Determination of the removal efficiency of a decentralized stormwater treatment system

A theoretical approach to assess a modified SediSubstrator L

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Prologue

This thesis was written during the COVID-19 pandemic. Therefore, the initial scope of the project changed from a practical to a more theoretical approach. The main reason were delays in the process of ordering and delivery of the devices to be used for the testing in the field. Furthermore, the working conditions were adapted accordingly to home office which made the collaboration in person more challenging.

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Abstract

Due to the predicted impacts of climate change on the frequency of storm events, water managers are challenged to improve and adapt the current urban infrastructure. Cities need to be able to deal with the adverse effects due to more frequent and heavier rainfall. This implies the need for sustainable urban drainage systems (SUDS) that can deal with these challenges. SUDS can be seen as designs that can improve both, the quantitative as well as qualitative characteristics of stormwater. The study area in the south of Amsterdam will be equipped with a SUDS, namely a SediSubstrator L by Fränkische Rohrwerke. The objective is to remove particles from stormwater discharge to prevent clogging of the infiltration facility (AquaBASE) installed in sequence. Additionally, it can remove harmful pollutants which are adsorbed to the fine particles.

This research aims to investigate the characteristics of the sediments in stormwater in theory and develop an appropriate sampling strategy to monitor the relevant parameters in the field. The long-term objective hereby is to **determine the removal efficiency of the SediSubstrator L using a finite amount of parameters**.

A threefold approach is used to identify the most important parameters influencing the removal efficiency of particles to be determined in the study area. Based on (1) a detailed literature review with respect to existing treatment theories, the potential parameters to be assessed are identified and their impact is analyzed. Using the gathered information, (2) the first stormwater sediment sampling is performed in the study area. This forms the basis for several input parameters to be used in the next step. From there, (3) a model to estimate the treatment efficiency of the sedimentation path of the SediSubstrator is developed.

The results are found to agree with existing theory and research studies that there is an evident relationship between runoff volume as well as sediment composition and the overall treatment efficiency of the sedimentation path of the SediSubstrator. In this specific case, rainfall intensities above 2.5 mm/h are necessary to significantly generate runoff from 75 % of the connected surfaces. These volumes are predicted to contain sediment loads with most particles in a size range of 125 µm and 250 µm, while the rest is assumed to be smaller than 50 µm. The overall treatment efficiency was simulated to be on average about 76 %, comparable to the 80 – 88 % measured under laboratory conditions by several previous studies.

Based on the identified parameters to be assessed, a specific monitoring and sampling setup is proposed to determine the removal efficiency of stormwater sediments in the study area. Along with the efficiency, the volume of sediments that are caught by the facility can be approximated. The latter needs to be removed once the entire storage volume of the sedimentation facility is filled. It is recommended that Waternet uses measured stormwater data to improve the model, while monitoring the efficiency under field conditions. Once the results of the model and the actual field measurements match, the model can be used to simulate the sediment removal for long time series. In this way the cleaning intervals can be predicted, while avoiding expensive long-term measurements to do so.

Acknowledgements

This graduation project has been challenging in several ways, all in all being a valuable and memorable learning experience. I am very grateful that I got the opportunity to work for Waternet together with inspiring colleagues and in collaboration with Fränkische Rohrwerke. Therefore, I would like to thank a few of the people that supported me throughout this project.

First of all, I wish to express my deepest gratitude to Frank. His continuous support helped me overcome many issues and introduced me to the practical world of water management in the Netherlands. Your guidance and dedication during the entire project helped me in realizing the project and getting to where I am today. Furthermore, I would like to thank my supervisory team. Frans, Jeroen and Boris, thank you for your critical feedback, for always asking the right questions and introducing me to different people in the field of urban water management in the Netherlands. Your valuable feedback helped me to be proud of my graduation project and gives me confidence to work in this field in the future. A big thank also to my colleagues at Waternet, that supported me in different stages of my project. Thank you, Wilko, Arjen and Wessel, for your support with the technical drawings, Najim for your advice and effort during fieldwork, Nico for your help in the study area and Juan for your support with hydrological modelling. Additionally, I would like to thank Matthijs Rietveld for his support in the Waterlab and advice on the sampling and fieldwork to be performed. I really appreciate I was able to use your device to determine the settling velocity of the particles of my samples.

Furthermore, the physical and technical contribution of Fränkische Rohrwerke by Michael and Sarah is truly appreciated. Without their exchange in information, support and enthusiasm, this project could not have reached its goal either.

Lastly, I would like to thank my family for all the support, especially I highly acknowledge the generosity of my father, without which this master would not have been possible. Furthermore, I want to express my appreciation for the support and love from my fiancé, Richard, who supported me from the beginning until the very end of my studies. Each of them kept me going on and this work would not have been possible without their various inputs.

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1 Introduction

1.1 Research background

Worldwide climate is expected to become more extreme, which will lead to an increase in storm frequency as well as magnitude (Verkade et al., 2017). Simultaneously due to urbanization less area is available to buffer this excess water and water quality problems arise in many regions. In the Netherlands too, the amount of precipitation has increased noticeably over the period of the past 100 years (KNMI, 2018). As the current infrastructure is not made for an increase in frequency of such extreme events (figure 1-1), urban water managers are forced to adjust the traditional urban design. In this case, sustainable urban drainage systems (SUDS) are installed with the main aim to reduce urban flooding. Since the early 1980's these installations are furthermore used to reduce the amount of pollutants being discharged from the urban stormwater discharge towards the surface water (Davis et al., 2001).

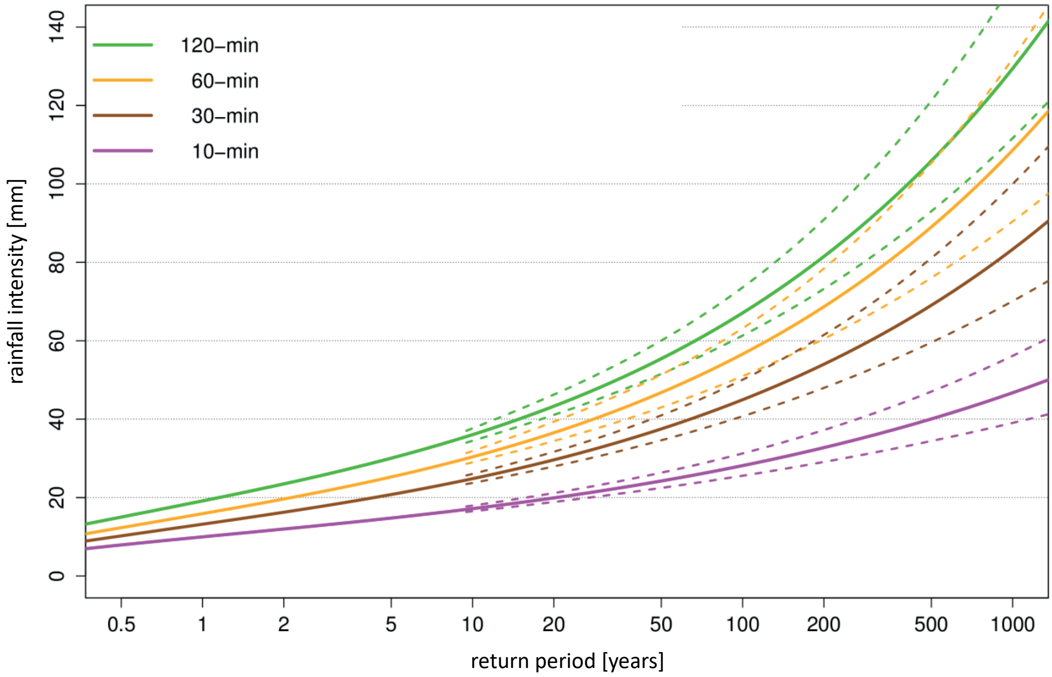

Figure 1-1 *Rainfall intensities and predicted return periods in the Netherlands (Gastkemper & Buntsma, 2016).*

SUDS can be used as decentralized stormwater treatment, by reducing the incoming pollution at its source (Boogaard et al., 2015). Depending on the chosen system, they are efficient in terms of the water balance and pollution control. However, on the downside they require space and the appropriate geohydrological conditions. These conditions are unfavourable in lower parts of the Netherlands, since the groundwater tables are high (Pellenbarg, 1989), and the permeability of the soils is low. Thus, it is important to respect these boundary conditions when creating and implementing a new design for the water treatment. Over the past years, many industries were involved in developing industrially produced decentral devices for the purpose of treating stormwater. These range from small scale devices for gully pots, to large devices such as pipes to be installed below longer road segments. The hydraulic performance and pollution removal efficiencies vary from design to design and also depend on the characteristics of the incoming stormwater (Boogaard, 2015; Johnson et al., 2003; Melcher, 2019; Selbig et al., 2016). At the same time, the choice of the appropriate treatment device depends on the stormwater sediment composition.

The exact composition of the stormwater, the characteristics of the sediments and their related pollution depend on several factors. On the one hand it is influenced by the type and use of the catchment. On the other hand, parameters such as the rainfall intensity, the surface properties and many other area-specific influences determine the exact characteristics. It has been shown, that traffic has a significant influence on the volume of solids in the catchment area and that the characteristics of the connected surfaces have a significant contribution on the transport of the solids (Fuchs et al., 2019). Different studies (Bathi et al., 2009; Fuchs et al., 2019; Morquecho et al., 2005; Pitt, 2002) have shown that most of the pollution is attached to the finest particles in the stormwater, namely the silt and clay particles with a size of < 63 µm. While heavy metals are considered as inorganic matter coming mainly from road-runoff, polyaromatic hydrocarbons (PAH) are organic substances (Feldhaus & Klein, 2009). Another problem, adding to the quality issue, is the clogging (Siriwardene et al., 2007) of the SUDS by these suspended sediments (SS) which will reduce their effectiveness and service life. Han et al. (2019) reported that fine particles that are smaller in size than the pore opening of the gravel layer, form links between the bigger particles in form of bridges. This results in clogging of the openings and thus decreases the permeability.

This research will investigate the characteristics of the sediments in stormwater and develop an appropriate sampling strategy to monitor the relevant parameters. By using the gathered information, the efficiency of a future stormwater treatment device to remove sediments can be determined and controlled under field conditions.

1.2 Problem statement and objectives of the research

To understand the efficiency of stormwater treatment devices, many researchers, amongst others Boogaard (2015) and Selbig et al. (2016), recognized that the accurate characterization of the suspended sediments (SS) in terms of their composition, particle size distribution and settling velocities is important. So far, most of the tests on these devices have been performed under laboratory conditions only. To better understand the removal efficiency, often silica material (Boogaard 2015; Leutnant et al., 2018; Uhl et al., 2013), calcium carbonate (Milke et al., 2010) or glass particles (Liu et al., 2019) are used to simulate the characteristics of stormwater sediments. These known particle properties as well as the laboratory conditions deliver reproducable and comparable results about the efficiencies of the treatment devices.

However, according to Boogaard (2015) many of these have not been compared to tests done in the field. Characteristics such as the specific density, the size distribution and particle shapes, the flow rate, the temperature of the water, the coagulation properties, the distribution of the settling velocities and retention time have a strong influence on the sediment transport. These vary from location to location, as well as within and between rainfall events. The assumption of such parameters or an unrealistic characterization of the concentrations and distributions can potentially result in errors and hence negatively influence the choice in the treatment design. Wrong assumptions can lead to under- or oversized structures and thus different efficiencies. Nowadays, most of the treatment devices use the principle of settling and therefore the determination of the true characteristics of stormwater sediments is significant (Selbig et al., 2016).

Up to date, designers as well as engineers tend to use average values from laboratory tests for both, particle concentration and size distribution, to choose the best treatment design. Nonetheless, the materials used in the laboratory cannot completely represent the properties of sediments of real urban stormwater discharge (Boogaard, 2015). The often used silica particles do not only have a different shape but also another specific density and coagulation properties than the sediments in the field (Boogaard et al., 2015). The variability in density amongst inorganic and organic particles in urban stormwater makes the validation of lab-determined removal efficiencies challenging under field conditions.

Since there are differences in performance of the facilities in the laboratory when compared to the field, tests under both conditions are important to get a better understanding. Boogaard (2015) mentioned external impacts such as seasonal variation, site environmental as well as climatic conditions that cannot be simulated in the laboratory.

Field research should be performed in order to gather representative data from the study area. This can provide better understanding of the efficiency of stormwater treatment facilities in real life. Therefore, a field experiment is designed to test such treatment devices in the Rooseveltlaan in future. This offers the opportunity to test the efficiency of such installations in the field.

To achieve reliable and representative results, first an adequate sampling setup has to be designed. Upon completion as well as installation of the system itself, the installed facility can be tested under field conditions. As a treatment step, a sedimentation pipe in combination with a substrate filter will be used to filter out as many solids as possible. For this research the *SediSubstrator L* from *Fränkische Rohrwerke* is used, since the very similar *SediPipe XL* showed the best results in terms of removal efficiencies during the laboratory tests by Boogaard (2015). It was able to remove about 88 % of the solids in the range of 0 to 400 µm (Fränkische Rohrwerke, 2018). During the laboratory research with silica material, the SediPipe was able to remove particles bigger than 25 µm with an efficiency of more than 50 %. For particles above a diameter of 60 µm, the efficiency even reached levels of over 90 %, at a flow rate of 10 l/s. Both treatment devices use a horizontal pipe as sedimentation path to remove particles, from the stormwater. the main difference between the SediPipe and the installed SediSubstrator is a filter cartridge (SediSorp) in the end shaft of the sedimentation path. The filter material inside these cartridges aims to remove the fine suspended fraction and its attached pollution and hence to improve the stormwater quality. This product combines the process of sedimentation with filtration and is able to achieve better results concering the fine suspended particles.

The objective of this master's thesis is to simulate the functioning of the sedimentation path of the SediSubstrator in order to design an appropriate measuring setup and to determine the actual suspended sediment composition in urban stormwater. This is needed to then further determine the sediment removal efficiency of the treatment device that is being installed in the study area. Thereby, the reduction in stormwater pollutants attached to specific particle sizes can be approximated.

1.3 Research Questions

Given the expressed thesis objective, the following research question is formulated:

> *Can the characteristics of the stormwater sediments and thereby the removal efficiency of the sedimentation path of the treatment facility called SediSubstrator L be measured using a finite amount of selected parameters as a proxy?*

The question consists of several sub-research questions to be answered:

(1) Sediment characteristics

- *(a) What are the relevant characteristics of stormwater sediments to assess the particle removal efficiency of the treatment step?*
- *(b) What is the expected sediment composition in the study area, according to particle size, particle density, particle concentration?*

(2) Measurement setup

How can the sediment composition in the study area be measured focusing on the prioritized parameters?

(3) Removal efficiency

- *(a) What is the expected removal efficiency of the sedimentation path of the SediSubstrator L (excluding the filter cartridge) taking the relevant sediment characteristics into account?*
- *(b) How can the particle removal efficiency in the installed SediSubstrator L be measured in the field?*

(4) Pollution

Can the removal of a certain particle size be taken as a proxy for the efficient removal of pollutants?

1.4 Structure of the report

This thesis is organized in five chapters. This initial chapter provides some background information on the current situation, outlines the importance of the research and introduces the research questions to be answered throughout the study.

Chapter 2: *Research methodology* describes the threefold approach used in order to find answers to the research questions. The contribution of the methodology applied to answer the research questions will be highlighted.

Chapter 3: *Literature Review* provides a detailed overview of studies and knowledge available at the current stage on the stormwater sediments and water characteristics, various stormwater monitoring, sampling as well as treatment techniques and the pollution present in stormwater.

Chapter 4: *Assessment of sediment loads and retention facilities efficiency in the field* introduces the study area and the sampling performed in the study area.

Chapter 5: *Modelling the loads and expected efficiency of stormwater sediment retention facilities* uses a model to estimate the treatment efficiency of the system under investigation. It explains the model in detail, focusing on the input data and assumptions made. Furthermore, the precipitation data is statistically analyzed on some characteristics.

Chapter 6: *Results* shows the outcome of the model and the sensitivity analysis. Furthermore, the results of the laboratory analysis are displayed.

Chapter 7: *Discussion* will elaborate on the results from both, the theoretical and practical analysis. The findings will be related to those encountered in literature and the approach used will be analyzed. Additionally, uncertainties and limitations will be introduced. Finally, the sampling and monitoring setup for the system under investigation is proposed, based on the findings in the previous chapters.

Chapter 8: *Conclusions and Recommendations* lists the key findings of the report to conclude the study. Furthermore, recommendations for improvements and for future research are given.

2 Research methodology

2.1 Introducing the general approach

This chapter will focus on the methodology used to answer the identified research questions. The approach is split into three steps, all of them aiming to gather information about the removal efficiency of the stormwater treatment facility to be installed.

