Whiskers represent the observations within the interquartile ranges. Outliers are values more than 1.5 times the interquartile range from the upper or lower bounds. R stands for rainfall events and S for snowmelt events.

For rainfall events the average TSS concentrations were 71.0 mg/L and 56.3 mg/L for inflow and outflow, for snowmelt events the average TSS concentrations were 7.2 mg/L and 6.5 mg/L for inflow and outflow. The removal efficiencies calculated using Equation 1 were 20.7% and 10.7% for rainfall events and snowmelt events, respectively. The Wilcoxon sign rank test showed no statistically significant difference between concentration in inflow and outflow for the two categories with p-values of 0.900 and 0.903 for rainfall and snowmelt events. Appendix G contains statistical summary of the TSS results.

The organic fraction in the runoff samples was determined by filtering through 1.2 µm followed by loss of ignition. Figure 6 shows a median inflow organic fraction of 22.9% and a median outflow organic fraction of 22.3%. Only rainfall events had a sufficient volume of the runoff samples.

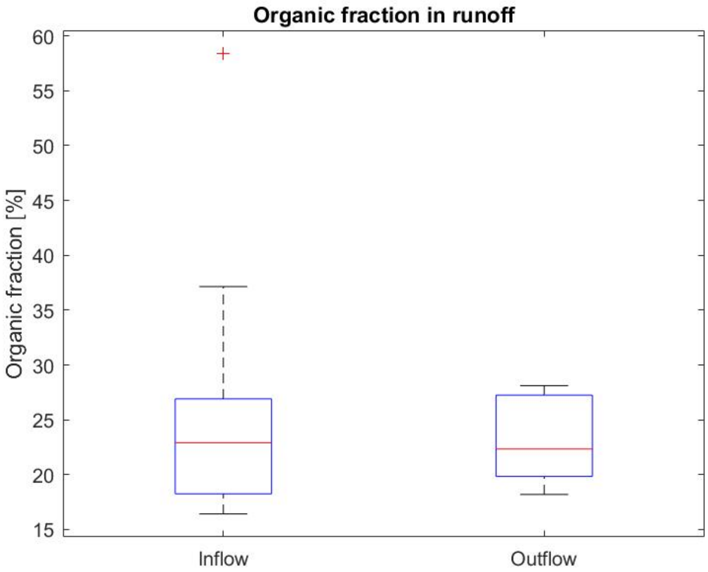

Figure 6: Box-and-whisker plot for TSS concentration in mg/L from the runoff samples. Upper and lower bounds of the box refer to the 25th and 75th percentiles and the difference represent the interquartile range. The line in the middle of the box is the median of the sample. Whiskers represent the observations within the interquartile ranges. Outliers are values more than 1.5 times the interquartile range from the upper or lower bounds. The organic fraction in runoff samples for samples with excess volume left after PSD and TSS analysis. The number of observations n=12 for inflow and n=7 for outflow.

Flow hydrographs were computed by the time-area method and applied to measured rainfall from the three rainfall events (Event 1, 2, and 5 in Table 1). The flow over the rainfall-runoff events is shown in Figure 7 A), B), and C). An uncertainty shade of ±30% were applied to account for uncertainty in the calculations and no real measurements to properly calibrate and validate the hydrographs. The uncertainties were calculated based on average flow. The average flow with 30% uncertainty was 20.6±6.2 L/s, 14.7±4.4 L/s, and 18.6±5.6 L/s for events 1, 2, and 5 respectively. Event 5 had the highest flow with 70 L/s included 30% uncertainty.

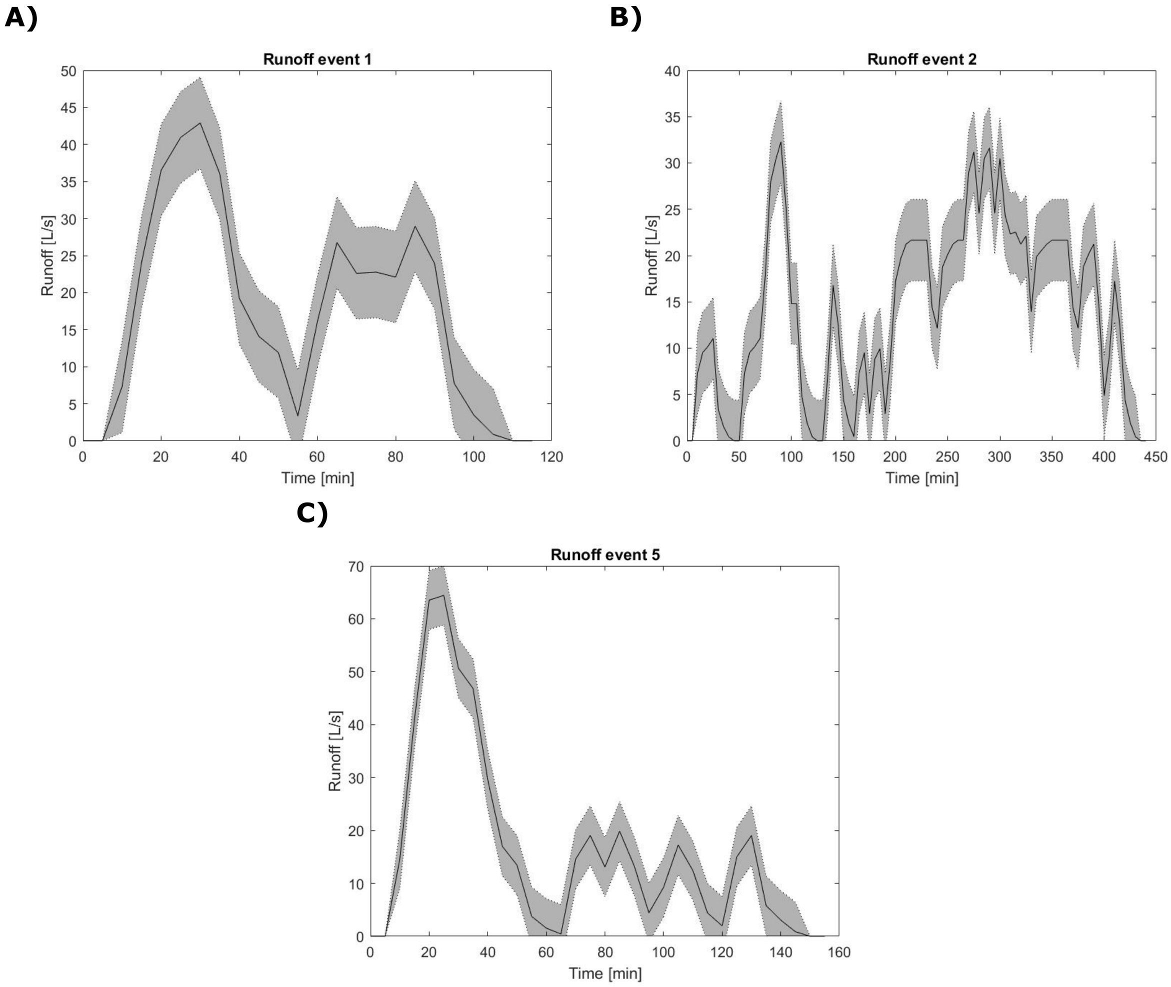

Figure 7: Flow hydrographs for the three rainfall-runoff events (Event 1, 2, and 5 given as **A)**, **B)**, and **C)**, respectively). The grey shade were added as ±30% uncertainty. The uncertainty were calculated based on the average flow during the event and added to account for estimations made during the calculation.