As a starting point, a detailed literature review (1) on the physical characteristics of the stormwater sediments as well as the existing treatment theories is performed. This allows to identify the most crucial parameters to be assessed in the field. Furthermore, this provides insight on the relationship between parameters as well as the functioning of the investigated facility. Using this information as a basis, stormwater sediments samples (2) are taken in the study area. These are then analyzed in the laboratory and further used as input parameters for the model (3). The model, consisting of two submodels, was developed to estimate the treatment efficiency of the sedimentation path of the SediSubstrator. It is based on a rainfall- runoff model as well as the principle of functioning of the treatment facility. Finally, the behaviour of the stormwater sediments can be simulated and the removed loads including its attached pollution are estimated. Statistically analysing the precipitation data of the past four years in more detail, computes additional information about the sampling volumes and frequencies. Due to the limitations introduced by the COVID-19 pandemic (§ 7.5), extra emphasis is placed on the literature research and the simulation with the model.

2.1.1 How the methodology relates to the research questions

In order to answer the main research question (RQ) given in § 1.3, the sub-questions should be answered first. To do so, a threefold approach is proposed, that allows to gather more detailed information at the time. While some might be answered by one part of the entire approach, others might require a combination of several steps.

The detailed study of international as well as local literature can provide useful information to determine the relevant physical parameters of stormwater particles to be assessed with regard to their removal efficiency (RQ 1.a).

A combination of information from studies on stormwater performed in Amsterdam and the own sampling performed in the field, can give insight on the particles encountered in the area. This will help to understand the stormwaters sediment composition and the particles characteristics (RQ 1.b). Along with that, it is identified what needs to be considered to determine the sediment composition. Here not only the sampling procedure but also the assessment in the laboratory gives important information (RQ 2).

The model and the sensitivity analysis give insight on the functioning of the system and its expected overall performance. Simulating the behavior of stormwater particles according to the principle of sedimentation represents the particle removal efficiency of the installed treatment facility (RQ 3.a). This load of caught and removed sediments is then related to the absorption surface of particles within specific sizes. As a result, the fraction that appears to carry most of the pollutants can be approximated (RQ 4).

Combining the information that was gathered by all the three approaches, the sampling and monitoring setup for the SediSubstrator is proposed (RQ3.b).

Finally, the answers to all sub-questions will respond to the main research question of this thesis.

2.2 The three components of the approach

In this section, the approach is explained step by step according to each one of the three components, including the literature review, the quantitative assessment in the field and the theoretical assessment using a model simulation.

2.2.1 Literature review

A detailed literature study (§ 3) is performed on the theory underlying the removal of stormwater sediments and its attached pollution in urban areas. To do so, first international literature about the general physical characteristics of stormwater as well as its components is studied. Having this in mind, stormwater treatment technologies and their principles of functioning are investigated. Since the characteristics of stormwater differ from location to location, in particular Dutch literature is studied in a further step. Hereby, the focus was placed on literature in Amsterdam to get the most representative information for the study area. However, a lack of information on the scale of the city is encountered.

2.2.2 Quantitative practical assessment

In this part of the approach, first, the study area will be introduced. In this way the specifications about the drainage situation and the stormwater treatment system are shown. Knowing the site characteristics, the location for the sediment sampling can be identified. The sampling of sediments will be the second step of this part. The latter is performed for a better understanding of the sediments expected to be measured within the treatment facility.

The study area

The project site is part of the case study that is simulated in the model. Therefore, it is important to introduce the local characteristics of the area. The latter include the type and area of connected surfaces, the sediment composition of the area and the current drainage situation. Furthermore, the stormwater treatment facility to be installed is presented.

Sampling of stormwater sediments in the study area

The practical assessment in the study area include the stormwater sediment sampling and the laboratory analysis performed hereinafter. During the sampling period no heavy storm events took place in Amsterdam. Therefore, only samples from the bed sediments as well as the stagnant water within the manholes were taken. Additionally, samples were taken from the gully pots within the study area. The samples are then analyzed for several parameters in the laboratory. These parameters are used in a further step to understand the behavior of the particles along the water flow. In this way, the composition of the sediments at different locations within the drainage system can be understood. They provide information that is further used as input data in the model simulation. By sampling in the field, measured values replace theoretical ones from literature. The sampling procedure as well as the analytical assessment are explained in § 4.

The results from the bed sediments give insight on the general stormwater particles expected in the area. The water samples instead can provide information on the behavior of the stagnant stormwater within the sedimentation pipe of the treatment facility. This happens in case there are longer dry periods in between rainfall events and the water remains in the facility for a longer period. As a result, the particles that need a long time to settle will have the opportunity to do so and the sediment concentration of the water that flows into the sedimentation system in the end will be reduced.

2.2.3 Quantitative theoretical assessment

This section of the approach is again divided into two parts. First, the functioning of the treatment facility installed in the area will be simulated by the built model. To finally understand the rainfall patterns and its implications on the sampling procedure, the precipitation data of four past years will be analyzed.

The simulation of the functioning of stormwater sediment retention facility

A conceptual model can be a useful tool to estimate the removal efficiency of the installed stormwater treatment system without performing a series of measurement in the field. Such measurement should be done for a long period in order to be able to get representative results. Instead, the model can predict the expected outcome without time-consuming and expensive monitoring. Furthermore, it helps to understand where the focus of the monitoring should be placed on. Additionally, the preliminary results of the monitoring can be used to improve the input parameters of the model itself.

The conceptual model is built to simulate the removal efficiency of stormwater sediments via the process of sedimentation inside the sedimentation path of the SediSubstrator. This sedimentation path is within the horizontal pipe of the facility, where stormwater particles will precipitation according to the main removal principle, the sedimentation. The process of filtration in the filter cartridge in the end shaft is neglected in the simulation due to the lack of information about the exact functioning. The behavior of the sedimentation path of the SediSubstrator is described by two sub-models. A rainfall-runoff model is used to compute the runoff generated from precipitation data given in 5-minutes intervals. Hereby, the loss processes occurring on the different connected surfaces are considered. Along that, the basic removal principle of the horizontal pipe of the SediSubstrator is used as a basis for the second sub-model. The influent sediment load is reduced according to the functioning of the treatment facility. This computes a sediment load being caught due to sedimentation. The latter is simulated to gradually fill up the storage below the flow separator in the horizontal sedimentation pipe. Once filled, it needs to be removed. On contrary, the sediment load leaving the treatment facility is expected to end up at the sewer system thereafter. A detailed explanation of the structure of the model as well as its input parameters and assumptions are given in § 5.2 & § 5.3.

The statistical analysis of the precipitation data

The precipitation data of the past four years is further statistically analyzed with regards to the duration of rainfall events. The average duration of the events in the past four years is then used as a basis to determine the sampling volumes and intervals. It is aimed to choose a sampling strategy that allows to sample an entire event within one storage container. Therefore, the average duration of rainfall events can be useful to determine the volumes as well as the frequency of taking samples throughout an event.

3 Literature review

3.1 Necessity of the monitoring of stormwater suspended sediments

The necessity to monitor stormwater sediments can be emphasized along with two major reasons. Taking track of the particles in urban stormwater discharge is important on one hand because they accumulate in drainage facilities eg. sewer pipes or sediment traps. This results in the clogging of these and requires maintenance in form of cleaning. Additionally, they carry a large load of pollutants, which, from an environmental point of view, should be removed. If not, they can cause toxic effects, impact the oxygen budget of the receiving water and enhance eutrophication (Feldhaus & Klein, 2009).

Rainwater contains both organic and inorganic substances, which can be present either in dissolved or particle-bound form. Looking into the constituents, Feldhaus & Klein (2009) defined the suspended solids as matter that mainly consists of minerals, but may contain organic components as well. They can be either settleable or filterable and origin mainly from construction sites, agricultural land or atmosperic pollution such as dust. These particles are the main cause for clogging as well as water contamination. According to Han et al. (2019), the particles in stormwater cause clogging of the openings of gravel layers due to the formation of links between the bigger particles in form of bridges. This results in a decrease the permeability and the reduction of the effectiveness and so the service life of e.g. facilities meant to infiltrate water like SUDS (Siriwardene et al., 2007).

The second issue related to stormwater particles is the change in water quality. Stormwater is known to contain many different pollutants which are collected by the runoff from different sources. More information about these sources can be seen in Appendix B-I. The main pollutants to be found are heavy metals, PAH, pesticides, nutrients and bacteria (Boogaard, 2015). The same study analysed 150 locations throughout the Netherlands for pollution data in stormwater. He found that the pollution levels did often neither meet the standards required by the European Water Framework Directive (WFD) nor the Dutch Water Quality Standards. Especially the mean values for copper, zinc and nutrients exceeded the maximum acceptable concentration (MAC) for receiving waters. Therefore, the stormwater that was analysed in that research needs to be treated with a focus on the mentioned pollutants with an efficiency of 80.5 %, 60.7 %. and 65.0 % respectively, to be able to meet the Dutch standards.

Usually, pollutants are adsorbed and attached to particles. In general, the smallest particles in stormwater offer the biggest specific surface area, meaning the surface area to mass ratio (Semadeni-Davies, 2009; Lin, 2003). This provides the best circumstances to adsorb pollution. Particles that contain high amounts of organic matter as well as specific clay minerals have strong adsorptive binding abilities for some chemical components. These two, are usually found in the smaller size range of particles. According to the report of Fuchs et al. (2019), 74 to 88 % of the heavy metals such as zinc, copper and lead are adsorbed to the particles of a size smaller than 63 µm. Depending on their physical nature, metals can be encountered either in dissolved or particulate bound state (Lacy, 2009). Looking into their removal from an environmental point of view, both particle-bound and dissolved form should be removed. However, most of the removal mechanism work on the principle of sedimentation or filtration and so only retain particulates. On the downside, dissolved metals are hardly removed due to relatively low contact times (Llandosa Farré & Rauch, 2015). Nevertheless, they state it is important to take care of the dissolved fraction since they contain most of the toxicity.

Several authors (Boogaard, 2015; Selbig et al., 2016; Johnson et al., 2003) mentioned, that to fully understand the efficiency of particle removal by stormwater treatment devices, it is crucial to characterize the suspended sediments. Hereby, taking physical samples that are representative for the area under investigation is important. These can vary within location due to differences in the hydrologic, climatic as well as site-specific conditions. As a result, different properties and concentrations of the sediments are encountered and hence the removal of these is affected (Melcher, 2019). Melcher (2019) emphazised that this variation limits the possibilities to use standard relationship and values to be used for different measurement conditions.

3.2 Suspended sediment characteristics

3.2.1 Sediment composition and loads

The characteristics of stormwater and thus the sediment composition and its related quality aspects can strongly differ per location. The composition is unique in size, shape, density and the properties of the particles. The most common stormwater constituents are suspended solids, nutrients, organic and inorganic substances, oxygen depleting substances and pathogens, each of them differing within sites (Arias et al., 2013). These variations depend on factors such as the catchment area, rainfall intensity, the surface properties and many other area-specific characteristics. Furthermore, even significant variations between and during rainfall events can be noticed (Boogaard, 2015). Factors such as rainfall and street characteristics, previous events (Pitt, 1984), traffic conditions (Andral et al., 1999; Huber & Helmreich, 2016) as well as the influence of trees and greenstrips (Dierschke, 2014) will determine the composition of the sediments in the stormwater discharge.

Sediment loads in urban runoff

The precipitation absorbs dissolved or particulate substances already in the air. Then it continues absorbing while washing away the accumulated sediments from surfaces. Hence, the rainfall intensity can be seen as the transport capacity for the loads. The amount of these loads in the surfaces further depends on the local emission situation (Reinhold, 2002), the land use and previous dry periods (Pitt 1984) causing accumulation of particles. Other processes, that determine this amount of pollutants on the surfaces is cleaning as well as transport by wind. Pitt et al. (2004) mentioned that street sweeping reduces the loads on the surfaces. Vaze & Chiew (2002) stated that the transport of particles by stormwater runoff results in a graded distribution of sediments, since different particles sizes have different abilities to being transported. This transport factor is more crucial to the sediment load than the actual presence of these in the surfaces. This is because not all particles deposited on the surfaces will actually end up in the stormwater sewer (Pratt & Adams, 1984).

Research by Pitt (1984) highlights the role played by the type of rainfall events on the character of the stormwater composition. He mentions that besides the intensity and the duration of the events itself, dry periods have a significant impact. Antecedent periods without rainfall will result in an accumulation of pollutants. In general, he concluded that moderate rainfall intensities in combination with extended dry periods, will result in the biggest pollution loads towards the sewer. During dry periods, a layer accumulated dirt builds up (Vaze & Chiew, 2003). This depends on the local conditions such as the land use, the structural design of the area and the climatic and meteorological conditions (Reinhold, 2002). These conditions as well as the transport processes causing losses or redistributions, ultimately determine the actual amount of sediments to be washed away by the runoff. High day temperatures, furthermore increase the availability of solids on the surfaces, since dry soil erodes better when compared to the wet condition (Rietveld et al., n.d.).

Additionally, the texture of the road itself will impact the composition of the particles in the stormwater (Huber & Helmreich, 2016; Pitt, 1984). Rough surfaces will decrease the sediment transport towards the sewer system, since the particles get trapped in the structure of the surface. Furthermore, such a surface will reduce scour velocities and thus some sediments will not be moved by a rainfall event. Hence, it is important to know these properties of the surfaces as well as the load of sediment deposited to determine the exact movement rate of particles (Burton & Pitt, 2002).

Besides the intensity and duration of a rainfall event, traffic plays an important role in the transportation of pollutants towards the sewer system. Looking into the actual transportation of sediments, the energy of traffic enhances the movement of particles. Thus, differing traffic volume and speed results in a variation in the loads composition. Dierschke (2014) mentioned that actually the driving speed in particular plays an important role in causing turbulence. For instance, during night or times with low traffic, only a small amount of litter on the road is moved and hence transported to the sewer. While coarse sediments > 63 µm are mainly moved by traffic and the cleaning of the roads, the fine particles < 63 µm will be transported predominately by surface runoff and wind (Fuchs et al., 2019). This energy needed for the detachment of particles from the surfaces was also investigated by Vaze & Chiew (2003). They reported that both, the rainfall and runoff energies, are responsible for moving and further transporting particles in the runoff. While the energy coming from raindrops is crucial for the loosening of particles, the runoff characteristics determine the carrying capacity of such.

Often, the highest loads of particles and its attached pollutants are being washed towards the sewer system within the early stage of a rainfall event. This phenomenon is called first flush (FF) and has been recognized to occur by various authors (Acharya & Piechota, 2010; Arias et al., 2013; Melcher, 2019; Nie, Li, Yao, Feng, & Zhang, 2008; Reinhold, 2002; Stenstrom & Kayhanian, 2005). During that period, the system experiences flows of relatively large concentrations compared to later moments. Stenstrom & Kayhanian (2005) measured around 30 to 50 % of the incoming stormwater pollutants within the first 10 to 20 % of the generated stormwater discharge by a single rainfall event. Acharya & Piechota (2010) further specified that 28, 38, 58 and 85 % of the incoming stormwater pollutant mass is transported by the first 20, 30, 50 and 80 % of total discharge volume respectively.

When referring to the concentration of these sediments in stormwater, literature mainly reports them as total suspended solids (TSS). This is due to the fact that the main concern has been the fine fraction (Leisenring et al., 2011). According to the research of Boogaard (2015) the mean value of TSS in the worldwide stormwater quality data is about 150 mg/l. The general benchmark in the United States for TSS in stormwater for instance is 100 mg/l, which is also the measured concentration in Amsterdam (Boogaard & de Graaf, 2013). However, the mean TSS concentration in the Netherlands is by far lower, showing only an average value of 29.5 mg/l in residential areas (Boogaard et al., 2015).

Sources of the main suspended sediments

In general, two main factors that influence the composition of the stormwater can be identified (Reinhold, 2002). The first source is pollution originating from the atmosphere that settle during dry weather periods or are washed out and dissolved by precipitation. They dominantely originate from combustion processes in the power production or the dust pollution caused by industry or wind erosion. Parts of this atmospheric dust already precipitates during the dry weather phase and contributes to the accumulation of sediments on surfaces. Hence, the pollution loads coming from the roofs fall into this category, since the emissions come from the atmosphere.

The second contributing pollution source highlighted by Reinhold (2002) can be understood as the sum of the pollutants accumulated on the connected ground areas. They are washed away to the drainage system by precipitation. These contaminants are mainly caused by the processes on the drainage areas themselves, including roads, parking lots, bike paths, green strips and side walks. They are composed by contamination caused by pedestrians and road users. A large part of this pollution is contributed by emissions from traffic, especially from the road surfaces. Here, abrasion from tyres, brake pads and road surfaces as well as fuel losses and combustion residues can be encountered. The amount of traffic-related pollution depends on the volume and the characteristics of such. Lastly, the de-iceing material used during winter, falls into this category and mainly contributes to the increasing loads in settleable or filterable substances and chlorides.

Sediment composition and loads in Amsterdam

At first glance, the literature seems to offers a lot of information about measured concentrations of substances in the urban stormwater discharge. However, the authors often refer to the same data sources, as the number of measurements carried out is ultimately quite small. Furthermore, it must be noted that the recorded concentrations differ considerably due to the different boundary conditions and thus are not representative for other locations (Boogaard, 2015; Reinhold, 2002).

Not much literature about the exact sediment composition in Amsterdam has been conducted yet. In a study at the Middenweg in Amsterdam, done by Waternet (Nijman, 2019), the sludge volume in gully pots as well as at the inlet and outlet of sedimentation pipes was analysed. From the observed sediments it could be seen that on average 31 % of the sediments are smaller than 63 µm, while about 17 % are smaller than 2 µm. Of the analysed samples, 12 % were found to be organic matter. Compared to the gully pots, this organic content increased by 10 % on its way to the inflow of the system. The same measurements in Amsterdam by Nijman (2019) illustrate that during small showers, the concentration of undissolved components flowing in and out of a sedimentation pipe is between 8 and 100 mg /l, while during high rainfall intensities, the concentration increases to maximum values of 130 to 320 mg /l.

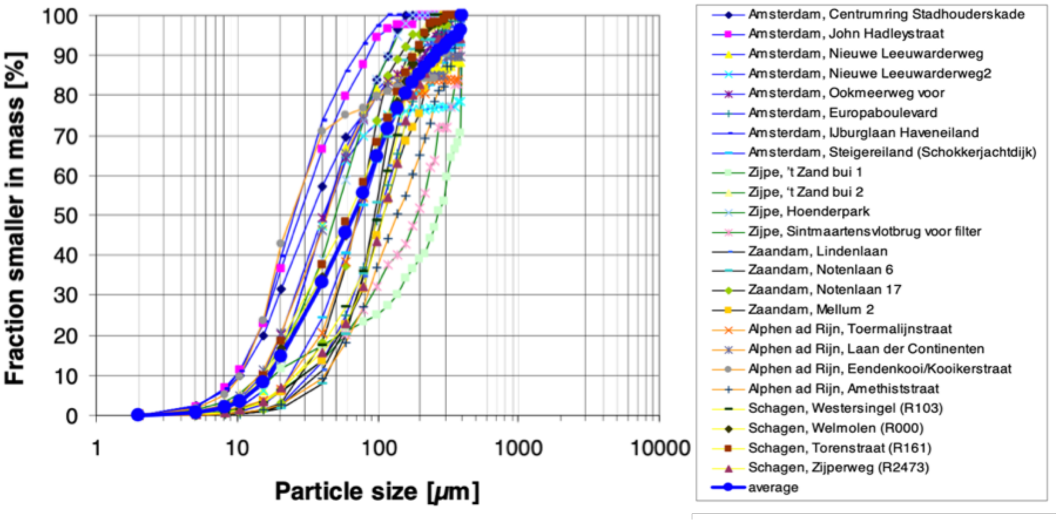

Figure 3-1 *Particle size distribution in stormwater sewers in the Netherlands by Boogaard (2015).*

Figure 3-1 illustrates the measured particle size distribution of Dutch stormwater sewer systems during the research of Boogaard (2015). From this graph it can be concluded that about half of the total amount of sediments in stormwater in Amsterdam is actually even smaller that 40 µm.

3.2.2 Size of the sediments

The particles in urban stormwater vary within a big range of different sizes. They range from colloidal organic material in nanometer-sized ranges to millimeter-sized sand, silt and gravel. There are different ways to distinguish the sediments according to size. One way, illustrated by Deforest Fowler (2008) classifies the sediments into a dissolved, a suspended and a bedload fraction. Others (Kim & Sansalone, 2008; Ying, 2007), characterize them according to the suspended fraction (1 to 25 µm), the settleable fraction (25 to 75 µm) and the sediment fraction (75 µm to 4.75 mm). Figure 3-2 provides an overview on how these sediments in urban stormwater discharge can be further classified by size. They can be divided into dissolved, non-settleable, fine, coarse and gross solids.

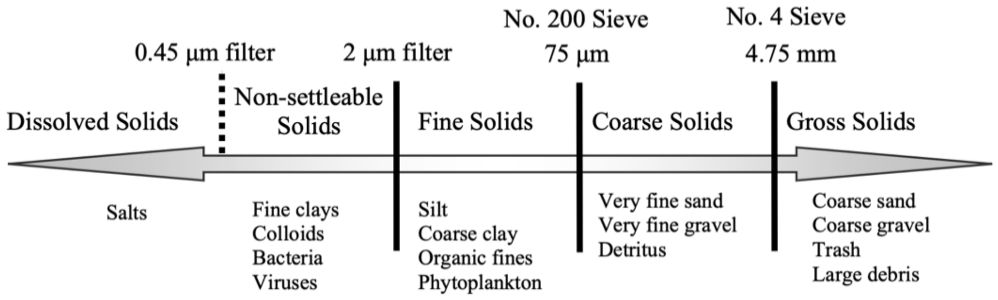

Figure 3-2 *Solids classification scheme (Leisenring et al., 2011).*

The dissolved and non-settleable solids require a lot of effort to be removed by sedimentation or filtration due to their size and low density (Kidner & Roesner, 2007). The fine solids are usually found in suspension as well but compared to the dissolved fraction they are settleable. Kim & Sansalone (2008) defined the settleable particles as the fraction to be used as an indicator for the treatability by settling through gravity. Colloids as well as the suspended fraction of the particles usually have a negative charge in stormwater (Lin, 2003). The next fraction in size, are the coarse solids. These particles are either found in suspension or as bedload. Those with densities similar to sand settle easier and thus can be removed by sedimentation and filtration. Together with the fine solids they form the fraction that absorbs and transports the most harmful pollutants (Boogaard et al., 2015; Fuchs et al., 2019; Vaze & Chiew, 2004). Furthermore this fraction increases the turbity of the water (Kidner & Roesner, 2007). Finally, the gross solids are transported, as bed sediment, in suspension or floating depending on their density.

Table 3-1 summarizes the grain size scales proposed by different authors. These scales can be used to identify and classify particles according to their size.

Table 3-1 *Particle sizes in microns (µm) typically found in stormwater.*

Classification	**Particle size [µm]**	
source	*Udden-Wentworth*	*ISO 14688-1:2002*
Colloid	< 1	n.a.
Clay	1 – 3.9	≤ 2
Silt	3.9 – 62.5	2 - 63
Very fine sand	62.5 - 125	n.a.
Fine sand	125 -250	63 - 200
Medium sand	250 - 500	200 - 630
Coarse sand	500 - 1000	630 - 2000
Very coarse sand	1000 - 2000	n.a.

Boogaard et al. (2015) highlighted that international studies have shown that sediments smaller than 50 µm represent more than 70 % of total suspended sediment load carried by stormwater discharge. In the Netherlands specifically, 50 % of the particles from urban stormwater discharge are within the size of 90 µm (Boogaard et al., 2015). Furumai et al. (2002) even narrowed the majority of TSS in stormwater discharge down to fine fraction of particles smaller than 20 µm. Kim & Sansalone (2008) showed that in the US on an event basis, fine particles smaller than 75 µm accounted for 25 to 80 % of the total suspended sediment mass, while gravel-size matter > 2,000 µm was only found in a range from 0.5 to 30 %. In general, findings of several studies (Kim & Sansalone, 2008; Shaheen, 1975; Ying, 2007) have in common that the main size range of particles found in urban stormwater discharge is composed by sediments between 75 and 250 µm. Roger et al. (1998) and Andral et al. (1999) found that in France, 70 to 80 % of the total suspended sediment load by weight are composed by particles less than 50 µm.

Sediment concentrations in stormwater discharge according to particle size

Furumai et al. (2002) published in this study the two graphs shown in figure 3-3. These illustrate the difference in particle size distributions according to the suspended sediment (SS) loads and concentrations.

The bar chart of the left depicts the particle size distribution arranged in relation to the concentration of suspended sediments. From this, it can be concluded that the higher the SS concentrations, the coarser the sediment fractions are in size. The diagram on the right, on the other hand, shows how the SS load behaves within the cumulative stormwater volume. Looking at the cumulative load with increasing volume, the finest fraction smaller than 20 µm increased throughout the whole event. All the other fractions (> 20 µm, > 45 µm and > 106 µm) contributed more or less equally to the load during the peak of the investigated stormwater discharge (average 2.14 mm/h).

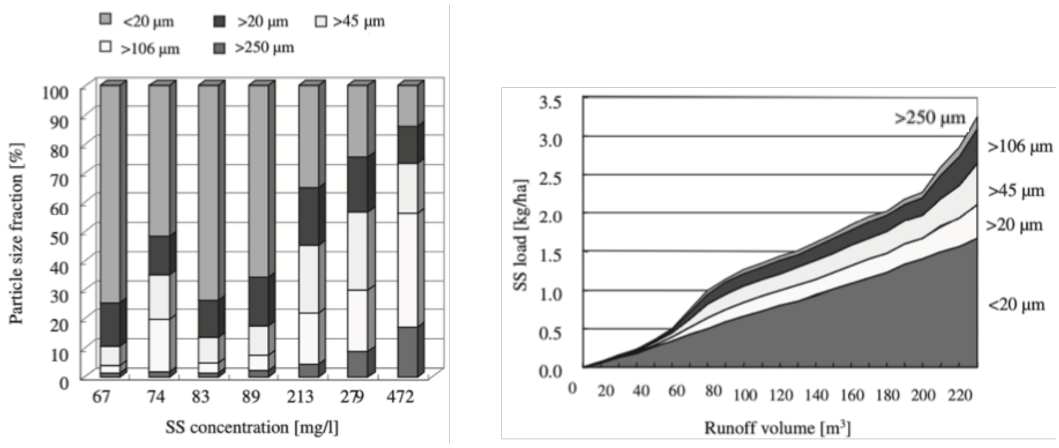

Figure 3-3 *Particle size distribution according to SS concentration and load (Furumai et al., 2002).*

3.2.3 Shape of the sediments

According to Hills (2016) the shape of particles can be classified according to its angularity and sphericity. Regarding the angularity, particles can be between very angular and well rounded. Looking at the sphericity, the shape can range from low to high. Comparing silica material to real stormwater particles, the actual stormwater sediments are more angular and show a lower sphericity. Their surface is rather rough and more porous. Due to the irregularity of the shape and its angular structure the surface area of real world sediments is way higher. Therefore, such particles are more likely to be filtered by the openings of filter media. In general, silt and clay particles tend to be more angular compared to coarser particles. Le Roux (2002) assumed that this might be due to the formation process of the fines, originating often from bigger fraction by chipping. When comparing well rounded particles with particles with sharp edges, the settling speed is reduced by 8 to 28 % in case all other particle properties were not changed (Williams, 1965).

3.2.4 Distribution of settling velocities

The settling behavior of the particles that are encountered in stormwater is crucial for the design of urban stormwater treatment facilities. Incorrect assumptions regarding particle size distributions and hence the settling velocities can result in miss-designed facilities. These either don’t manage to meet the removal objectives or may result in too large construction and related costs (Erickson et al., 2013).

The particles encountered in stormwater are non-colloidal and have different densities, shapes and sizes. Their settling velocity is a very crucial parameter to describe the transport of sediments in stormwater treatment systems (Lin, 2003). The ability to settle is determined by several parameters: the size, shape and density of the particle, the concentration of the particles, the cohesion-flocculation behavior, the temperature of the stormwater (density and viscosity), the depth of the fluid in the device, and the speed of the fluid as well as its turbulence (Semadeni-Davies, 2009). Due to this complexity to determine the settling velocity for each particle, often theoretical values are used to calculate. However, they vary in the field and also significantly from location to location.

According to Semadeni-Davies (2009) particles that have been washed from roads and hence origin amongst other from tire wear and tear, most probably have different settling velocities than those coming from impervious surfaces. The latter mainly consist of mineral sands. Semadeni-Davies (2009) stated that larger particles will settle or be trapped in gully pots and might not even reach the treatment facility. A research from Waternet (Nijman, 2019) on the sedimentation of particles in the stormwater in pipes could proof that the bigger the sand content and the coarser the material, the faster a settling process takes place. Erickson et al. (2013) confirmed this evident relationship of particles size and settling velocity. While this coarse material bigger than 125 µm will fall quite fast, the dissolved fraction and colloids will flow through the sedimentation facility (Semadeni-Davies, 2009). Erickson et al. (2013) furthermore mentioned the apparent relation of higher densities settling faster than less dense particles of the same size. In case particles are below a certain size, the Brownian motion will become dominant relative to gravity. This leads to an infinite settling time in theory. Hereby, stormwater treatment through sedimentation is not practical anymore and additional treatment such as e.g. sand filters are needed.

Density

Most researchers investigating the settling behavior of sediments have utilized the density equivalent to mineral sands of approximately 2600 to 2800 kg/m^3 for spherical particles. More precisely, it is very common to assume a density of quartz of 2650 kg/m^3 (Semadeni-Davies, 2009). However, again, this does not really represent the actual circumstances in the field.

This especially applies because the particles can either be organic or inorganic, depending on their source. Those, that origin from e.g. leaves are called organic and usually show a lower density than sand particle but are bigger in size. Their density range is usually between 1100 and 2500 kg/m^3. Inorganics instead, which are those formed from e.g. tires. This is confirmed by the findings of the literature review of Semadeni-Davies (2009), outlining a density range of organics between 1400 and 2300 kg/m^3. Inorganic particles on the other hand have higher densities than organics, ranging between 2700 to 3010 kg/m^3 (Semadeni-Davies, 2009). Table 3-2 summarizes the densities related to the particle size range (Andral et al., 1999).

Table 3-2 *Overview of particle size range and respective densities for inorganics.*

Particle size range [µm]	Density range [kg/m^3]
< 50	2400 - 2650
50 - 100	2530 - 2860
100 - 500	2500 - 2820
> 500	2510 - 2790

The study performed by Bäckström (2002) on the other hand experimentally determined the densities of different particles sizes to be the following: 2610 kg/m^3 for particles smaller than 75 µm and 2580 kg/m^3 for the range between 75 and 250 µm. He furthermore mentioned that the settling formula by Stoke can be only used to accurately determine the settling behavior of particles bigger in size than 20 µm.

Many stormwater devices are based on the principle of sedimentation and hence depend on the settling velocity of particles. The process of sedimentation should take place within the installation, thus ideally the stormwater should be accommodated inside these long enough for settling to occur.

3.2.5 Coagulation and cohesion properties

The particles in stormwater are transported from their original source, usually from deposited or eroded surface, until they either enter a treatment facility or a receiving water body. Droppo et al. (2002) divided the pathway of particles into four stages. Throughout these, the particle changes its physical, chemical and biological properties. The first stage is the dry stage where particles are deposited on the surface or within the structure of the surface itself. From there, they will be mobilized by runoff and eroded from their original stage. After that, particles will be encountered in the drainage system, before reaching the last stage, being treatment plants or receiving water bodies.

So far, most of the models used to simulate sediments in sewer systems assume that there is no change in the physical properties of the particles. This lack is mainly due to the missing methodologies and knowledge about the behaviour of particles along the continuum. The same study by Droppo et al. (2002) observed that street sediments almost do not show any aggregation behaviour in the first stage. Those sediments that are washed off from the surface and transported by runoff in the second stage, undergo a significant change in size. Fines are separated from the coarse material by hydraulic sortening. This is mainly influenced by the characteristics of the storm event and the flow, the source and the ability to build flocs or defloc (Droppo et al., 2002).

Non-cohesive particles

Looking further into detail, the concentration of particles impacts the aggregation of such and so further the settling velocity. This is due to their cohesive or non-cohesive character. Raudkivi (1990) emphasized that the settling of particles must be rather determined for clouds than single particles. Hereby, the character of the sediments in terms of cohesion is decisive. Sediments that are bigger than 62 µm are the non-cohesive fraction (Lin, 2003; Semadeni-Davies, 2009). These particles are coarse-grained and only interact mechanically, they push each other. They usually tend to be unevenly dispersed in a water column, building a heterogeneous cloud with particles in different distances. Hence, the bigger the concentration of these particles, the higher the chance of interaction and so the settling velocity increases.

Cohesive particles

Cohesive particles on the other hand, which is the fraction smaller than 2 µm, have the ability to flocculate or aggregate due to the electrochemical interaction of single particles. Fine silts and clay rank among these sediments with cohesive character. The strength of the forces as well as the frequency of interaction of the flocs determine the size of these.