Sediment samples

Sediment samples were taken from the upstream GP and the HVS to further evaluate the sediment removal performance of the treatment train. Figure 8 shows the mass-based PSD from wet sieving as differential weight in each size range with (DIS) and without dispersant (NAT). The particles above 2000 µm were disregarded to not underestimate the finer particles.

The HVS showed 91.1% and 90.5% particles in the fraction <50 µm with and without dispersant, respectively. In the upstream GP, the fraction <50 µm contributed to 84.4% with dispersant and 89.6% without dispersant. Appendix H contains extended information about results from the sediment samples.

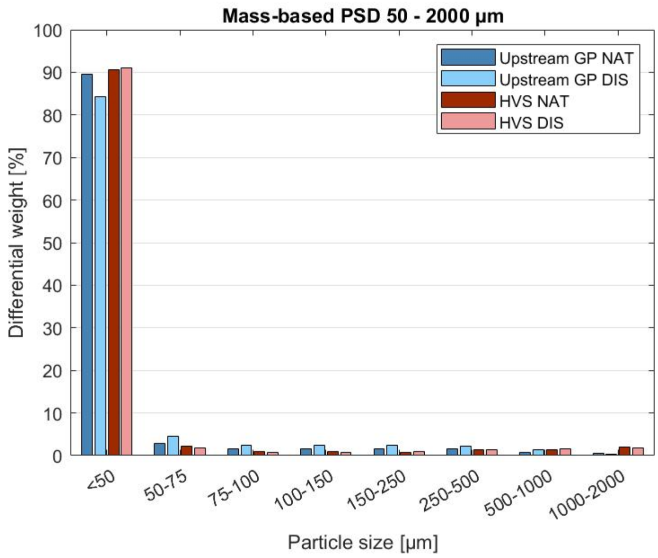

Figure 8: PSD by wet sieving for the size range 50 -2000 µm showing the percent of the mass retained in each size fraction. The results are displayed with and without dispersant, as DIS and NAT, respectively.

The size fraction <50 µm is shown in Figure 9 A) and B) as a differential volume- and number-based PSD. The differential volume-based PSD showed most particles in the size 7.42 µm and 8.94 µm for the HVS with and without dispersant contributing to approximately 3.3.% of the volume. The upstream GP had 3.4% of the volume in particle sizes 9.82 µm and 17.18 µm with and without dispersant. The number-based PSD in the HVS had 7.8% of the particle sizes at 0.084 µm and 0.077 µm with and without dispersant. The upstream GP had approximately 9% of particles at 0.077 µm both with and without dispersant. A summary of the cumulative statistics is also given in Appendix H.

A) B)

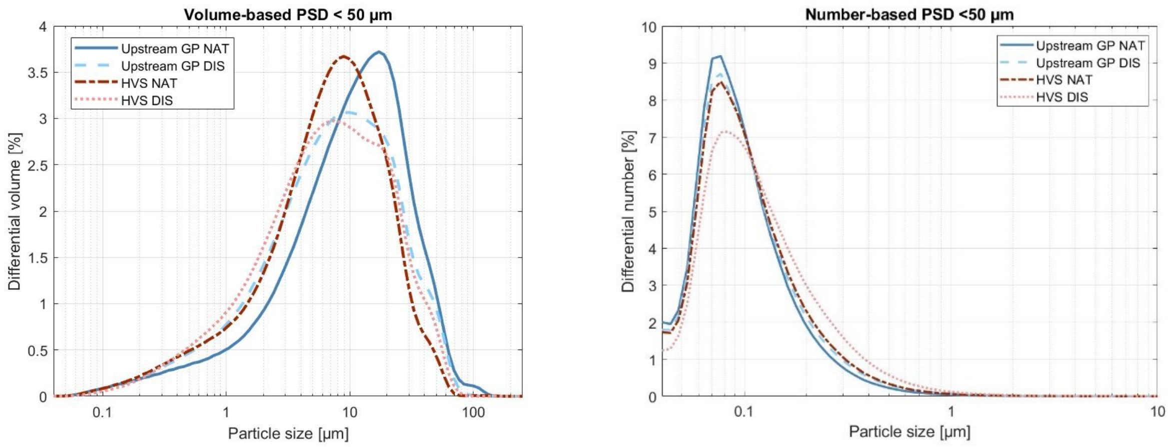

Figure 9: Differential PSDs in sediment samples from the upstream GP and the HVS. The results are displayed with and without dispersant, as DIS and NAT, respectively. **A)** Volume-based PSD for the fraction <50 μm given as percent of volume in each size fraction with a logarithmic x-axis, **B)** Number-based PSD for the fraction <50 μm given as percent of volume in each size fraction with a logarithmic x-axis.

The organic fraction in each size range was determined by ignition at 550 °C to determine the ignition residue, or the organic fraction displayed in Figure 10. The upstream GP had an organic fraction in the range 17.4-41.2%, with an average of 26.6%. Fractions from the HVS ranged from 5.75-24.29%, with an average of 17.29%. Particles in the fraction >2000 μm were disregarded.

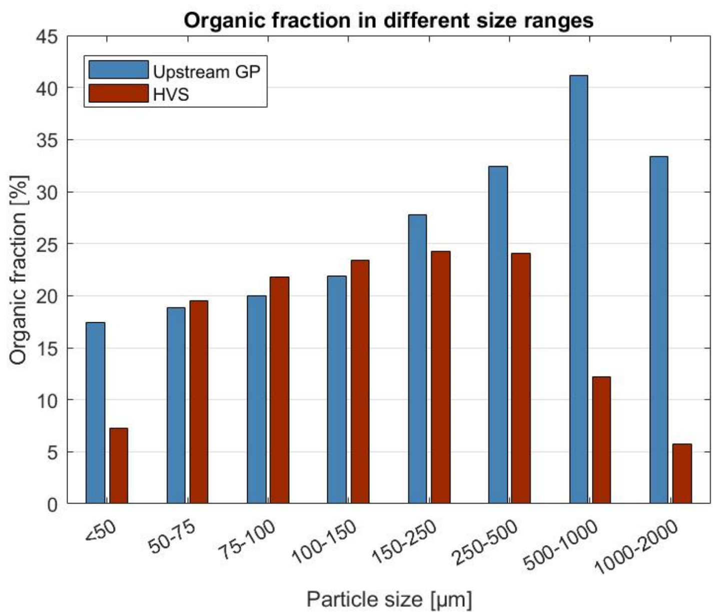

Figure 10: Organic fraction of particles in every size range from wet sieving.

Discussion

This paper set out to evaluate the sediment removal performance of an HVS in separating particles from road runoff by conducting a field study. The sediments captured within the treatment train were also collected, analyzed, and compared to standard gully pot sediments in literature.

Sediment removal performance

The results of the PSDs given in Figure 4 indicated that the inflow and outflow distributions are quite similar for both event categories. Especially the number-based PSD showed little differences between inflow and outflow for rainfall events, whilst the variations were slightly bigger for snowmelt events. Similar results in the PSDs were also seen from Curwell (2015) in the same proprietary HVS as in this study, with a volume-based D_{50} of 15.85 and 16.60 µm in the inflow and outflow, respectively. The land use was slightly different with a mix of residential, highway, and light industrial.