The formation of flocs itself furthermore depends on the mineralogy of the particle, the electrochemical nature of the stormwater discharge, the particle concentration and characteristics and the water temperature (Krishnappan et al., 1999; Semadeni-Davies, 2009). Besides the density, also the shape of the flocs impacts the fall velocity. Semadeni-Davies (2009) found that flakes are likely to have lower fall velocities, while discrete and larger sediments (e.g. clumps) of the same mass and density settle faster.

3.3 Stormwater characteristics

3.3.1 Unique characteristics of urban stormwater discharge

There are several unique characteristics that urban stormwater discharge has compared to other water streams such as e.g. natural water bodies or wastewater. Some on these include the relatively short residence time (usually less than several hours) and the unsteady flow conditions, leading to different flocculation behavior. In general, the water columns are only a few millimeters to centimeters high and nonetheless carry a mixture of colloidal and suspended sediments and settleable fractions (Lin, 2003). The same research furthermore stated that urban stormwater is additionally low in hardness, which results in a good stability of colloids. This is because the electrostatic repulsion increases.

3.3.2 Temperature, density and viscosity

The fluid density and viscosity are the key parameters of the stormwater that influence the settling velocity of particles. Both depend on the temperature of the fluid, hence the stormwater (Erickson et al., 2013). An increase in temperature results in a decrease of the viscosity of the fluid (Anggraini, 2018). This change in viscosity (table 3-3) then again affects the settling velocity, since they have an inversely proportional relationship (Lau, 1994). This process of sedimentation of particles takes place if the particle density is higher than the one of the fluid.

Table 3-3 *Overview of different fluid densities and respective viscosities as a function to the temperature.*

Temperature [°C]	Density [kg/m³]	Dynamic viscosity [Pa.s]
4	1000	0.001560
10	1000	0.001304
15	999	0.001137
20	998	0.001002
25	997	0.000890
30	996	0.000798

Figure 3-4 shows the effect of the water temperature on the settling velocity illustrated by Semadeni-Davies (2009).

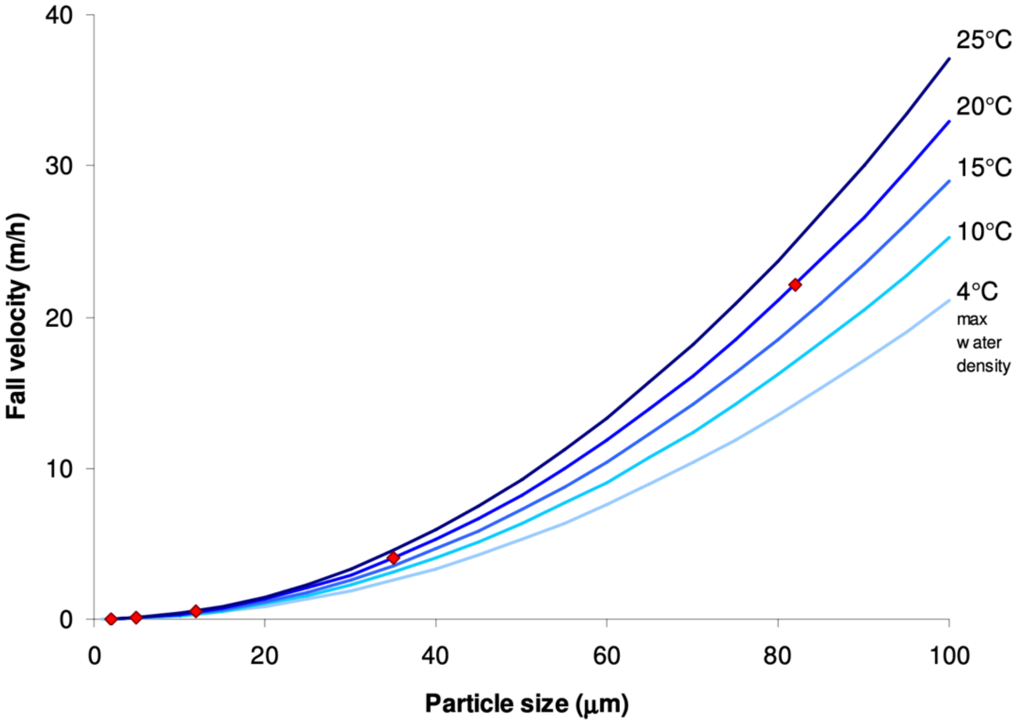

Figure 3-4 Relationship of particle size (ρ_p = 2680 kg/m^3) and settling velocity in a fluid.

Erickson et al. (2013) stated in their handbook that, when looking into stormwater, the fluid under investigation is water and hence the density can be assumed as constant. Hereby, a value of 1000 kg/m^3 can be used. Therefore, only the viscosity will vary as a function of the temperature. Using Stokes' Law, he computed that the fall speed of in water with a temperature of 0 °C is almost halved (approximately 43 %) compared to the one in water at 40 °C for the same sediments.

In general, the temperature of the stormwater is influenced not only by the actual temperature of the precipitation, but also the successive processes on the surfaces that cause heating or cooling (Erickson et al., 2013). These are controlled by solar radiation and heat fluxes. According to Erickson et al. (2013) the largest temperatures of the stormwater that can be produced in this way are about 30°C.

3.3.3 Rainfall intensity and duration

The importance of the intensity and duration of rainfall events was already mentioned earlier, when talking about the sediment loads in urban stormwater discharge in § 3.2.1. The intensity of the storm event can be defined as the ratio of the total amount of rain (rainfall depth) within a given period of time. Often, the rainfall intensity is expressed in mm per hour (mm/h). Besides influencing the loads of sediments that are moved by the event, these variables also determine the volume of water that is drained towards the stormwater sewer. Together with the connected surface area to the system, it will results in the volume of stormwater that needs to be treated by the devices. Deforest Fowler (2008) highlighted that the rainfall depth is one of the required supplemental data to monitor the suspended sediment concentration.

However, not all this fallen water actually translates into runoff. Some parts will be lost on the surfaces via depression storage, wetting losses or are infiltrated into the pervious surface. Melcher (2019) mentioned that for instance the land development and the increase in paved surfaces by urbanization change the runoff behavior. Surfaces with different levels of imperviousness result in varying hydrologic responses. The so-called initial losses include the depression storage and wetting losses. Roads are considered to hold back around 2 mm, while flat roofs can hold twice the amount (van de Ven, 1985). Looking into the wetting losses, van de Ven (1985) found that tiles and concrete bricks are expected to absorb about 0.5 mm in 10 minutes, while asphalt can absorb about 0.07 mm within 15 minutes. The water stored on the surfaces will then only be removed via evaporation and eventually infiltration.

The second important factor to be considered is infiltration. This value depends on several factors such as the soil porosity, moisture content, groundwater level, surface conditions and storage capacity. Van de Ven (1985) stated that the infiltration loss can be computed as the weighted average infiltration capacity. The heavier and longer the storms, the smaller the infiltration rate and the bigger the contribution to runoff. The interception loss can be neglected for paved surfaces, while for unpaved surfaces it is included in the wetting loss (van de Ven, 1985).

According to Law et al. (2008) it is recommended to study historical rainfall data to better understand how the runoff events for the study area are constituted and to know what kind of events can be expected. Due to their important contribution compared to very large or small rainfall events, Burton & Pitt (2002) emphasized the importance of intermediate flows for the total annual volume.

3.3.4 Turbidity

Turbidity is an apparent optical property of water (Ziegler, 2002) and can be defined as the cloudiness of a solution caused by suspended or dissolved particles. This presence results in a decreasing transparency of the water (Ziegler, 2002). The larger the number of individual particles in the solution, the higher the turbidity and the lower the clarity. Especially in surface waters, the measurement of turbidity gives insights on the quality of the water. Turbidity is expressed as nephelometric turbidity units (NTU or FNU), formazin turbidity unit (FTU) or Jackson turbidity unit (JTU). Which unit is used is defined by the wavelength of light that is emitted from the turbidity meter. Several studies mention that the monitoring appears to be an attractive way to measure the suspended sediment concentration, once a relationship between both is known. This is because turbidity measurements are cheap compared to sediment sampling, since it can be done in a short time in the field (Al-Yaseri et al., 2013). However, Deforest Fowler (2008) highlighted that turbidity is not representative enough to replace the measuring of suspended sediments. Al-Yaseri et al. (2013) mentioned that this is a suitable method to monitor suspended sediments in case sampling and testing is not feasible. It can be used as a surrogate for suspended sediments to avoid expensive gravimetric analysis of the stormwater discharge.

3.4 Monitoring and sampling techniques

The first step to any monitoring study is to define the exact objective of the study. This means it needs to be identified what should be accomplished by monitoring and how this can be achieved. The selection of the specific physical parameters to be monitored should be based on the information needed to fulfill the monitoring objectives within the available project resources. Hereby, the assessment of the suspended sediments as well as the stormwater characteristic itself are of great importance. Furthermore, the characteristics of the study area as well as the characteristics of the flow need to be monitored.

3.4.1 Stormwater sediment sampling techniques

The different parameters that can be studied when looking into the characteristics of suspended sediments in stormwater were already pointed out in § 3.2. Each of these factors are further influenced by other components. While some of them are easier to assess, others require more effort. For the suspended sediment characteristics specifically, samples are taken preferably in the field while the actual analytical determination of the parameters takes place in the laboratory (Arias et al., 2013; Dierschke, 2014; He et al., 2010; Reinhold, 2002). Melcher (2019) emphasized in his study that the collection of physical samples that represent the hydraulic and site-specific characteristics of the area, is crucial to understand the relationship between sediment concentrations and loads.

Collection of the samples

In general, the collection of samples can be divided into dry and wet collection. While the dry collection can be seen as a kind of vacuuming surfaces of interest (DeGroot & Weiss, 2008), the wet collection can be further divided into automated or manual sampling (Law et al., 2008). Additionally to that, Deforest Fowler (2008) mentioned that samples can be divided by storage type into discrete (or grab) and composite samples. This is referred to as sampling techniques. Hereby, discrete samples represent those that are taken individually without interruption during a specific (short) timeframe. Furthermore, they are stored individually. The short sampling period usually is around maximum 15 minutes (US EPA, 1992). Composite samples, on the other hand, represent an average composition of the concentration. The latter are a combination of individually taken samples within an extended period of time. Either way, the samples can be collected manually or by automated samplers. Which technique to choose depends on the available budget, the objectives and goals of the study and the capacity of available personnel (Erickson et al. 2013). Usually, samples are called by collection and storage method (e.g., flow-weighted composite sample) while additionally mentioning the type of sampling technique used such as manual or automatic (Erickson et al., 2013). In case it is desired to make a statement about the removal efficiency of pollution in e.g. stormwater, it is necessary to measure both influent and effluent concentrations.

More detailed information on the manual and automated sampling approach are given in Appendix B-II. Additionally, their advantages and disadvantaged will be compared in this section.

Sampling frequency and sampling approach

The frequency or spacing of the sample-collection can be structured in different ways. Samples of a constant volume can be either taken at constant time intervals or the volume can vary according the change in flow rate, to grab samples proportional to the flow. DeGroot & Weiss (2008) calls this flow-weighted sampling. Similar to that, the volume can again be held constant, while the time interval is adjusted according to the flow volume increment (Deforest Fowler, 2008). Lastly, samples can be grabbed in user defined intervals.

According to several manuals (US EPA, 1992; Erickson et al., 2013) stormwater sampling usually requires flow-weighted sampling. This is because the samples represent the mean sediment concentration for the entire cumulative volume to which it relates. However, this sampling approach also leads to inaccurate results for the mean concentration of sediments for the cumulative volume, if the concentration of such changes fast. For instance, volumes increasing in small steps require a lot of samples to be taken. This might exceed the storage capacity of the sampler. Alternatively, samples could be taken in longer intervals, where potentially only parts of the event will be sampled (Erickson et al., 2013). The advantage on the other hand is the simplification when calculating the mean concentration, since the discharged volume is constant for each representative sample. The study of Wichern et al. (2017) for instance took a sample of 300 ml for every volume of 0.6, 0.9 or 10 m^3 that passed by, depending on the location.

In contrast, samples can be also taken according to constant time intervals. This approach to collect samples is usually used for manual sampling (Erickson et al., 2013). Such samples cannot take constant volumes with respect to time, since the flow rate of storm events is not constant either. Before the mean concentration of each sample can be computed, the total discharge flow for each time interval must be determined. Therefore, these calculations are more complex, demanding samples to be weighted by the corresponding discharge volume.

How many samples to take depends on two main factors, the influent volumes for each rainfall event as well as the incremental volume (Erickson et al., 2013). The latter is influenced by several components such as the size and type of connected area, the slopes and the storm characteristics, including the intensity and discharged volume. Hence, the increment in flow depends on the expected rainfall. Since the latter can be relatively uncertain, it is relatively hard to estimate the exact value. To finally get to a number of samples needed for each event, the stormwater discharge needs to be divided by the estimated incremental volume. In order to get more accurate results, Erickson et al. (2013) advise to use historical precipitation data from one or more preceding years for the computation of the incremental volume.

Varying the frequency in sampling can influence the outcome of the results and have to be chosen considering the spatial and temporal conditions. For instance, if samples are being collected in lower frequencies such as e.g. hourly, this might deliver appropriate results to make statements about seasonal trends. However, this frequency cannot monitor the loads in the stormwater discharge that may change with high intensities of rainfall. Such events potentially only last for short periods and might be over before the next sampling step takes place (Melcher, 2019).

Handling of the samples

Samples should be homogenized prior to filtration, to avoid a potential source of error when determining the content of fines. The reason for that is the agglomeration of fine particles to larger ones. Here, especially those fines originating from traffic are of concern (Dierschke, 2014). They tend to build larger particles within a short time and hence will be already retained in the sieve with a pore size of 63 µm. This leads to reduced amounts of particles smaller than the mentioned size. In case metals are analyzed, the sample bottles and storage containers should be plastic, plastic coated or glass (Ongley, 1996). Furthermore, the used equipment should be cleaned with acid or distilled water. For samples that will be analyzed for organic micropollutants, plastic is not ideal and metal equipment should be chosen. Sampling bottles and storage containers for the analysis of phosphorous can be made of metal, plastic or glass and only require a phosphate-free detergent for the cleaning process.

Either way, is has to be assured that the sample is dispersed before analyzing for the particle size distribution. Otherwise, particles that might have agglomerated while being in the sampling collector and are not separated (Goncalves & Van Seters, 2012). The same is advised by Dierschke (2014), emphasizing that these fine particles tend to unite to bigger agglomerates within less than 30 minutes. This can result in false results. To avoid flocculation of the particles, Andral et al. (1999) separated them by vibration. Hereby, an ultrasonic vibration device was used for a minute to disperse the sample beforehand. For this purpose, Baum et al. (2018) proposes to use a disperser used for common laboratory procedures while Kidner & Roesner (2007) on the contrary, suggest using a magnetic stirrer. Hereby, they advise a stirring velocity of 600 rpm to avoid the settling of particles. However, they mention that too long mixing times can also result in the change of particle size. Therefore, they advise not to stir for more than one minute.

3.4.2 Analytical methods

The analytical methods used to determine the particle characteristics such as size, shape and density are explained into detail in Appendix B-III. Furthermore, additional information on the techniques to detect heavy metals and nutrients are given.

3.4.3 Monitoring of the stormwater characteristics

Temperature, density and viscosity

As already mentioned in § 3.3.2 the temperature of the stormwater discharge is an important factor to be assessed, since it influences its density and viscosity. This especially matters if the downstream objectives such as e.g. stormwater treatment devices rely on this parameter. Compared to quality parameters, this parameter can be measured easily with on-site techniques according to Erickson et al. (2013). The determination of such can be either done by measuring the temperature instantaneously on the spot after collection or by using sensors to monitor throughout the event. These sensors can be integrated into another monitoring device or be externally attached. The latter are often called data loggers. Erickson et al. (2013) mentioned that some pressure transducers already have an integrated temperature sensor to correct the measured water depth.

Once the temperature is determined, the relationship to the corresponding density and viscosity can be used. In contrast to this approach, Erickson et al. (2013) used a default value for the density of water of 1000 kg/m^3. Ferguson & Church (2004) refer to a dynamic viscosity of 1.0 x 10^{-6} Pa.s for water with a temperature of 20°C. The laboratory test performed by Boogaard (2015) used a water temperature of 15 to 20°C.

Precipitation data

Precipitation data is another additional parameter needed to determine the load of suspended sediments transported by stormwater. Each form of rainfall can be measured based on the principle of water accumulating on a surface. This results in a specific depth if it would remain on the location where it fell (US EPA, 1992). The information about the precipitation can deliver important information about quantity and quality of the stormwater (Burton & Pitt, 2002). Church et al. (1999) highlighted the importance of such for the planning, design, collection, and interpretation of results for stormwater-quality studies. Due to the huge spatial variation in rainfall amounts and intensities, Church et al. (1999) and Erickson et al. (2013) emphasized the importance of on-site rainfall measurements. According to them each study area should be equipped with at least one rainfall gauge. This gauge can be either a nonrecording gauge, also referred to as manual measurement, or a recording gauge, that takes measurement automatically. The latter has the advantage of providing information about the timing, duration and intensity of a storm event while also registering the total amount of precipitation (Church et al., 1999). An issue of such devices mentioned by Church et al. (1999) is the need of more than only one gauge, in case rainfall intensities vary a lot. Furthermore, rain gauges tend to have problems in recording big showers with an intensity larger than 76 mm/h.

The most used rain gauges stated by Church et al. (1999) are weighing gauges, float gauges or tipping-buckets. Weighing gauges relate the amount of precipitation to weight. The float gauges instead, record the accumulated rain with the position of the float in a collector. The third method, the tipping-bucket, uses a small rocker. Here, the precipitation is determined by adding up the volume of the collectors at each side of the rockers. These have a specific volume and depending on that, when full, the rocker will tip and empty the collector. The device itself, then registers the number of times it tipped within a period of time. In this way the volume of the rain event can be computed. Kilpatrick & Kaehrle (1986) and Church et al. (1999) reported that the latter is the most widely used device. They are easily available on the commercial market. Furthermore, also Erickson et al. (2013) mentioned, that for purposes such as monitoring precipitation volumes and intensities digitally, the tipping-bucket with a data logger is an appropriate device to be used. Tipping-bucket gauges are a more accurate device compared to depth gauges measurement, since they continuously record the data and so avoid any losses caused by evaporation or spillage (Erickson et al., 2013).

To reduce measurement errors and achieve reliable results, the proper placing of rain gauges is crucial. Therefore, the devices should be shielded, since precipitation measurements are greatly impacted by wind. In this way errors induced by wind can be reduced. If not present, the movement of the air hinders the capturing of the rainfall. In general, a higher location of the measurement device results in bigger errors due to wind (Burton & Pitt, 2002). Therefore, the measurement on ground level is recommended keeping a distance of at least twice (Burton & Pitt, 2002) or four times (FAO, 2002) of the height of surrounding obstructions. Furthermore, to avoid raindrops from splashing from the ground into the gauge, the height of the lip of the funnel should be at least 50 cm above ground (FAO, 2002).

3.4.4 Monitoring of the flow characteristics

In order to make a reliable statement about the sediment loads as well as the treatment efficiency of a system, it is important to monitor the flow rate through these. The urban runoff mobilizes sediments and pollutants that will be washed towards the sewer system. Thus, the monitoring of the flow can provide information about the quantity and quality of the expected particles. These can vary not only temporally, but also spatially according to the discharge volume and site specific characteristics (Melcher, 2019). Hence, in addition to the sample collection, the flow rate and volume for each storm event should be determined (US EPA, 1992). The flow rate is defined as the total volume of stormwater discharge being discharged in a specific time. The measurement of such is especially important to collect flow-weighted samples, since they are collected in proportion to the incoming volume.

According to Salguero (2015) the flow can be either monitored in an instantaneous or a continuous way. There are various methods developed to measure flows in many types of conduits (e.g. natural and engineered channels, pipes, overland flow) and under various flow regimes (steady- or unsteady-state flow, subcritical, supercritical, or pressure flow). Here, one of the primary problems of the flow measurement in stormwater systems are the varying regimes. Especially the transition zone between free surface and pipeful, pressurized flow is hard to predict (Kilpatrick & Kaehrle, 1986).

Church et al. (1999) emphasized that to accurately measure flow rates in small streams, encountered in urban drainage conditions, several factors are critical. These include the timing, frequency, and duration of flow measurements. The reason is, amongst others, the fast rainfall-runoff response as well as the huge differences in flows within a short period of time. Additionally, stormwater flows increase way faster than they later decrease. Church et al. (1999) mention that the measurement should start at the beginning of the rainfall event and last until the end. The measurements itself should be performed at a frequency corresponding to the rate of change of flow and related concentrations. This can assure that the measurements are accurate and representative. Different information is needed to determine the timing, the frequency and the duration of flow measurements. These are for instance the type of drainage system (e.g. urban drainage), the connected area and percent of impervious area, the stream channel or pipe slope, climatic and meteorological data. To achieve accurate results, a relatively straight and homogeneous flow regime upstream of the device should be guaranteed.

The methods used to measure flows can be divided into two main types, the primary and the secondary devices (Church et al., 1999; Kilpatrick & Kaehrle, 1986; Salguero, 2015; US EPA, 1992). While primary devices relate the hydraulic responses to flow rates through the construction and directly interact and control the flow (Salguero, 2015), secondary devices measure water depth and pressure. Whether a primary or secondary device is more appropriate, depends on site-specific conditions such as flow regimes, fluctuations in flow, channel geometry, the range of flow and their depths. Furthermore, the capabilities and the accuracies of the methods available matter (Church et al., 1999). Examples of primary and secondary flow measurement devices are given in Appendix B-IV.

3.5 Stormwater treatment techniques

Stormwater treatment can be defined as the improvement of the stormwater discharge quality by capturing pollutants and contaminants before reaching a connected water body or an infiltration system. The processes behind this mechanism do not only reduce the incorporated pollution but can also further decrease the discharge volume, discharge peak flow or any combination thereof (Erickson et al., 2013). Since the different treatment techniques are based on varying mechanisms, the behavior of the installation should be known to understand the process. Additionally to that, the characteristics of the pollution and the hydrodynamics of the area need to be identified (Kim & Sansalone, 2008).

3.5.1 Dominant removal mechanisms

The effective removal of sediments from urban stormwater discharge depends not only on the properties of the sediments itself, but as well on the process within the treatment device. The dominant removal mechanisms used are sedimentation and filtration, which can both be additionally supported by coagulation and flocculation (Leisenring et al., 2011).

Sedimentation

The process of sedimentation is characterized by the settlement of particles to the bottom of a water column. According to Erickson et al. (2013) it is considered the dominant removal process in stormwater treatment facilities. However, having short residence times within the facility, sedimentation is only effective for large but not small particles (Lin, 2003). The velocity of the sedimentation is determined by the density of both, fluid and particle. Additionally the characteristics of the sediment, defined by diameter and shape, are impacting the settling of particles. Since the suspended particles from stormwater typically have a huge range in size (Leisenring et al., 2011), it is important to know the particle size distribution to select the best available stormwater treatment process and device.

The settling formula (equation 3-1) by Stoke is the most often used formula in practice to determine the settling velocity of particles in a fluid (Leisenring et al., 2011). It considers gravity, buoyancy and drag force. However, the formula can be used only for small spherical particles while ignoring the possible occurrence of turbulent eddies in the flow. Andral et al. (1999) described particles with a diameter < 50 μm to be spheres. The formula is as follows:

$$v_s = \frac{g d_p^2 (\rho_p - \rho_f)}{18\mu}$$

Eq. 3-1

where:

v_s = settling velocity [m/s]
g = gravitational acceleration [m/s^2]; *using the value 9.81 m/s^2*
d_p= particle diameter [m]
ρ_p = particle density [kg/m^3]
ρ_f = fluid density [kg/m^3]; *using the value 1000 kg/m^3*
μ = dynamic viscosity [m^2/s], *using 0.001304 m^2/s*

According to Andral et al. (1999) the settling velocity of particles in the range of 50 to 100 μm cannot be determined following Stokes' law. Therefore, the relationship developed by Ferguson & Church (2004) needs to be consulted, in case larger particles such as sand are considered as well. This equation can be seen in 3-2. While this formula equals the Stokes' Law for fine particles, it results in a constant drag coefficient for particles with a large diameter.

$$v_s = \frac{g d_p^2 (\rho_p - \rho_f)}{18\mu + \sqrt{0.75 g C d_p^3 (\rho_p - \rho_f)}} \qquad \textit{Eq. 3-2}$$

where:

v_s = settling velocity [m/s]
g = gravitational acceleration [m/s^2]; *using the value 9.81 m/s^2*
d_p= particle diameter [m]
ρ_p = particle density [kg/m^3]
ρ_f = fluid density [kg/m^3]; *using the value 1000 kg/m^3*
μ = dynamic viscosity [m^2/s], *using 0.001304 m^2/s*
C = constant; *0.4 for smooth spheres, 1 for natural grains (typical sand)*

The difference in the settling velocities computed by the just mentioned approaches is illustrated in Appendix B-V. Furthermore, the impact of different flow conditions on the sedimentation is shown.

Filtration

The process of filtration removes particles by the movement of the influent water stream through a bed of media. The filtration of stormwater can consist of various mechanisms. Depending on the filter media they can be referred to as chemical and physical adsorption, biological degradation, straining or adhesion.

According to Leisenring et al. (2011) filtration can be categorized into three mechanisms based on filter media size d_m (the mass-based median filter media size) and particle size d_p (the mass-based median particle size). In case the ratio of $d_m/d_p < 10$, the removal mechanism is surficial straining, if the ratio d_m/d_p is between 10 and 20, the removal mechanism is called depth filtration and if $d_m/d_p > 20$, the removal mechanism is physical and chemical adsorption (Leisenring et al., 2011).

Filters can remove sediments at two different locations. They either strain the matter on the surface of the filter media and build a so called filter cake. Alternatively they can remove particles through depth filtration inside the filter. This cake layer increases in the course of filtration, because particulate matter is retained. Either way, the accumulation of particles will result in an increase in head loss, hence the potential flow rate is reduced. This phenomenon is called clogging and requires back-washing, scraping or a replacement of the media. Another parameter indicating a clogged system is the raising time of water to flow volume through the media (Anggraini, 2018). Erickson et al. (2013) emphasizes that filters with larger pores compared to small ones, demonstrate an increasing filtration rate, using the same head. The downside of gravel as filter media, thus greater pores, is the possibility of particles to escape through those instead of being trapped. Media made from grains such as sand or silt could be considered to have small interconnected pores according to Erickson et al. (2013).

It can be seen that pretreatment is an important step to reduce the buildup of a layer of particles. Hence, the frequency of maintenance to keep the permeability of the filter media is crucial. Usually, this pretreatment is achieved by sedimentation. Leisenring et al. (2011) state that, in practice, the sediment influent concentration should be below 50 mg/L, in order for the filter to work effectively. This furthermore depends on the type of filter material used, the exact design and the frequency of maintenance.

Coagulation/Flocculation

As mentioned earlier, neither coagulation nor flocculation can actually remove particles themselves but should be rather seen as processes that improve the sedimentation and filtration process. Coagulation involves the destabilization of the charge of particles which so enhances the formation of larger particles (Erickson et al., 2013). Flocculation is the physical process where through particle collisions, smaller particles aggregate into larger ones, so called “flocs”. In both cases, the newly build particles are bigger in size and tend to settle easier.

3.5.2 Sedimentation devices

Sedimentation or settlement devices use the principle of sedimentation to remove particles from the stormwater discharge. Since many pollutants are absorbed to the particles contained in stormwater, the sedimentation of these can improve the quality of the water. Examples of such sedimentation devices are for instance settlement basins or chambers, ponds, lamella filters or sedimentation pipes (Boogaard et al., 2015).

Removal efficiency of settlement devices

As already mentioned, the sedimentation efficiency of these sedimentation facilities mainly depends on the characteristics of the particles, the hydraulic loading and the geometry of the device. A combination of the settling velocity of the particles and the so called surface load (Eq. 3-3) determines the sedimentation efficiency of each particle in the stormwater (TU Delft, n.d.). The surface load is defined as the velocity equal to the settling velocity of a particle entering the sedimentation pipe at the very top of the facility and settle exactly at the end of its entire length.

$$v_{sL} = \frac{Q}{(w * l)} \qquad \textbf{\textit{Eq. 3-3}}$$

where:

v_{sL} = surface load [m/s]
Q = stormwater discharge or hydraulic load [m^3/s]
w = width of the flow separator [m]
l = length of the flow separator [m]

The theoretical settling efficiency of a sedimentation facility for each specific particle can be estimated using the equation by Hazen (Eq. 3-4). The latter uses this relationship between the settling velocity and the surface load to compute the probability of a particle to settle within the treatment device.

$$\eta = \frac{v_s}{v_{sL}} \qquad \textbf{\textit{Eq. 3-4}}$$

where:

η = settling efficiency [-]
v_s = settling velocity of the particle [m/s]
v_{sL} = surface load [m/s]

The parameters that determine the composition and characteristics of the stormwater sediments should be determined in the field. Once known, the settling velocities per particle size ranges can be computed. Using these, the equation by Hazen can be used to estimate the removal efficiency of the treatment device.

Figure 3-5 (Boogaard, 2015) depicts the determined removal efficiencies of different sedimentation devices.

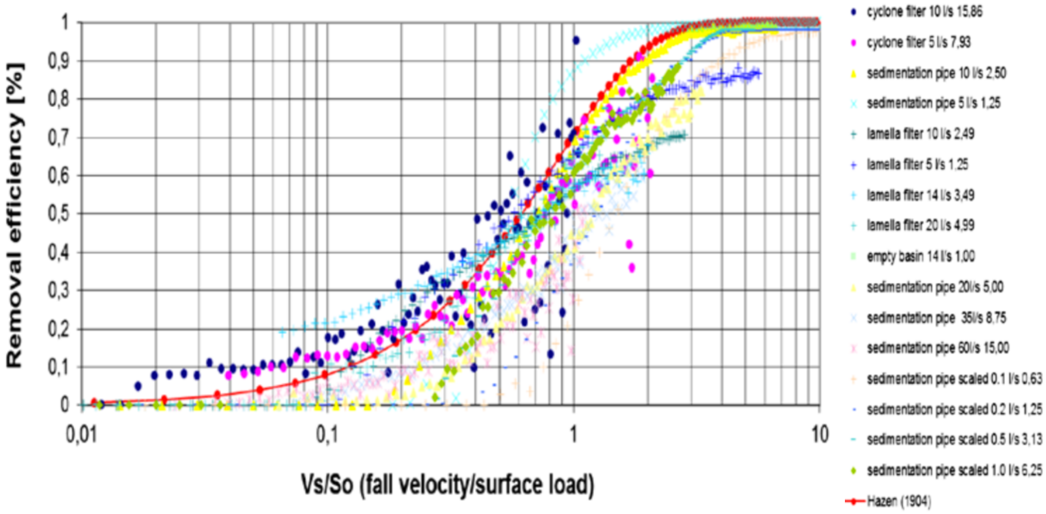

Figure 3-5 *Total removal efficiency of all tests related to the surface load against the theory of Hazen (red curve). The legend indicates the type of device with its discharge (l/s) and surface load (m/h).*

The experiments performed by Boogaard et al. (2015) illustrate the behaviour of sedimentation devices at different flow rates. They advice to avoid rates higher than 10 l/s to be able to remove more than 50 % of fine particles below 60 µm for the SediPipe 600/24. Another research on a sedimentation device executed by Uhl et al. (2013) showed that particles bigger than 70 µm can be removed at low and medium flow (6 to 25 l/s/ha), while finer particles may not be withhold. The overall removal efficiency of the annual load was computed to be around 80 % for particle in the range of 4 to 200 µm. The study by Milke et al. (2010) that tested the performance of the sedimentation device called SediPipe 500/6 from Fränkische Rohrwerke, showed a characteristic stabilisation of the particle removal at 80 to 85 %. A bigger sedimentation pipe of the same company (SediPipe XL 600/12) could remove about 87.9 % of the fine sediments (0 to 400 µm of Millisil W4) and 100 % of sand particles and gravel (Fränkische Rohrwerke, 2018). Boogaard et al. (2015) tested the same device just with a longer sedimentation pipe of 24 m instead of 12 m with Millisil W4 under laboratory conditions. They concluded a removal efficiency of 50 % for particles below 25 µm, while particles bigger than 60 µm are removed with an efficiency higher than 80 %.

In case longer dry periods occur, the stormwater remains stagnant in the facility. As a result, even particles with low settling velocities will manage to settle and the sediment concentration in the water that leaves the facility is low. This effect is referred to as the batch effect by Weiß & Schütz (2019). The batch effect describes the water discharged immediately after a period with long residence times inside the sedimentation part of the facility. Such an effect has a major positive impact on the efficiency of the system. However, they concluded that in Germany, dry periods resulting in residence times of more than a week only occur 3-8 % of the time. In Amsterdam instead, the dry periods longer than a week were even only in between 2 to 4 % in the past four years.