Based on field observations of the catchment area in the sampling period, the snowmelt events did most likely not come from road runoff. The only snow storage in the catchment areas was around the five gully pots on the west side located in the residential area (Figure 1). These results contributed to the evaluation of the performance of the HVS. Nevertheless, they say nothing about the performance in separating particles from road runoff.

The volume-based PSDs showed higher variations with multiple outliers in Figure 4 A. Due to few observations, the outliers were kept in the PSDs. Variations in PSD was especially large for the events 1, 2, 3, and 4 that had been stored for 2 weeks due to COVID-19 compared to event 5 which was analyzed the day after sampling. This may be explained by particles aggregating during storage time. A study on particle aggregation in stormwater samples in storage indicated that particles aggregate rapidly after 10 hours (Li et al., 2005). Besides variation in the individual PSDs, the inflow and outflow samples for each event were stored equally long, minimizing the difference when comparing these samples.

The PSDs based on volume are higher than the distribution based on the number of particles. This may be due to some big particles with a high volume biasing the PSD towards larger particle sizes. The number-based PSD was thought to better represent the finer particles. Over 99% of the particles were below 1 µm by number, however by volume over 90% of the particles were below 220 µm. This implied that some particles with large volumes and low numbers were influencing the volume-based PSD. Finer particles are often many in number but contribute only to a minor fraction of the mass and volume (Kayhanian et al., 2012, Li et al., 2005).

The concentration of TSS showed only a small difference between inflow and outflow. The rainfall events had a higher TSS concentration than snowmelt events, most likely due to less supply of accumulated sediments on the road. New particles were not supplied from vehicular activities in these snowmelt events as mentioned above. Highway runoff pollutant concentrations were found in literature to be significantly influenced by total event rainfall, antecedent dry period, catchment area, and AADT, as well as surrounding land use and geographic regions (Kayhanian et al., 2007). A larger number of observations and events are needed to establish a similar trend in TSS supplied in these catchment areas.

The sediment removal performance was lower than expected for the sampled categories, ranging from 10-20%. A similar removal efficiency was also seen in the study of Curwell (2015) with an average removal performance of 21.1%. The manufacturer stated a removal of supplied particles of 80% for particles larger than 146 μm in size when the flow is below the capacity of the HVS (Q<192 L/s) (Hydro International, 2015). In the following, possible reasons for the low removal performance are discussed.

Since it was not possible to measure the flow going into the HVS, flow hydrographs were estimated using the time-area method. Event 5 had the highest flow up to 70 L/s, including 30% uncertainty with the average flow for this event 24.1 L/s. Both peak and average flow were well below the capacity of the HVS. The flow regulator in the upstream manhole has a capacity of 135 L/s. If the flow exceeded the capacity of the flow regulator, the detention basin will fill up. This ensured that the flow did not exceed the capacity of the HVS resulting in low treatment performance in these events. The installation of a flow meter to monitor the flow could be beneficial to evaluate sediment removal performance as the event mean concentration in future research (Barrett, 2005).

Looking at the PSD in Figure 4 A and B, it was apparent that the sediments coming into the HVS consisted of fine particles. By volume in rainfall and snowmelt events 90% of that particles were below 130.25 μm and 224.94 μm, respectively. By number, 90% of the particles were below 0.27 μm and 0.76 μm in rainfall and snowmelt events. This could to some extent explain the low treatment performance observed for the sampled events in this study. Very few particles coming into the HVS are larger than 146 μm, as was the limit for 80% removal of particles promised by the manufacturer.

The inflow of fine sediments may be attributed to the design of the treatment train. The runoff is diverted through two gully pots before reaching the HVS. The first gully pot is a standard gully pot with a diameter of 1000 mm, the second gully pot is larger than normal with a diameter of 1600 mm. Due to the varying PSDs of road runoff (Charters et al., 2015, Kayhanian et al., 2012, Selbig, 2013), it was difficult to determine if the road runoff from these catchment areas consisted of fine particles or if most of the coarser particles were removed by the two upstream gully pots. The removal performance of these gully pots will also vary with inflow and PSD (Butler and Karunaratne, 1995, Ciccarello et al., 2012). Besides, some particles may also be removed by filtration in the drainage swales before entering the drainage system. This was not further investigated in this thesis.

The percentual removal performance was also strongly dependent on the influent concentrations of solids. If the inflow solid concentrations are low, the percent removal will be correspondingly low (Barrett, 2005). Looking at the events individually, the removal performance varied from -5.4% to 54%. Combined with the low number of samples, the removal performances were not suitable to fully evaluate the general performance of the HVS. The results of this study can only indicate how the HVS performed with the road runoff in this treatment train.

The median organic fractions in the inflow and outflow were quite similar with approximately 22-23%. Looking at the distribution, the inflow had more variations in the samples, ranging from 16.4-58.4%, whilst the organic fraction in the outflow ranged from 18.2-28.1%. These samples were not paired as the rest of the runoff samples but were analyzed to characterize the fraction of organic matter. The results could indicate that a portion of the organic matter is captured in the HVS, however, more samples are necessary to conclude in this case.

There was no statistically significant difference between the inflow and outflow median particle size, possibly due to the low number of observations. The five events were also sampled over less than 30 days, suggesting that they may not be representative of the annual performance. Thomson et al. (1997) indicated e.g. that a sample size of 15-20 was needed to characterize road runoff. Time constraints and restrictions after the COVID-19 made it impossible to obtain more samples in this study. However, more runoff samples over a larger period are necessary to further evaluate the differences in PSD between inflow and outflow.

Another operational problem resulting in the low number of samples was the skewed distributions between inflow and outflow samples. As the automatic samplers were programmed to start sampling at a pre-defined threshold, fluctuating time lag was experienced together with lower flow levels in the outflow. In total over 80 samples were collected in the inflow but only 38 in the outflow. This resulted in at least four events being disregarded from this study as only the inflow sampler was triggered. Curwell (2015) experienced the same problem with the delayed flow and suggested installing a flow meter in the outflow sampling point as a solution. Since this already existed in this study, the problem may be an over-dimensioned treatment train needing a larger storm event to generate enough flow to trigger the sampling program. Future studies should also tempt to experiment with the pre-determined water level threshold to minimize this problem.

Comparing the PSD of the runoff samples before and after the HVS to road runoff in literature was difficult. PSD in rainfall-runoff studies varied substantially attributed to differences in sampling method, analytical methods, spatial and temporal variations (Kim and Sansalone, 2008, Monrabal-Martinez et al., 2018, Selbig, 2013). Monrabal-Martinez et al. (2018) investigated runoff on the road surface in Trondheim, the same city as in this study. The volume-based D_{50} was in the range of 5-10.5 μm with AADT of 22140, which is substantially smaller than the D_{50} of 19-36.97 μm found in the inflow and outflow of this study. Westerlund and Viklander (2006) conducted a study in Luleå, Sweden, and found number-based D_{50} ranging from 4-6 μm, which is higher than the findings of this study (0.11-0.32 μm by number). A site-specific PSD is often necessary to conclude on what particles are entering the drainage system (Selbig et al., 2016).

Comparison of sediment samples

The PSDs for the fractions 50 – 2000 µm and <50 µm were not directly comparable due to the differences in mass-based PSD from wet sieving and volume- and number-based PSD from the Coulter LS230. The different PSDs will be used to complement the discussion to characterize the whole PSD from 0.04 – 2000 µm.

The sediment samples taken from the HVS and upstream GP showed that the majority of particles by mass were in the <50 µm fraction. The fractions 50 – 2000 µm had mass percent in each fraction ranging from 0.4 – 4.5%. It was expected that the PSDs in the sediments in the gully pot and the HVS should deviate from each other as the configuration of these devices is different. However, the PSDs were quite similar, except that the upstream GP had slightly lower mass in the <50 µm fraction. Looking at the inflow runoff this could be explained by the runoff coming into the upstream GP consisting of coarser particles. This could also indicate that the HVS was not performing better than a gully pot in this treatment train. The site-specific inflow of particles are largely determining what particles are captured in the sediment sumps.

As for the mass-based PSD, the PSDs for the fraction <50 µm were also quite similar for the upstream GP and the HVS. The volume-based median particle sizes were slightly different in the non-dispersed samples, with a D_{50} of 11.3 µm for the upstream GP and 7.43 µm for the HVS. The number-based PSDs were more similar with D_{50} ranging from 0.092 µm to 0.11 µm. More than 99% of the particles by number were less than 1 µm, indicating that few particles have a larger volume, increasing the median particle size in the volume-based PSD.

Using a dispersant only minimally affected the PSD in all fractions. For the volume-based PSD below 50 µm in the upstream GP, the difference for the median particle sizes were larger than those found in the HVS. The D_{50} ranged from 8-11 µm in the upstream GP with and without dispersant, whilst the HVS had a D_{50} of around 7 µm for both sub-samples. The number-based PSD showed only minimal difference using dispersant. The variations are difficult to explain without more samples to substantiate the results but could be due to inexperience in splitting of samples as the upstream GP were analyzed first. Similar PSDs with and without a dispersant were also reported by Adler (2020) in a study on gully pot sediments. An explanation proposed by the author was that the method of wet sieving and laser diffraction destroys the aggregated particles. This could imply that the aggregation of particles was formed by weak bonds.

A field study conducted by the manufacturer, Hydro International, suggested that sediment samples from similar HVSs had a median particle size from 7-112 µm (Faram et al., 2007). Several land use categories were sampled twice within a year to investigate variations in the sediments. The highway site showed volume-based D_{50} to be between 30 µm and 112 µm, whilst an urban road with less traffic resulted in D_{50} to be 11 µm and 15 µm. The highway showed larger seasonal variations in the sediment samples, indicating differences in the inflow of particles coming into the HVS. Sand used as anti-skid material in winter is suggested as a possible explanation by the author. Compared to this study the mass-based D_{50} was in the fraction <50 µm, and the volume-based D_{50} around 7 µm for the HVS which is finer particle sizes than in the study of Faram et al. (2007). The methods used for analyzing the PSD are the same, however, the PSDs are not directly comparable as the mass-based and volume-based PSDs are combined to a single PSD, whereas in this study they are held separate. Sand was not used as anti-skid material in this case study, together with extended pre-settling this could explain the finer PSDs compared to Faram et al. (2007). Consequently, the availability of particles on the road surface could substantially influence the sediment composition in these devices.

The upstream GP and the HVS have similar PSDs from sediment samples, however, both have quite different PSDs than standard gully pots reported in the literature. Table 2 shows an overview of studies on gully pot sediments with similar AADT, spatial, and temporal characteristics. Adler (2020) investigated standard gully pots in Trondheim, showing similar PSDs in the sediments from traffic and no-traffic areas. Consequently, the results were expected to be similar to this study. Especially for the gully pot with similar AADT as given in Table 2. The median particle size by mass was below 50 μm, nevertheless approximately 66% of the mass was below 50 μm, compared to 90% in this study. The traffic load was also similar, indicating that the sediments transported in these catchment areas were different, or that a larger portion of the coarser sediments was collected in the first gully pot shown in Figure 2.

Bennerstedt (2005), Karlsson and Viklander (2008), and Leikanger and Roseth (2016) all characterized sediments in gully pots in Norway and Sweden as given in Table 2. D_{50} varies from 320 μm to 1500 μm with a variation in AADT from 9300 – 25500 vehicles. The upstream GP and the HVS generally have finer median particle sizes than gully pot sediments from literature with somewhat similar AADT and geographic location.

Table 2: Overview of mass-based PSDs in gully pots in literature. PSDs are taken out for the samples that are most similar to this study. Days with precipitation are defined as days with more than 1 mm rainfall.

	Location	Annual precipitation [mm]	Days with precipitation	AADT [vehicles/ day]	Sediment volume [m^3]	D_{50} [μm]
Adler (2020)	Trondheim	855[1]	146[1]	18250	0.8	<50
Bennerstedt (2005)	Stockholm	527[2]	87[2]	17000-18000	0.2	320-500
Karlsson and Viklander (2008)	Luleå	494[2]	93[2]	25500	0.4	500-1500
Leikanger and Roseth (2016)	Oslo	830[1]	115[1]	9300-12000	0.45-0.81	350
This study	Trondheim	855[1]	146[1]	24500	2-3.8	<50

Downloaded from [1]www.eklima.no and [2]www.smhi.se

Since traffic load was the dominant activity in all studies, it would be expected to see some similarities in PSDs. However, the ranges in D_{50} were quite large and no clear trend was evident from Table 2. Adler (2020) found little difference in PSDs in sediments in traffic zones and no-traffic zones. Karlsson and Viklander (2008) found that sand used as anti-skid material will be crushed with increasing AADT and result in finer particles.

Differences in sediment volume and maintenance frequency could influence which particles were retained in the gully pot. The smallest gully pot was investigated by Bennerstedt (2005) with only 0.2 m^3, whilst the largest standard gully pot was 0.81 m^3 investigated by Leikanger and Roseth (2016). Especially for small gully pots, regular maintenance becomes important as they will fill up more quickly. These gully pots will be more exposed to washout of particles. In comparison, the HVS has a sediment volume of

3.8 m^3, which suggests that a less frequent emptying is necessary. Some studies have indicated that having gully pots that are not regularly maintained are worse than not having gully pots at all, as it leads to accumulation of pollutants and increased costs for maintenance (Lager et al., 1977, Storhaug and Magnussen, 2015). The standing water phase in gully pots could also be a source of pollutants, being washed out with high inflows (Karlsson and Viklander, 2008).

Charters et al. (2015) found that rainfall characteristics such as peak and average intensity, event duration, and volume influenced the PSD of sediments in road runoff. Besides, the pollutant concentration will be influenced by the antecedent dry period as mentioned above (Kayhanian et al., 2007). The rainfall pattern will consequently largely decide the build-up of particles on the road surface and which particle sizes will be washed off. In Table 2 some rainfall characteristics are given for the studies conducted on gully pots. An explanation of the variations seen in the composition of gully pots could be that the frequency and intensity of the rainfall determine what particle sizes and the amount transported to the drainage system. Trondheim experiences more rain than Oslo, in terms of both frequency and volume. This means that overall intensity may be higher in Oslo, leading to increased build-up and wash-off when it first rains.

The rainfall volume and intensity will also determine the flow into the gully pots. Several studies have suggested that the sediment removal performance of both gully pots and HVSs decreases with increasing flow, among others Butler and Karunaratne (1995), Ciccarello et al. (2012), and Wilson et al. (2009). The removal performance could therefore increase as a consequence of higher intensity and volume of flows as it means that larger particles also will be transported. However, a larger flow decreases the performance of the sedimentation-based devices. A problem with gully pots could indicate that for larger flows, the sediments will be washed out for the duration of the rainfall-runoff event. When the event stops, a smaller portion of the sediments will be deposited in the pot. This could to some extent explain the fine particles found in gully pots. The hypothesis needs to be further evaluated by taking inflow and outflow samples from standard gully pots over the event duration.