4 Assessment of sediment loads and retention facilities efficiency in the field

4.1 The study area

The area of the research is located at the Rooseveltlaan (figure 4-1), one of the major roads in the district called Rivierenbuurt. This district is situated in the eastern part of Amsterdam-Zuid. It is surrounded by three surface water bodies, the river Amstel to the east, the Boerenwetering canal in the west and the Amstelkanaal in the north. In the south the highway A10 draws the border. In this research, only a part of the Rooseveltlaan will be investigated.

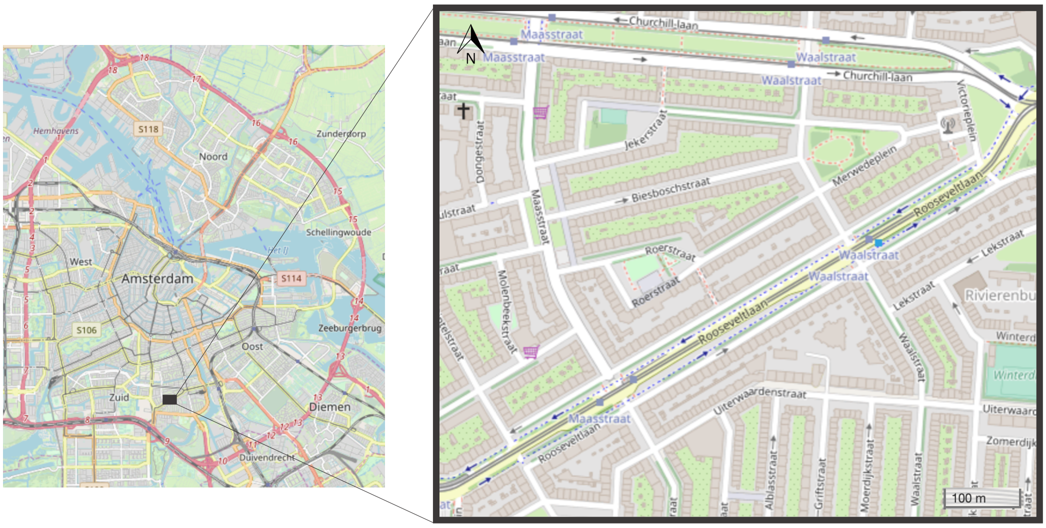

Figure 4-1 Location of the Rooseveltlaan, Amsterdam.

The Rooseveltlaan is oriented south-west to north-east. With a total width of approximately 42 m it is used for different kinds of transport. These can be seen in figure 4-2. In particular, the roof surfaces, the side walks, the green areas and the feeder road will be of interest in this research. The latter are smaller and less frequented roads, called *ventweg* in Dutch. They usually run parallel to the main road and is meant for cars to stop and eventually park.

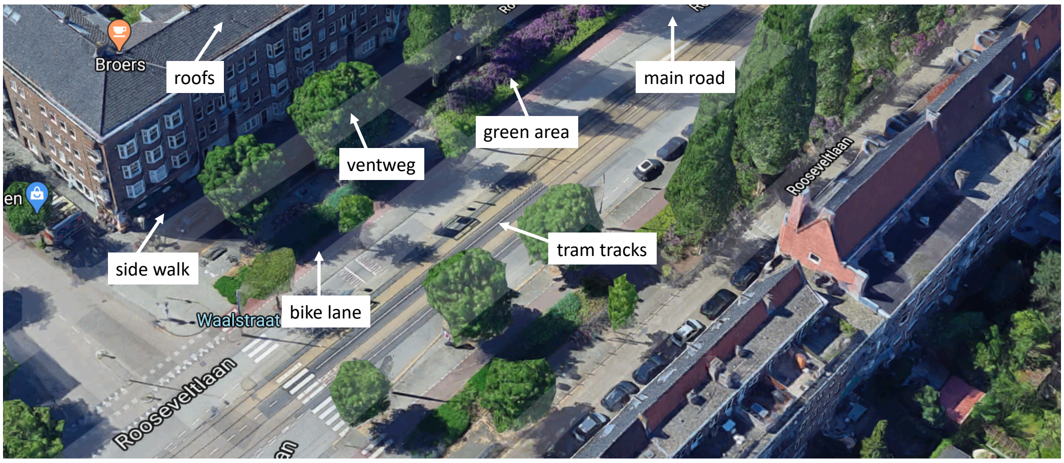

Figure 4-2 Areal image of the Rooseveltlaan before the recent reconstruction, Amsterdam.

This study only investigate the part in between the Maasstraat and the Waalstraat. The main focus will be on the treatment device installed in the south-east of the Rooseveltlaan, nearby the cross-section with the Waalstraat.

4.1.1 The drainage situation

This part of the Rivierenbuurt is provided with a separate sewer system. The wastewater sewers are drained towards the treatment plant, while the stormwater sewer is connected to nearby surface water bodies. A detailed overview of the overall drainage system can be seen in Appendix A. Due to its topographical conditions, this disctrict is considered to be prone to damage caused by floodings. Therefore, measures are taken to protect the area and prepare it for heavy intense storm events predicted in the future. In the course of that, an infiltration facility (AquaBASE) is installed underneath the tram tracks in this part of the Rooseveltlaan. In this way, excess water can be temporarly stored and stormwater discharge peaks can be delayed. Additionally, a stormwater treatment device called *SediSubstrator L* by *Fränkische Rohrwerke* will be installed with the purpose to remove particles transported by the discharge volumes. As a result, the water being introduced to the AquaBASE is more purified from particles that might clog the system. Furthermore, the pollution such as heavy metals that are absorbed by these particles will be reduced.

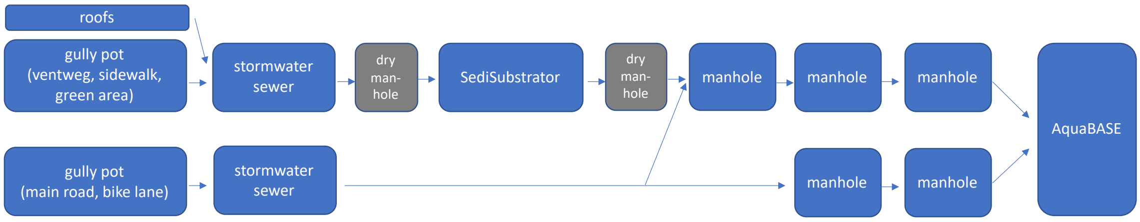

Figure 4-3 *Schematic overview of the water flow through the system.*

Figure 4-3 depicts how the stormwater flows through the drainage system in the Rooseveltlaan. It can be seen, that only parts of the runoff from surfaces will be treated by the SediSubstrator. All in all, these sum up to a total amount of approximately 8900 m^2. The stormwater from the main road and bike lane will be directly discharged towards the AquaBASE. This means it won't be treated by the SediSubstrator and hence might introduce pollution to the AquaBASE. A solution has to be found to reduce the risk of clogging by these stormwater particles. More detailed specifications on the connected surfaces are given in § 5.2.4.

4.1.2 The SediSubstrator L

The *SediSubstrator L* (figure 4-4) is designed to allow the settlement of particles over the length of the horizontal pipe as well as inside the connected shafts. An elongated and compact sedimentation pipe is thought to provide enough distance for sediments to settle and so be removed. At the bottom of the horizontal pipe, there is a so called flow separator. This special construction is a kind of grid, that creates slow flowing conditions and so allows sediments to fall through the grid and to settle there. It furthermore avoids the remobilization of particles. This flow separator is placed at the height of 0.11 m above the bottom of the sedimentation pipe.

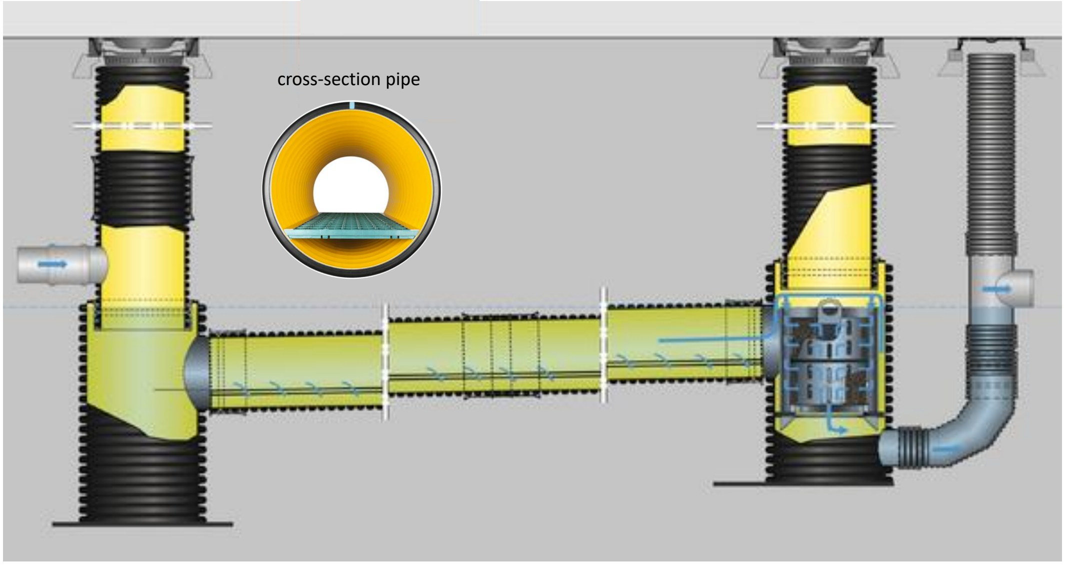

Figure 4-4 *Longitudinal section of the SediSubstrator L and the cross-section of the sedimentation pipe with the flow separator (Fränkische Rohrwerke).*

At the end of the sedimentation pipe, the so called end shaft is equipped with catridges that are filled with a filter material. This material called SediSorp is designed to adsorb pollution and filter out smaller particles that did not yet settle. To allow the cartridges to be equally charged and hence strained, a cladding tube will be filled with the inflowing water first. In this way, the water evenly distributes over the surface area of the catridges. After making its way through the filter material, the water will end up in the hollow shaft in the centre of the cartidges. From there it is being discharged towards the bottom and further into the smaller outlet shaft at the end of the system. This shaft simultaneously fulfills a scimming board function, necessary for the separation and retention of oil. The adjustments needed for the study area can be found in Appendix C-II. Furthermore, an alternative idea to be used as filter material is given there.

4.2 Sampling location

The samples for the bed sediment are taken within three manholes as well as seven gully pots on the southern side of the Rooseveltlaan. All spots are located along the ventweg between Rooseveltlaan 189 and 67 and are relatively easy to access due to the light traffic there. The locations that were chosen are meant to be representative for the stormwater sediments inside the gully pots and as well as those leaving the latter and entering the treatment device.

The sediments encountered in the manholes come from the runoff that originates along the ventweg, sidewalk as well as roofs. Those encountered in the gully pots are meant to represent the sediments being trapped here. Up to date, no connection between the drainage system of the main road and the ventweg is being made. Therefore, only runoff that is washed off the mentioned connected surfaces will contribute to the sampled bedload sediment composition. The same surfaces will be later also connected to the SediSubstrator. Impressions of some sampling locations in the field can be found in Appendix C-I.

Depending on the cleaning of the gully pots, the number of particles that will stay trapped as bed sediment can be estimated. While full gully pots are expected not to capture any sediments, the clean ones have the capacity to store a certain volume of particles within its structure. The grab samples of the stagnant water taken from a manhole in the area (Appendix D) are assumed to represent the stagnant water situation within the impounded sedimentation pipe during short dry periods.

4.3 Sampling equipment

Different tools have been used to grab and store various types of samples. The bed sediments are captured using a special shovel, allowing to reach the bottom of the manhole or gully pot. For each location (manhole and gully pot), six sample bottles of 550 ml are filled. This means, for all the sampled locations one entire composite sample has been made for manholes and gully pot separately. Half of the bottles of the bed sediment samples are sent to the laboratory from Waternet, while the rest is assessed in the Waterlab of TU Delft. The water samples on the other hand are grabbed by using an automated sampler, placing the suction hose approximately in the center on the water column. The sample bottles used for this purpose have a volume of 1 l (figure 4-5).

Figure 4-5 *left: shovel; middle: sampling bottle (550 ml); right: sampling bottle (1 l).*

The mentioned sampling procedure is performed in a secure way. Therefore, locations that were easily accessible are chosen. Furthermore, in case the sampling location is situated in the road, the traffic has to be blocked and redirected around the location. The sampling setup is illustrated in Appendix G.

4.4 Laboratory analysis of the samples

The sediment samples taken in the field are further analyzed in the Waterlab of TU Delft as well as the laboratory of Waternet located in Edam, called Waterproef. At both locations, the particle size distribution of the samples is analyzed. However, both laboratories use a different method to determine this composition. The results of both analyses are compared, as well as the settling velocity of the particles.

At Waterproef, furthermore the fraction of mineral and organic matter as well as the total suspended sediment concentration (TSS) is investigated. At the Waterlab at TU Delft on the other hand, the settling velocity of the particles is determined. Furthermore, the membrane fouling index (MFI) of the samples is analyzed with an instrument of Waternet. This might give an idea whether the fine suspended sediments within the water sample will cause clogging issues within the infiltration system installed hereafter.

All the results from the laboratory (Appendix E) are finally analyzed, interpreted and compared. They give better insight of the type of sediments to be expected in the area. Furthermore, they are used as input data for the model simulation. In this way, the model can predict the treatment efficiency in a more accurate way. Additionally, to that, the potential of the fraction that does not settle within the treatment system and might end up in the infiltration facility installed in sequence, is estimated.

4.4.1 Methods used in the laboratory of Waterproef

Each of the parameters are analyzed in the laboratory according a specific procedure and method. The particle size distribution of the water sample is being determined following the wet sieving procedure. Here, the particles are categorized into the following size ranges: <2, <16, <32, <50, <63, <125, <250, <500, <1000 and >1000 µm. The organic fraction of the same sample is computed using NEN 5754. This method describes a calculation of the content of organic matter in soil, and water soils according to the ignition loss method. The ignition or annealing loss gives an estimate of the content of organic matter once it is corrected for moisture loss. This standard applies to samples that have been pretreated according to NEN 5719. This pre-treatment includes the preparation of a suitable sample that contains enough content of the compound(s) to be determined. This content is as close as possible to the mean content in the original aqueous sample. The specific gravity (density) of the sample will be determined, again using Waterproef's own method. Finally, the total suspended solids within the water sample is analyzed by filtering over glass fiber filters (NEN-EN 872).

4.4.2 Devices used in the Waterlab of TU Delft

Simultaneously, the same sample will be analyzed in the Waterlab of TU Delft. Here, the particle size distribution will be assessed using the laser scattering device Blue wave (Microtrac). This device can be seen in figure 4-6.

Figure 4-6 *Blue wave (Microtrac).*

Furthermore, the apparatus (figure 4-7), built by M. Rietveld himself to measure settling velocities of sludge samples will be used. The functioning of the system and the pre-treatment of the samples is explained in more detail in Appendix D.

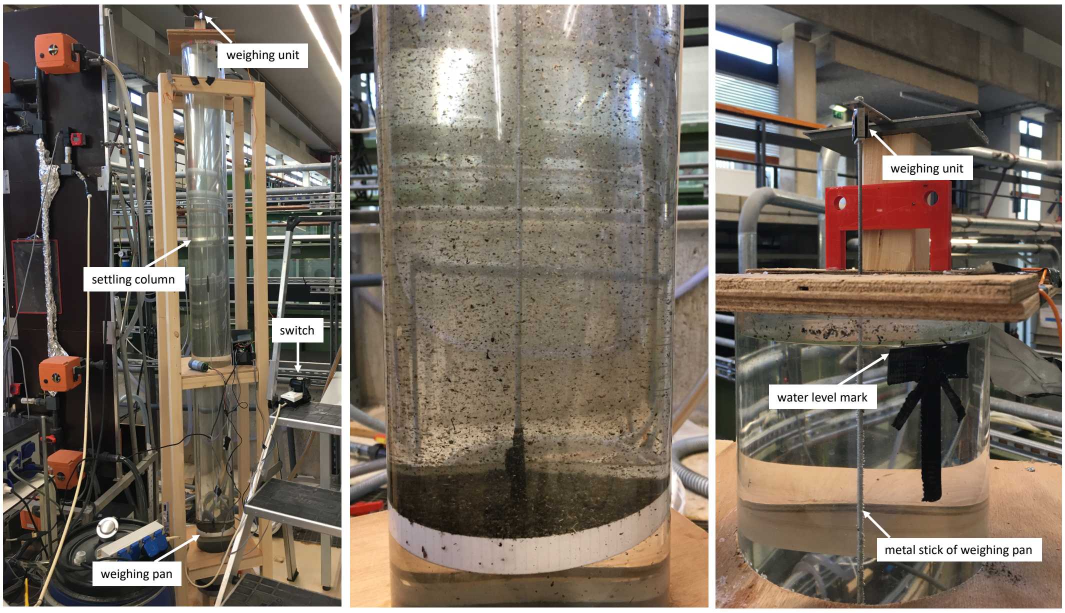

Figure 4-7 *left: settling velocity apparatus; middle: settling column with weighing pan; right: lid including weighing unit and water level mark.*

To determine the potential of clogging by the sampled stagnant water, the Inspector SDI/MFI by Convergence (figure D-21 in Appendix D) is used. Comparing the results to those samples of water that is introduced to infiltration wells, a better understanding on the risk of clogging can be created.