The organic fraction in each size range implies that the upstream GP had more organic matter in the fractions from 250-2000 µm. For these sizes, the organic matter constituted 30-40% of the particles. The HVS had lower fractions of organic matter in the smallest sizes and for the largest sizes. The results indicate that the upstream GP may be better at removing organic matter. Investigations by Adler (2020) showed organic fractions between 0-17%, on a general basis more organic matter in the fractions below 150 µm. Faram et al. (2007) had an average organic fraction of 10% in sediment samples from similar HVSs. The difference between organic matter content in these gully pot sediments and the sediments from this study could be due to differences in catchment areas and age of the sediments. There are no obvious sources to the high organic matter content in the road runoff from the catchment areas. However, the residential area on the west side includes some trees and gardens that could be sources of organic matter. The sediments collected in this study were also relatively new, at the most 2 years. The standard gully pots sampled by Adler (2020) were most likely older than this, as most gully pots in Trondheim are not regularly emptied. This could reduce the organic matter content caused by biological degradation over time. The HVS also have a separate storage volume for oil and floatables which could influence the organic matter content in the sediments. Leikanger and Roseth (2016) found increased concentrations of oil compounds in gully pot sediments in Oslo. This could explain the lower organic fractions found in the HVS.

The comparison discussed above indicated that the upstream GP and the HVS in this treatment train contain finer particles than standard gully pots in literature. Due to variations in road runoff presented in the literature, the reason for this is not clear. It is not known if the coarser particles are removed in the first gully pot in the treatment train, or if the road runoff from this catchment area contains very fine particles. To get an overall impression of this treatment train, it is recommended to characterize these gully pot sediments to investigate the treatment train further. It could also be assumed that the drainage swales provide some removal of particles, especially during low flow events.

Overall, the results of this study could indicate that the treatment train is over-dimensioned regarding flow and sediment supply. As mentioned above, very similar results were also obtained from Curwell (2015). The HVS was of the same size, however, the catchment area had a size of 200 ha and no pre-settling, compared to 4.7 ha and pre-settling in this study. Despite the difference in area and treatment trains, the performances were the same. This weakens the argument that the low sediment removal performance is only attributed to the two upstream gully pots and low sediment supply.

It is not possible to conclude if the sediment removal performance of the HVS is prominently better than standard gully pots in this study. More work is needed to establish a fundamental understanding of how the HVS and gully pots work in different treatment trains. HVSs are in general more expensive than gully pots and replacing gully pots with such devices require that they treat an additional removal of fine particles. By shifting perspective towards wet ponds, the HVS could be a space-efficient alternative if the sediment treatment performance is equally good. The HVS will also be less dependent on correct execution in the construction phase than a wet pond (Åstebøl and Hvitved-Jacobsen, 2014).

Conclusion

Comparing the measured sediment removal performance of the HVS in this study to the report of the manufacturers, the performance was lower than expected. The PSDs in inflow and outflow did not show a statistically significant difference. The inflow consisted of particles very fine particles, with over 99% of the particles by number under 1 µm. This could partly originate from the design of the treatment train, where road runoff is directed through two gully pots before reaching the HVS. More research is necessary to investigate the performance over a longer time period. The size of the system with the detention basin and the enlarged upstream gully pot may be over-dimensioned concerning the supply of sediments and event flows.

The PSDs in the sediments from the upstream GP and the HVS showed that over 90% of the particles by mass were in the size fraction <50 µm. The difference between the upstream GP and the HVS was insignificant, indicating that their performance in this treatment train was very similar for the sampling period. However, the sediment samples had a larger fraction of fine particles compared to gully pots in literature with similar AADT and land use. In order to fully understand the road runoff, sampling of the first gully pot in this system is lacking. If the HVS have a better sediment removal performance than standard gully pots. The performance of the HVS compared to standard gully pots was not uniquely proven in this study.

Further research is needed to fully evaluate the HVS and gain knowledge about the particle sizes in road runoff. Below is given a summary of suggested research to obtain knowledge about this treatment train:

- Sediment samples from the first gully pots in the treatment train from Figure 2
- More runoff samples over a whole year to investigate differences by season
    - Flow-measurements together with runoff samples to better evaluate the performance of the treatment train
- Samples from other gully pots with similar AADT and land use
    - Preferably inflow/outflow samples to find out how much stays in the pot during the event
- Development of criteria for designing a suitable treatment train for the HVS