5 Modelling the loads and expected efficiency of SS retention facilities

This section introduces the model in detail. First, the general structure of the model will be explained. Then, the input parameters as well as the assumptions made are presented.

5.1 General structure of the model

The conceptual model is built to describe the removal efficiency of stormwater sediments via the process of sedimentation inside the sedimentation path of the SediSubstrator. Hereby, a rainfall-runoff model as well as the basic removal principles of the treatment facility are used as a basis. Additionally, information about typical sediment loads as well as the relationships and processes behind the system are introduced. The model results are computed in a step by step calculation in MS Excel.

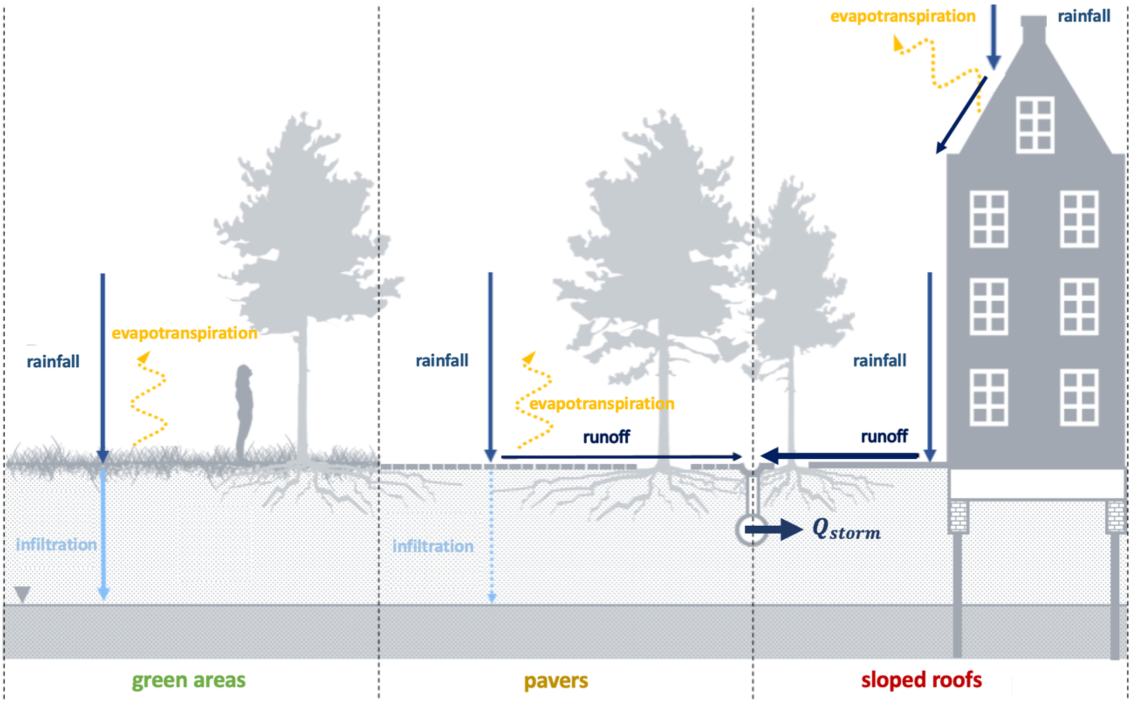

Figure 5-1 Water balance used in the rainfall-runoff model (modified from MSc thesis of Elien Naert).

The first part of the twofold model addresses the runoff generation (figure 5-1). The rainfall-runoff process is a function of the losses on the surfaces due to the topographical characteristics of the catchment itself. In this case, a proportional loss model is used to transform the input precipitation into a design runoff. The losses in the urbanized catchment that need to be considered are factors like the initial wetting loss, the depression storage, the infiltration of different surface types and the evapotranspiration. The rainfall-runoff model is explained into more detail in § 5.3.1.

The precipitation is assumed to be equally distributed over the whole connected area. First, the precipitation data for each five minutes are accumulated to determine the gross rainfall per timestep. Then, different factors that reduce the actual rainfall are considered following the characteristics of the different surfaces. These include the initial losses as well as infiltration losses. Hence, the losses per surface type are studied respectively.

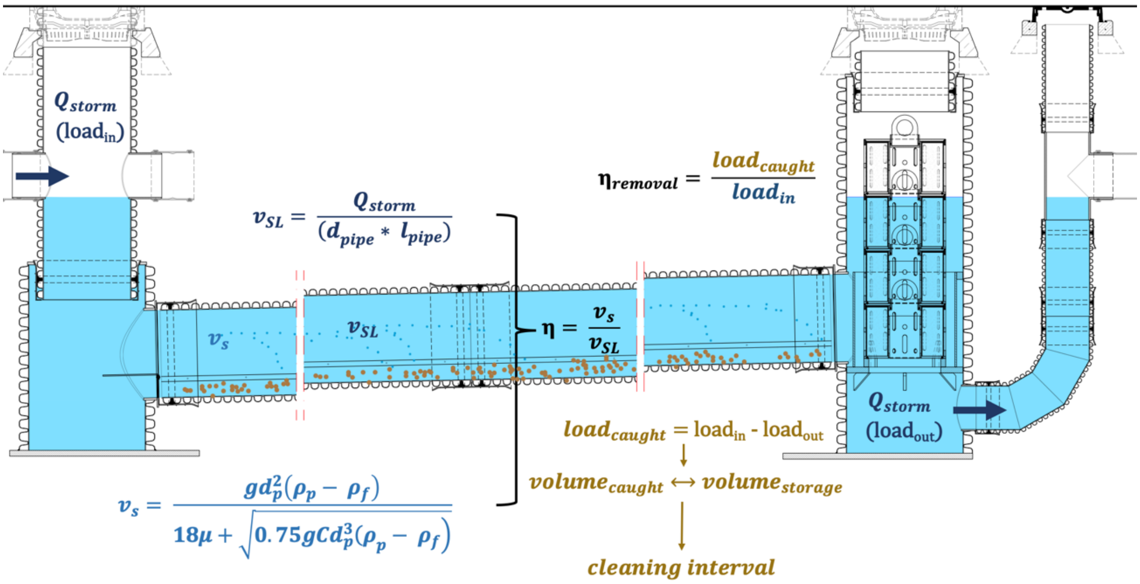

Figure 5-2 Schematic overview of the functioning simulated by the model.

The output of the rainfall-runoff model, the stormwater discharge, is further used in the second submodel (figure 5-2). The latter estimates the sediment removal efficiency of the installation. Here, the model distinguishes the *flow-phase*, where stormwater discharge flows through the sedimentation path and the *batch-phase*, where stagnant conditions are present. Considering the nature of the site, the dimensions of the treatment facility as well as the composition and characteristics of the sediments, the particle loads that are removed are determined. During the flow-phase, the stormwater discharge per time-step is used to generate the surface load (Eq. 3-3) of the stormwater for the same time-steps. The latter depends on the dimensions of the sedimentation facility as well as the discharge volume. Furthermore, sediments specific characteristics together with fixed physical stormwater parameters are used to compute the settling velocities for each particle size range. Combining these two, a sedimentation efficiency for each particle size range at each specific moment during the rainfall event can be computed (Eq. 3-4). During the batch-phase in dry periods, only the settling velocities and the pipe's dimensions are decisive to determine the sedimentation efficiency of the particles. More detail on the approach is given in § 5.3.5.

Not every surface type will contribute the same amount of sediments to the incoming concentration. Therefore, the concentration per surface type needs to be considered separately. Adding up these concentrations, the total incoming concentration can be estimated. This is then transformed into a total incoming sediment load using the total runoff volume. The equation used can be seen in Eq. 5-1.

$$C_{in} = \frac{(c_r * V_r + c_p * V_p + c_g * V_g)}{V_{runoff}} \qquad \textit{Eq. 5-1}$$

where:

C_{in} = total mean influent concentration [mg/l]
c_r = influent concentration contributed by the roofs [mg/l]
V_r = runoff volume coming from the roofs [l]
c_p = influent concentration contributed by the pavers [mg/l]
V_p = runoff volume coming from the pavers [l]
c_g = influent concentration contributed by the green areas [mg/l]
V_g = runoff volume coming from the green area [l]
V_{runoff} = total runoff volume of the entire connected area [l]; *summation of* V_r, V_p *&* V_g

The influent sediment concentration will be further transformed into an influent sediment load L_{in} [kg]. To do so, the latter is multiplied with the total runoff volume per timestep. Once the incoming load is determined, the amount that will leave the treatment facility can be estimated. This will be referred to as outgoing load. Here, the respective sedimentation efficiency of each size range needs to be considered. Furthermore, each range is represented by a certain size to be respected. Thus, the outgoing sediment load can be determined using the incoming load, the fraction of each size range and their respective efficiency to settle. This relationship is shown in equation 5-2.

$$L_{out} = L_{in} * f * (1 - \eta_s) \qquad \textit{Eq. 5-2}$$

where:

L_{out} = total outgoing sediment load [kg]
L_{in} = total influent sediment load [kg]
f = fraction of the respective particle size from the total load [-]
η_s = sedimentation efficiency of the respective particle size [-]

Comparing the incoming and the outgoing load, finally the removal efficiency of each particle size range within the treatment facility is determined. Using the relation in equation 5-3 the summed removal efficiency can be computed.

$$\eta_{tot} = \frac{L_{out}}{L_{in}} \qquad \textit{Eq. 5-3}$$

where:

η_{tot} = total sediment removal efficiency of the system [-]
L_{out} = total outgoing sediment load [kg]
L_{in} = total influent sediment load [kg]

Knowing the sediment removal efficiency, the number of particles that will be removed in the system can be determined. The latter, also referred to as caught load, is the difference between incoming and outgoing load. This caught load is composed by the loads caught during flow- and batch-phase.

Since the stormwater treatment device works according the principle of sedimentation, the total amount of the settled sediments is stored below the flow separator (figure 4-4). The cumulative caught load will fill up this storage volume until being fully filled. From there, the settled sediments can be removed by cleaning with a jet stream. Depending on the incoming load and the removal efficiency, this storage capacity will be filled in specific intervals.

5.2 Input data for the model

This paragraph will present all the input data, parameters and variables used in the model. Some of them are fixed values, while others depend on the study area and its characteristics.

5.2.1 Precipitation data

In order to have representative rainfall data for the study area, data from measuring stations in the area are used. In this case, precipitation data given in five minutes intervals are obtained from the wastewater treatment plant in Amstelveen (Appendix G, figure G-1). This data is measured by using a weighing rain gauge (OTT Pluvio^2) that is installed by Waternet. This rainfall data is transformed into runoff considering losses within the area.

Statistical analysis of the precipitation data

The precipitation data is statistically analyzed to determine the minimum, maximum and average rainfall duration. Knowing that, the minimum and maximum incremental volumes per 5-minute time step are analyzed. These results in the respective lowest and highest stormwater discharge volumes within 3 hours. Changing the incremental volume will reflect in the respective change in number of samples to be taken. Finally, the intake volume of each sample depends on the volume of the storage containers and the incremental volume chosen to send a signal from the flowmeter to the automated sampler.

First, the average rainfall duration is determined. It is assumed that a dry period of at least two hours is necessary for the surfaces to be relatively dry again. Therefore, rainy timesteps with breaks shorter than two hours in between each other are considered to be one rainfall event. The same approach has been used to identify the longest rainfall duration in the timeseries. To determine the minimum rainfall duration, the average amount of rainy 5 minutes timesteps in a row was assessed.

To identify the incremental volume for each time-step, the runoff volumes computed in the rainfall-runoff model are assessed. Using the relationship shown in Eq. 5-4, the number of samples to be taken throughout the duration of an entire event is estimated.

$$N_{samples} = \frac{V_{tot}}{V_{incr.}} \qquad \textit{Eq. 5-4}$$

where:

$N_{samples}$ = number of samples to be taken during one event [-]
V_{tot} = total stormwater discharge volume during event [l]
$V_{incr.}$ = incremental stormwater discharge volume per time step [l]

5.2.2 Evapotranspiration data

The evapotranspiration is retrieved from KNMI-station 240. This station is located at Schiphol Airport and provides the daily potential evapotranspiration (Makkink), with a precision of 0.1 mm.

5.2.3 Particle size distribution

The incoming stormwater sediments are divided into ten categories of different particle sizes. The categories in the model can be seen in table 5-1. For each category a mean particle size was chosen for further calculations. The same was done with the density for each range. Hence, each of the ten categories is represented by a mean particle size as well as its average density. Furthermore, each range is represented in the stormwater with a certain fraction of the total amount of sediments. The numbers used for the fraction are the average values determined from the sampling performed in the Rooseveltlaan (§ 6.1.1) as well as from the study performed by Nijman (2019) in Amsterdam. The same study by Nijman (2019) also provided the fraction of organic matter in each particle size range. Studies performed in the Netherlands so far, only assessed the stormwater discharge composition as a total without distinguishing the source of origin (e.g. roofs, roads, etc.). Therefore, due to the lack of information, this model assumes the same particle size distribution as well as the same fraction of organic content for the incoming load of each connected surface type. The impact of a variation in the particle size distribution of the various fractions will be tested in the sensitivity analysis in § 6.3.4. All these input values can be seen in table 5-1.

Table 5-1 *Particle size distribution and respective fraction and densities used in the model.*

Particle size range [µm]	**Mean particle size [µm]**	**Particle classification of the mineral fraction**	**Fraction of mineral matter [%]**	**Fraction of organic matter [%]**	**Density minerals [kg/m³]**	**Density organics [kg/m³]**
0.2 – 2	1	clay	18.4	1.2	2904	1400
2 – 16	9	silt	13.2	2.0	2525	1625
16 – 32	24		2.1	1.3		
32 – 50	41		0.6	0.3		
50 – 63	57	fine sand	0.3	0.2	2695	1850
63 – 125	94	medium sand	2.9	1.7	2660	2075
125 – 250	188		19.0	5.3		
250 – 500	375		15.9	4.5		
500 – 1000	750	coarse sand	5.7	1.6	2650	2300
> 1000	1400		3.1	0.9		

5.2.4 Connected surface area

Using topographical and technical maps from the database of Waternet and site visits, the connected surface area for each type of land use was determined. The total area is divided into the northern and southern side of the Rooseveltlaan. It is assumed, that either of them will only drains towards the two installed SediSubstrators at the respective side.

Table 5-2 *Connected area to the drainage system.*

Drainage location	**Land use**	**Area [m^2]**		**Fraction of total area [%]**
		north side	***south side***	
Drainage towards SediSubstrator and subsequent AquaBASE	roofs	3650	3710	31
	sidewalk	2798	2901	24
	ventweg			
	green area	2489	2311	20
Drainage directly towards AquaBASE	bike lane	1500	1553	13
	main road	1475	1566	13
Drainage towards wastewater	tram tracks	1917		-
TOTAL		11912	12041	100

According to the drainage situation, the total surface that is connected to the installed SediSubstrator is computed. Hereby it needs to be considered that the roofs, the sidewalk, the ventweg and the green areas will be draining towards the drainage system that feeds the SediSubstrator. The main road, the parking lots along it as well as the bike lane, will be drained towards the drainage system that does directly end up in the AquaBASE and will not be treated by the SediSubstrator. The tram tracks will be directly drained towards the wastewater sewer. Table 5-2 illustrates the division of the connected area according to the differences in use.

5.2.5 Stormwater properties

Another input parameter used in the model are the stormwater properties. Hereby, the viscosity for the specific temperature of the water is introduced. This parameter depends on the temperature of the water and hence an average value is assumed. According to The Royal Netherlands Meteorological Institute (KNMI), the average temperature in the Netherlands is around 10°C. Therefore, the precipitation is assumed to be of the same temperature when arriving at the stormwater treatment facilities. The respective value for the dynamic and kinematic viscosity is used to compute the settling velocities in the model (table 5-3). A change in water temperature can be assessed when testing the sensitivity of the model.

Table 5-3 *Stormwater temperature and the related properties [Semadeni-Davies, 2009].*

Temperature [°C]	**Density [kg/m^3]**	**Dynamic viscosity [Pa.s]**	**Kinematic viscosity [m^2/s]**
4	1000	0.001560	0.000001560
10	1000	0.001304	0.000001304
15	999	0.001137	0.000001137
20	998	0.001002	0.000001002
25	997	0.000890	0.000000890
30	996	0.000798	0.000000798

5.3 Assumptions for the setup of the model

This paragraph will elaborate on the assumptions made throughout setting up the model. It will describe why they have been made and which source was taken as a reference.