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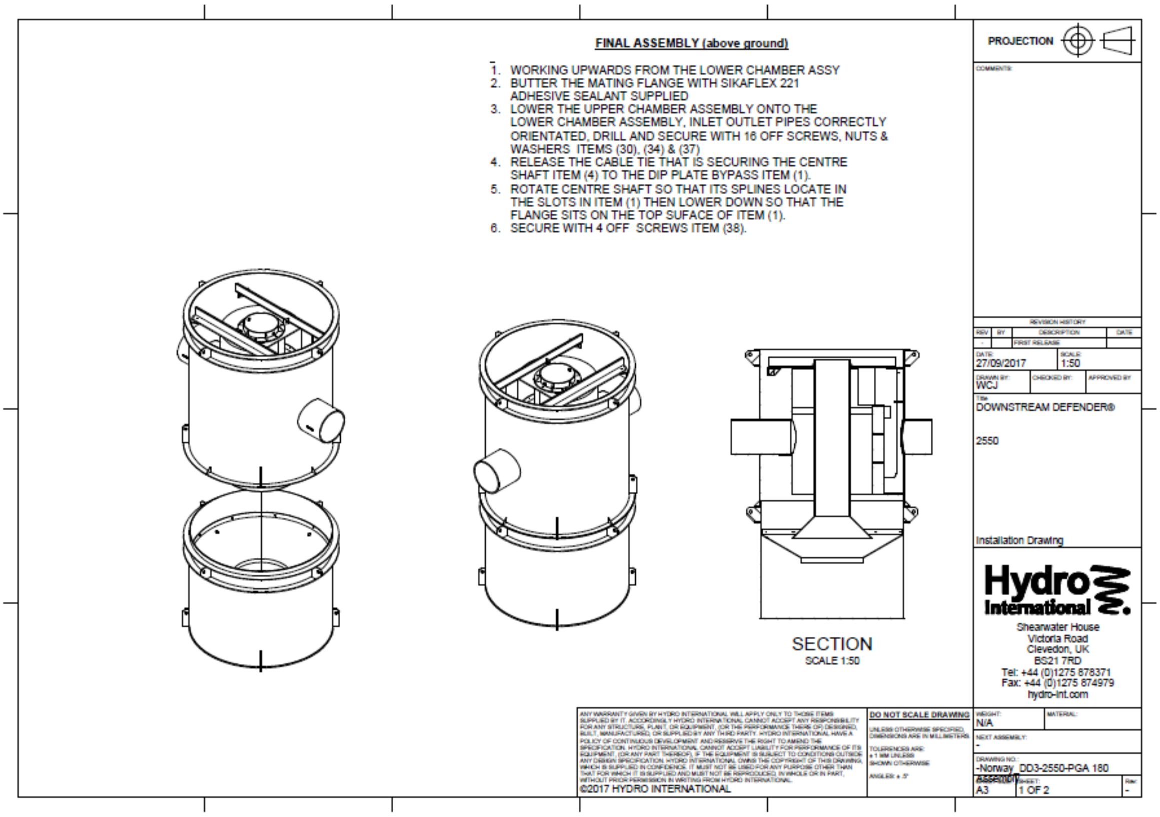
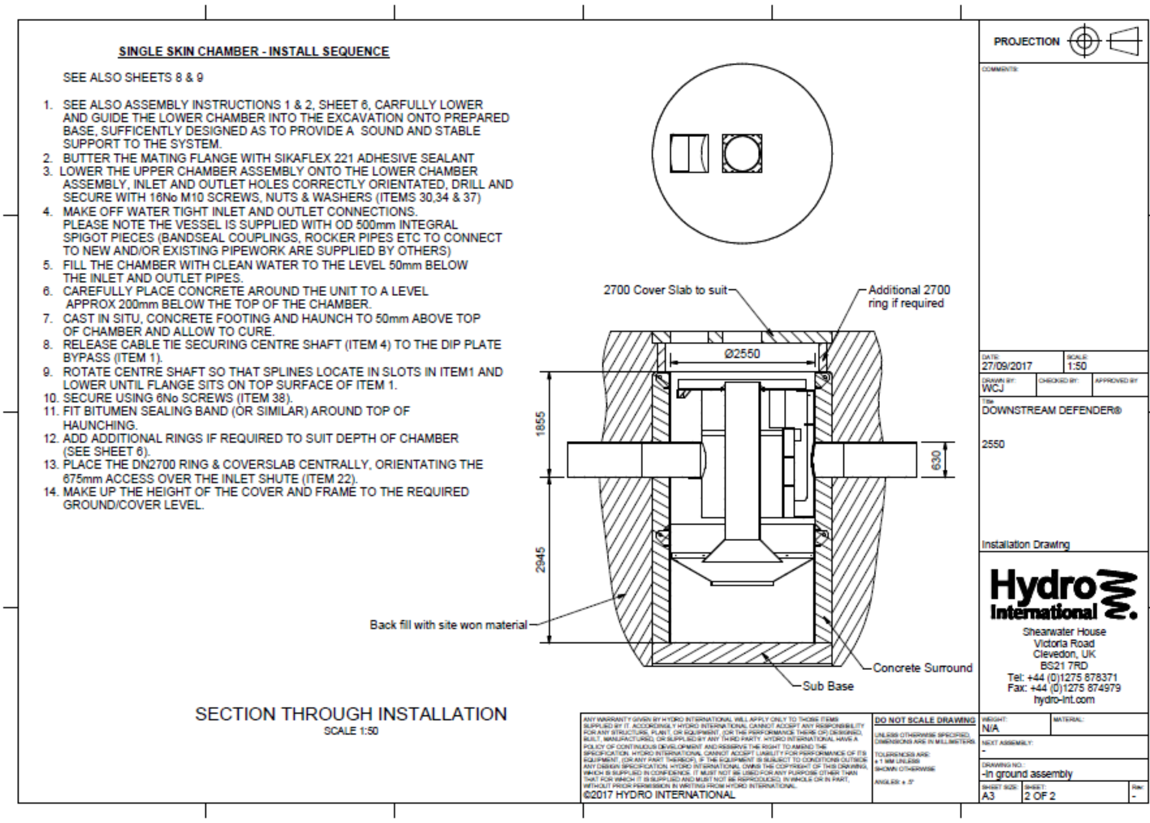
Appendix A – Technical drawing of Downstream Defender

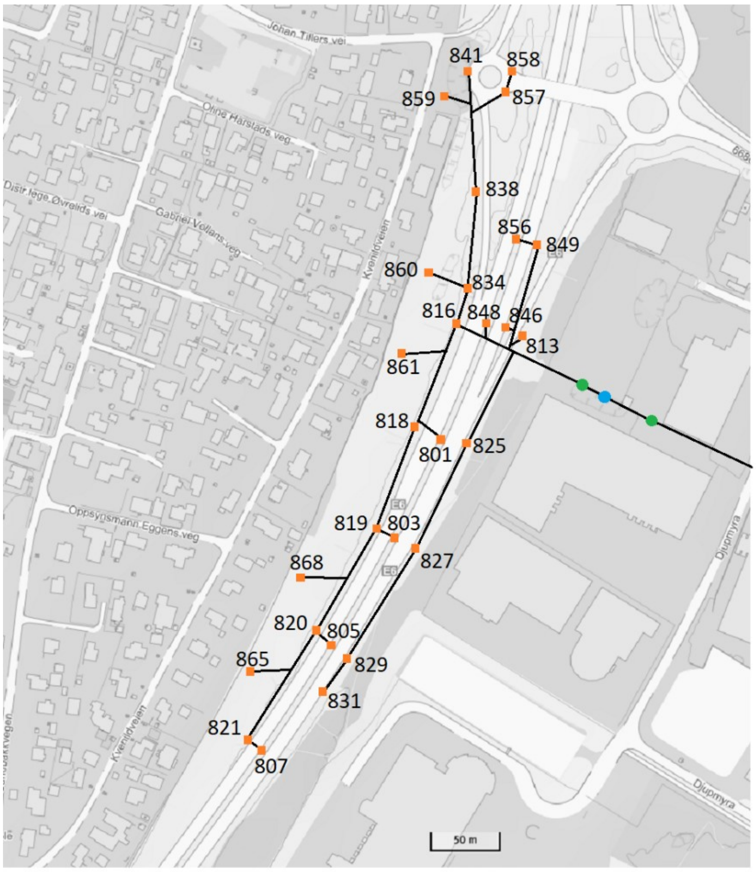




Appendix B – Experimental setup for runoff sampling

Experimental setup of the sampling equipment for the inflow and outflow sampling at the HVS. The two pictures at the top show the installment of the automatic sampler in the manhole. The pictures at the bottom show the AV sensor mounted in the pipe.

Appendix C – Estimated drainage areas



Catchment no.	Area [m²]	Road [%]
821	1615	26.0
807	1532	68.4
831	2837	22.8
829	537	20.3
805	1024	69.2
820	1238	24.3
827	1542	25.4
803	1086	66.9
819	1574	23.4
801	1294	72.6
818	1709	22.3
841	274	32.4
858	323	88.8
857	183	99.8
838	1468	43.9
834	993	32.0
816	2723	25.0
848	1329	72.1
856	1247	74.5
849	481	34.6
813	596	23.4
846	972	45.4
865	2758	0.0
868	2151	0.0
861	5479	0.0
860	2626	0.0
859	3915	0.0
825	3503	40.1

Appendix D – Time of concentration

$$T_C = t_f + t_e$$

T_c	Time of concentration [min]
t_f	Time of flow
t_e	Time of entry

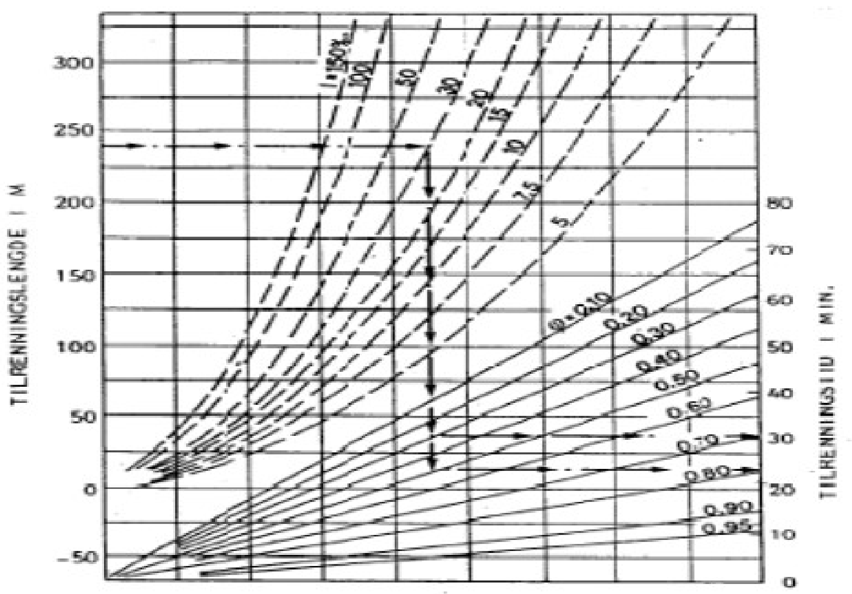
Manning's equation for estimating the pipe-full velocity

$$v = \frac{1}{n} R^{2/3} I^{1/2}$$

v	Velocity [m/s]
n	Mannings roughness coefficient
R	Hydraulic radius
I	Slope

$$t_f = \frac{L}{v}$$

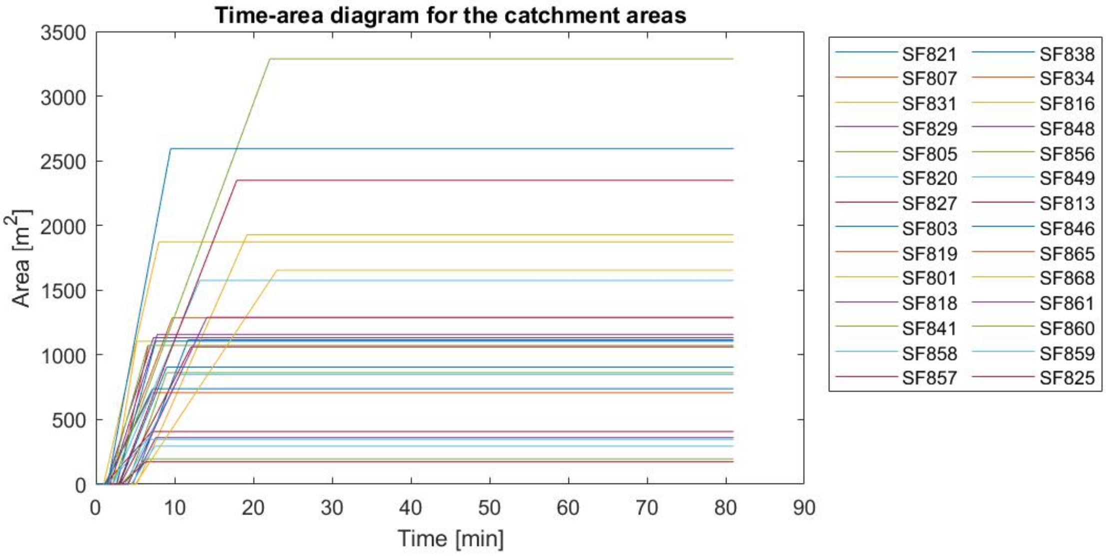
where L is the length of the pipe



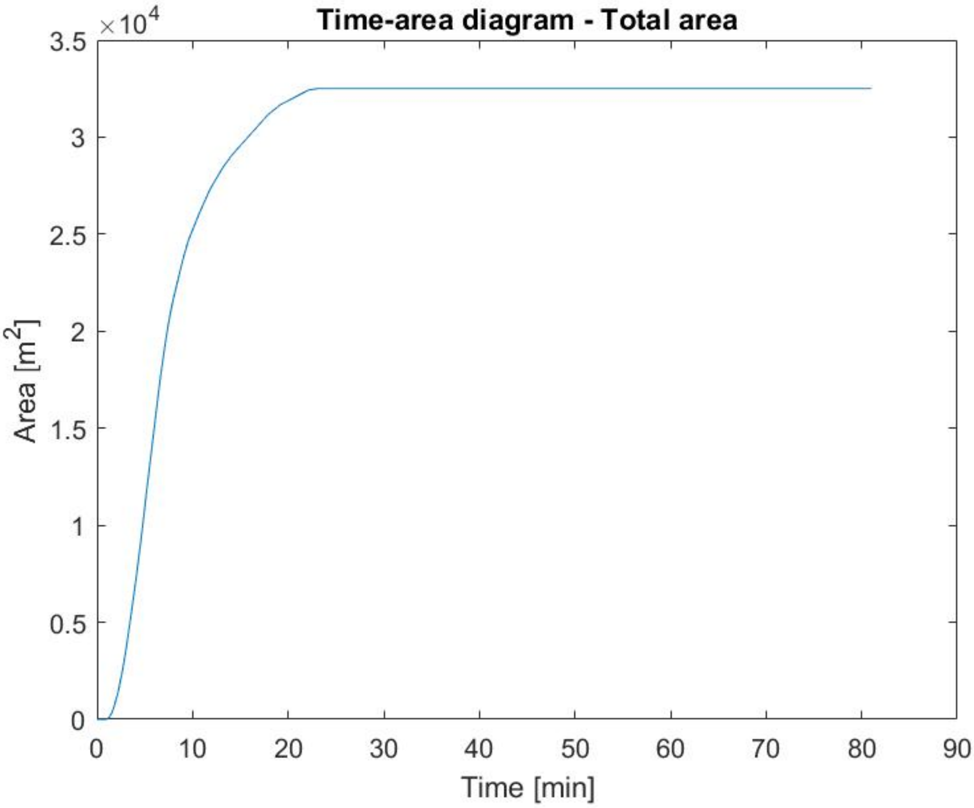
Eksempel: Tilrenningslengde 240 m, fall I=30 ‰, Φ er 0,30 og 0,50.
Tilrenningstiden blir hhv. 30 og 25 min.

Nomograph for estimating overland flow (Trondheim Kommune, 2020a)

Appendix E – Time-area diagram



Time-area diagram for each of the 28 drainage areas



Total time-area curve used to calculate runoff hydrographs

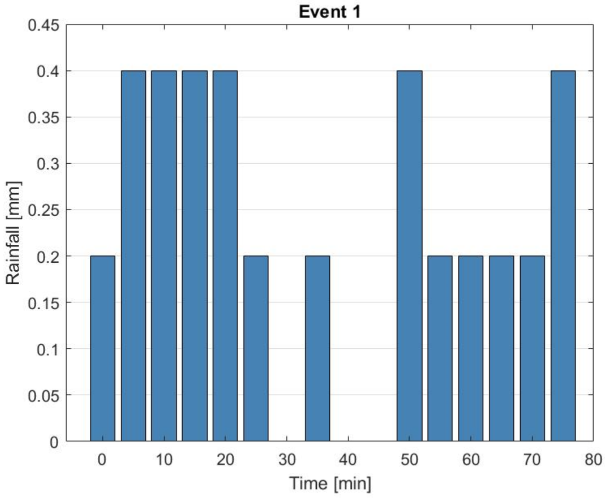
Runoff hydrographs are calculated from:

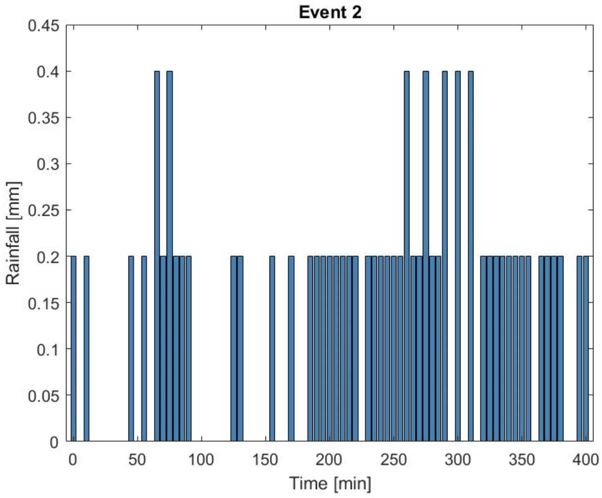
$$Q(t) = \sum_{w=1}^{N} \frac{dA(j)}{dt} I_w$$

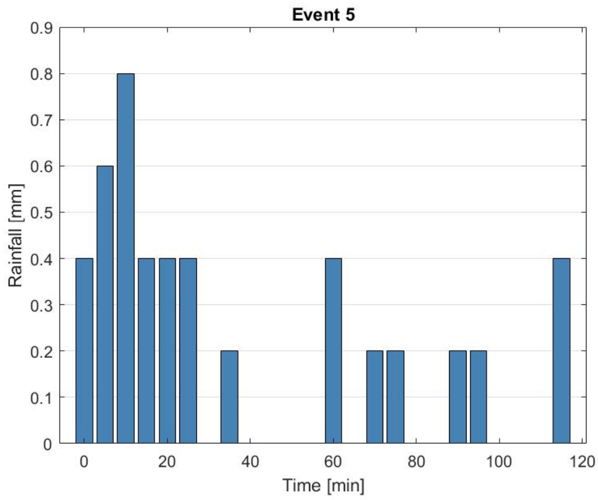
Q(t)	Runoff hydrograph ordinate at time t (m^3/s)
dA(j)/dt	Slope of time-area diagram at time j (m^2/s)
I_w	Rainfall depth in *w*th of N blocks of dt (m)
j	Time interval (s)

Appendix F – Rainfall data

Rainfall events used as input to calculate the flow hydrographs







Appendix G – Summary statistics for runoff samples

Cumulative summary statistics of PSDs represented as the average D_{10}, D_{50}, and D_{90} (i.e. the particle size at which 10%, 50%, and 90% of the particles pass). The p-value from the Wilcoxon sign rank test is also given for the particle sizes. The number of observations is given as n.

Volume-based PSD

			Average [μm]	Median [μm]	Max [μm]	Min [μm]	n	p-value
D_{90}	Rainfall	Inflow	130.25	63.30	334.80	27.49	16	0.0386
		Outflow	102.59	55.84	257.40	27.23	16	
	Snowmelt	Inflow	224.94	234.20	269.80	164.80	14	0.454
		Outflow	219.10	228.55	244.80	169.00	14	
D_{50}	Rainfall	Inflow	19.00	9.16	117.10	6.73	16	0.528
		Outflow	11.95	9.95	21.94	6.47	16	
	Snowmelt	Inflow	36.97	35.34	77.70	16.11	14	0.241
		Outflow	44.42	35.79	99.23	25.78	14	
D_{10}	Rainfall	Inflow	1.39	1.12	3.00	0.95	16	0.0155
		Outflow	1.51	1.24	3.18	0.92	16	
	Snowmelt	Inflow	7.38	7.78	11.20	2.83	14	0.217
		Outflow	7.93	8.15	9.32	6.09	14	

Number-based PSD

			Average [μm]	Median [μm]	Max [μm]	Min [μm]	n	p-value
D_{90}	Rainfall	Inflow	0.27	0.2205	0.437	0.166	16	0.352
		Outflow	0.26	0.2265	0.502	0.202	16	
	Snowmelt	Inflow	0.76	0.407	5.567	0.109	14	0.217
		Outflow	0.32	0.3225	0.627	0.124	14	
D_{50}	Rainfall	Inflow	0.11	0.09665	0.192	0.0775	16	0.501
		Outflow	0.11	0.09765	0.231	0.0929	16	
	Snowmelt	Inflow	0.32	0.171	2.239	0.0684	14	0.358
		Outflow	0.15	0.1275	0.389	0.0684	14	
D_{10}	Rainfall	Inflow	0.07	0.0593	0.109	0.053	16	0.254
		Outflow	0.07	0.0595	0.131	0.0584	16	
	Snowmelt	Inflow	0.21	0.0859	1.629	0.0513	14	0.391
		Outflow	0.09	0.0666	0.268	0.0505	14	

TSS concentration per category. Removal efficiency is calculated based on average concentration

Event category		Average [mg/L]	Median [mg/L]	Max [mg/L]	Min [mg/L]	n	p-value	Removal efficiency [%]
Rainfall	Inflow	71.0	40.6	461.2	11.0	16	0.900	20.7
	Outflow	56.3	46.0	211.9	11.3	16		
Snowmelt	Inflow	7.2	6.4	19.5	3.8	14	0.903	10.7
	Outflow	6.5	5.8	9.9	4.6	14		

Appendix H – Summary statistics for sediment samples

The results are displayed with and without dispersant, as DIS and NAT, respectively.

Differential PSD given as percent by mass in each size fraction [%]

		<50	**50-75**	**75-100**	**100-150**	**150-250**	**250-500**	**500-1000**	**1000-2000**
Upstream GP	NAT	89.6	2.9	1.6	1.6	1.6	1.5	0.7	0.4
	DIS	84.4	4.5	2.4	2.4	2.4	2.3	1.3	0.4
HVS	NAT	90.5	2.2	0.9	0.9	0.8	1.3	1.5	1.9
	DIS	91.1	1.74	0.75	0.84	0.86	1.36	1.65	1.71

Organic fraction given as percent in each size fraction [%]

	<50	**50-75**	**75-100**	**100-150**	**150-250**	**250-500**	**500-1000**	**1000-2000**
Upstream GP	17.39	18.84	20.00	21.88	27.78	32.43	41.18	33.33
HVS	7.26	19.50	21.79	23.38	24.29	24.11	12.21	5.75

Cumulative summary statistics of the PSD in the sediment samples. Results from wet sieving in the mass-based PSD was linearly interpolated between size fractions.

Mass-based PSD 50 - 2000 μm

		D_{10} [μm]	**D_{50} [μm]**	**D_{90} [μm]**
Upstream GP	NAT	<50	<50	53
	DIS	<50	<50	87
HVS	NAT	<50	<50	<50
	DIS	<50	<50	<50

Volume-based PSD <50 μm

		D_{10} [μm]	**D_{50} [μm]**	**D_{90} [μm]**
Upstream GP	NAT	1.67	11.3	35.1
	DIS	1.17	7.98	30.1
HVS	NAT	1.14	7.43	23.6
	DIS	1.09	7.13	27.5

Number-based PSD <50 μm

		D_{10} [μm]	**D_{50} [μm]**	**D_{90} [μm]**
Upstream GP	NAT	0.058	0.0926	0.200
	DIS	0.059	0.0961	0.221
HVS	NAT	0.060	0.0983	0.229
	DIS	0.063	0.112	0.285

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