5.3.1 Rainfall-runoff transformation

Several processes transform the initial precipitation into a runoff volume. The actual rainfall intensity that turns into runoff is reduced by initial losses and infiltration as well as evapotranspiration of the volumes stored on the surfaces (figure 5-1). It is assumed that the precipitation equally falls on the connected area. This area again uniformly drains towards the four installed SediSubstrators (figure A-1 in Appendix A). In general, a quarter of the flow is expected to be arriving at the investigated stormwater treatment facility. Since the second SediSubstrator on the south-western side of the Rooseveltlaan will only be installed in a later moment, first the entire runoff generated on the southern side will be drained towards the SediSubstrator under investigation.

The initial loss is composed by the wetting losses and the depression storage. In this model, these initial losses, referred to as depression storage, are reduced only via evapotranspiration. The values suggested by Van de Ven (1985) of 2 mm and 0.5 mm are used for the depression storage of asphalt streets and pavers respectively. The depression storage threshold for the streets is considered in such way, that the respective surfaces only generate runoff in case the cumulative precipitation exceeds that value. Based on aerial pictures and information from the database from Waternet is it assumed that no houses have flat roofs. Hence, the initial loss from roofs are only composed by a wetting loss of 0.1 mm. For the green areas no depression storage is considered.

In general, the initial losses, hence wetting losses and depression storage, are considered together, the entire initial loss is on pavers will be treated as depression storage. Since the water lost because of depression storage is only reduced by evapotranspiration, the entire storage will be emptied in this way. Usually these puddles build up on the same spots and therefore a thin sludge layer can hinder the infiltration at this spot. Furthermore, the infiltration capacity is assumed to decrease in case the soil underneath is already saturated. Due to these two reasons, only evaporation will reduce the depth of the depression storage. A constant time-dependent evapotranspiration loss over time is considered. Hereby, the daily potential evapotranspiration according to Makkink measured by KNMI at Schiphol Airport is used. This value is first equally distributed over the five minutes time steps. Then, in case any water is present in the depressions, the stored water is reduced by the evaporated amount. In case of precipitation, the evapotranspiration is simulated to stop. For simplification, it is assumed that the evapotranspiration-ration stays the same during day and night-time. Furthermore, the wetting losses are also considered to take place even if surfaces are wet.

In addition to the evaporation, the infiltration is another process that reduces the actual rainfall significantly. Here, based on the experience of Waternet a value of 20 mm/h is assumed for green areas. This means that for rainfall intensities smaller than that, the green areas do not contribute to the runoff. For the precipitation data of 2019 used in the model, these surfaces only contribute to the total runoff for 0.02 % of the time. For semi-pervious pavements, pavers are assumed to infiltrate on average 2 mm/h, while asphalt does not infiltrate at all. This value was chosen according to experience of Jeroen Langeveld, mentioning default values of 0.5 and 2 mm/h considered for infiltration capacities for design purposes in urban drainage sewer models. Van de Ven (1985) on the other hand stated infiltration capacities of 10 to 30 mm/h for semi impervious pavements. Choosing the lower boundary of this range of 2 mm/h, will most likely underestimate the losses but so allow to be on the safe side. This impact of this choice will be tested in the sensitivity analysis (§ 6.3.3). In this model, the ventweg as well as the sidewalk are covered in such paver's material. The remaining paved surfaces are assumed to be asphalt. In the model, the infiltration rate per surface type is transformed into the used five minutes time steps.

As explained earlier, in case the actual cumulative precipitation exceeds the threshold of depression storage, the area is considered to generate runoff. This runoff is then further reduced by the rate of infiltration. Only what is left will end up as stormwater discharge in the sewer system, from which it will flow towards the SediSubstrator. It is assumed that the rate of infiltration stays the same over time. So, the runoff per surface type is composed by the cumulative rainfall per timestep, reduced by any losses occurring along the way. Finally, the total runoff is the sum of the respective runoff volumes of each surface type.

5.3.2 Particle size, distribution and shape

The classification into the particle size ranges was taken following the examples of several authors and has been mentioned in § 3.2.2. For each range, the mean value was taken as the input value for the particle size for further calculations. Furthermore, a representative density range for each particle size range presented by Andral et al. (1999) was used as a basis for the density of the mineral particle fraction. Furthermore, each range consists of an organic fraction. Since the density of the minerals and the organics is different, a mean value for each size range for the organic fraction was chosen as well. This difference in density impacts the settling velocity and therefore is important to be distinguished.

For the organic fraction, a density range between 1400 and 2300 kg/m^3 (Semadeni-Davies, 2009) is assumed. This range was equally distributed over the particle size range steps. The proportional amount of mineral and organic fraction for each range was taken from field data of Nijman (2019) and Badin et al. (2008), respectively. These values were used to compute the settling velocity for the mineral and organic fraction separately. The exact values that have been used can be seen in table 5-1.

To simplify the assessment of the loads, the particles are assumed to be discrete. This means that they do not change in size, shape or weight during the sedimentation process, meaning that they also do not form aggregates.

5.3.3 Suspended sediment concentration

The concentration of suspended sediments that is encountered in rainwater differs among sites and events due to e.g. the intensity of the precipitation. To simplify the model simulation, only a seasonal variation in concentration of the stormwater sediments is considered.

Hereby, a mean concentration of the sediments entering the gully pot is taken as a reference. This data is taken from an unpublished study of Rietveld et al. (unpublished). Since this number represents the amount of sediments entering the gully pot but not the amount leaving the gully pot, the values need to be adjusted. Parts of the sediments will be trapped inside the gully pots and taken out by cleaning; it is assumed that only 80 % of the incoming sediments are being washed towards the stormwater treatment facility. The remaining 20 % are assumed to be stored in the sand trap of the gully pot and later removed during cleaning by Waternet.

The mean solids load given in kg/day/ha is first multiplied by the total connected surface area of about 5300 m². As a next step, the load [kg/day] is converted to a monthly value [kg/month] which can be then further transformed into a concentration [mg/l] by considering the monthly runoff volume during that study. The average annual solids load assumed to enter the system is approximately 270 kg/ha. The concentrations used in the model can be seen in table 5-4. It is assumed that each runoff will flush the mean sediment concentration of the respective month towards the SediSubstrator. This load will be then reduced by 20 % as just mentioned to correct for the trapped sediments in the gully pot.

Table 5-4 *Sediment concentration in 2019 sampled in Rotterdam by Rietveld.*

month	**total runoff**	**solids load**		**sediment concentration**
-	*[m³/month]*	*[kg/day/ha]*	*[kg/month]*	*[mg/l]*
Jan.	134.30	0.60	9.65	72
Feb.	162.85	0.21	3.33	20
Mar.	198.33	0.45	7.25	37
Apr.	95.68	0.91	14.74	154
May	52.01	0.44	7.12	137
Jun.	251.77	1.63	26.34	105
Jul.	102.57	0.86	13.81	135
Aug.	198.81	1.23	19.85	100
Sep.	160.99	1.12	18.04	112
Oct.	357.77	1.08	17.37	49
Nov.	153.47	0.14	2.28	15
Dec.	204.90	0.22	3.52	17

Furthermore, not every connected surface type contributes equally to the total sediment load. Therefore, the roads are assumed to contribute the entire mean concentration, since this value was measured by Rietveld in the gully pots along the roads and represents the solid loads collected there. Roofs on the other hand, are only assumed to contribute a small amount of pollution. In this model, 20 % from the total mean concentration is taken as a default value. This number is an average observed value by studies performed by Charters et al. (2016) and Zhang, et al. (2010). The same incoming load as from streets is assumed to originate from the green areas. However, due to the lack of very extreme rainfall events, these areas hardly ever contribute to the total stormwater discharge and hence the incoming solids load. Furthermore, it needs to be highlighted that a difference in composition of the sediment loads from each of the different connected surfaces is neglected. All the connected surfaces are assumed to have the same particle size distribution and the same ratio of mineral and organic fraction.

Another assumption regarding the composition of the total concentration was made within the fraction for each particle size range. As explained earlier, each sample has a specific composition, where each particle size range is assigned to a fraction within the sample. However, the total concentration for each month, measured by Rietveld, only includes particles above 50 µm. Nevertheless, the model assumes particles within the size range of 1 µm to more than 1000 µm in all samples. Therefore, although the fraction smaller than 50 µm was not captured within the measured loads by Rietveld, it is assumed to be contained in the calculation of the model.

5.3.4 Settling process

The two formulas that can be used to determine the settling velocity of particles were explained in § 3.5.1. The formula by Ferguson & Church (2004) given in Eq. 3-2 was selected to compute the settling velocity of the particles within the SediSubstrator. This selection was made because it better represents the given conditions of turbulent flows and differences in particle size. The Stokes' settling formula (Eq. 3-1) on the other hand is only applicable for laminar flows and particles of small sizes.

The formula by Ferguson & Church contains two constants that represent the influence of the particle shape. In this model, the values 18 and 1, for C_1 and C_2 respectively where chosen. These two are a possible intermediate relation for grains of varied shape (Ferguson & Church, 2004). Furthermore, the density as well as the particle size itself for both, organic and mineral fraction (table 5-1), will be considered respectively for each size range. The computed settling velocities per particle size range can be seen in table 5-5.

Table 5-5 *Settling velocities per particle size range by Ferguson & Church.*

Mean particle size	**Particle classification of mineral fraction**	**Settling velocity minerals**		**Settling velocity organics**	
[µm]		*[m/s]*	*[m/h]*	*[m/s]*	*[m/h]*
1	clay	9.63E-07	0.003	2.02E-07	0.001
9	silt	5.16E-05	0.186	2.12E-05	0.076
24		3.67E-04	1.321	1.50E-04	0.541
41		0.001070	3.853	4.39E-04	1.580
57	fine sand	0.002257	8.125	0.001132	4.077
94	medium sand	0.006104	21.975	0.003956	14.243
188		0.024100	86.759	0.015643	56.316
375		0.094338	339.618	0.061490	221.363
750	coarse sand	0.353794	1273.657	0.281529	1013.503
1400		1.084870	3905.531	0.874133	3146.879

Surface load

To compute the surface load the formula presented in Eq. 3-3 is used. Therefore, the flow rate (Q) as well as the dimensions of the sedimentation pipe (sedimentation surface, A) need to be considered. For the latter, the length as well as the width of the sedimentation structure are used in this case. The length of the sedimentation pipe of the SediSubstrator is 12 m. For the width, the width of the flow separator of 0. 46 m is considered. This results in a cross section (A) of 5.57 m^2. To estimate the incoming flow rate, that is generated by the rainwater, the rainfall-runoff model described in § 5.3.1 was used. Using this information, the surface load (Q/A) for each time-step can be computed.

5.3.5 Sedimentation efficiency

During the *flow-phase* the sedimentation efficiency per particle size range at each time interval can be determined by dividing the particles' settling velocity by the surface load at each specific time-step (Eq. 3-3). Particles having a settling velocity equal to or greater than the surface load, are removed. Since the SediSubstrator's removal mechanism relies on sedimentation, this equals its removal efficiency per particle size during that phase.

During dry periods, the *batch-phase* causes water within the sedimentation path to be stagnant and the sedimentation is only impacted by the settling velocity of each particle size range, the dimensions of the sedimentation path of the SediSubstrator and the length of the dry period. In this phase, particles of different sizes have different abilities to settle within the height of the sedimentation path above the flow separator (0.49 m). To simulate the precipitation of particles during a specific time of stagnant flow conditions the following approach was used.

Starting from the settling velocity for each size range according to Ferguson & Church, for minerals and organics separately, the time for each particle to settle within the height of the pipe can be determined. To calculate the maximum sedimentation time needed for all particles of a size range to settle, a height of 0.49 m is used. A perfect distribution of particles within the stagnant water is assumed, i.e. the same concentration of each particle range at every location of the water volume. Therefore, every 5 minutes of stagnant conditions, a certain fraction [%] of the total load of each size range within the water volume can settle. Hereby, the dry minutes are divided by the minutes necessary for the respective particle to settle in the total considered height of 0.49 m. Knowing which fraction can settle in the investigated dry period of time, the related load can be calculated. This is done for each period of stagnant conditions respecting that the sediment load varies significantly over the year. Therefore, for each dry period the respective load for that specific month is used. To estimate the load of particles that are available for sedimentation in the batch-phase (Eq. 5-5), the monthly sediment concentration is converted to a monthly load within the volume above the flow separator in the sedimentation path (2.97m^3 = 2,970 l).

$$L_{FS} = c_{inflow} * V_{Fs} \qquad \text{Eq. 5-5}$$

where:

L_{FS} = load of sediments in volume above flow separator [mg]
c_{inflow} = sediment concentration in stormwater inflow of each month [mg/l]
V_{FS} = volume of the SediSubstrator above the flow separator [l]

This load is then further divided into a mineral and an organic load, considering a share of 81 and 19 %, respectively. From there, the sedimented load for both, mineral and organic fraction, can be computed separately for each 5 minutes of each dry period. Therefore, the respective load above the flow separator is multiplied with the fraction that is able to settle within this timeframe as well as the fraction by which the size range is represented in the total load for each size range respectively (Eq. 5-6). Summing up all the caught loads for each size range the total caught sediment load per mineral and organic fraction can be computed. Adding up both, mineral and organic caught load for each time-step, the total caught load at that point in time is determined. Due to the variation of the sediment concentration within the water volume throughout the year, this concentration is different for each month.

$$L_{caught} = \sum p * f * L_{SF} \qquad \textit{Eq. 5-6}$$

where:

L_{caught} = total caught sediment load during the dry period [mg]
p = amount of settled particles of the respective size range [%]
f = fraction of particle size range from the total load [%]
L_{FS} = load of sediments in volume above flow separator [mg]

From there, the 5 minutes time-steps during which no stormwater discharge enters the sedimentation pipe, are identified from the timeseries of one year. During these, it is assumed that the last volumes of the previous stormwater discharge that entered the sedimentation pipe during rain events, stays within the volume of the horizontal pipe. From these volumes, the respective load that can settle within each dry period is estimated. However, during flow phase parts of the sediments that enter the sedimentation pipe did already settle. Therefore, the available amount of sediments to precipitate from the stagnant water during the batch phase needs to be adjusted first. To do so, the sediment load that enters the system with each discharge volume is reduced by the amount of sediments being caught by sedimentation during flow phase while entering the SediSubstrator. This adjustment results in the sediment load that is available for sedimentation in the sedimentation path volume during the successive batch phase. Knowing what percentage this available load makes up of the maximum load that could be present each month, the maximum caught load during the batch phase can be reduced accordingly. In this way, it is assured that only the sediment load that did not yet settle during the flow phase will be simulated to precipitate from the stagnant water volume. For those particles that have high settling velocities and therefore precipitate fast, a sedimentation of 100 % is achieved quickly. For these particle size ranges precipitation will only occur again after fresh loads are introduced by stormwater discharge.

Finally, the total caught load of the SediSubstrator is composed of the load being caught from stormwater discharge during the flow phase as well as the load caught during each dry period in the batch phase.

5.3.6 Filling of the storage

The storage below the flow separator is assumed to be filled with the sludge that is accumulated due to sedimentation during the flow- as well as batch-phase. It is assumed that the water underneath the flow separator is stagnant, no resuspension takes place and the entire load of sediments stays in place. Additionally, an equally distributed filling of the storage over the length of the system is assumed. Knowing the dimensions of the sedimentation pipe of the SediSubstrator, the available volume to store particles can be computed. To do so, the general equation for the segment of a cylinder is used (Eq. 5-7).

$$\mathrm{Vs} = \mathrm{l} * \left[r^2 * \cos^{-1}\left(\frac{r-h}{r}\right) - (r-h) * \sqrt{2rh - h^2} \right] \qquad \textit{Eq. 5-7}$$

where:

Vs = storage volume below flow separator [m^3]
l = length of the sedimentation pipe [m]
r = radius of the sedimentation pipe [m]
h = height of the flow separator with respect to the bottom [m]

The storage volume considered is determined to be 0.426 m^3. Comparing the cumulative caught sludge to the storage volume, the rate of filling can be estimated. To be able to do so, the cumulative caught load [kg] needs to be transformed to a caught volume [m^3] first. This is done by multiplying the caught mineral and organic load with their mean densities respectively as well as considering a porosity of 30 % for the caught sediments. Adding up both, the total caught volume is determined.

When looking into the total caught load after one year, the latter can be compared to the available storage as well. In this way, a statement about the frequency of cleaning can be made. This is the case if the cumulative load of settled sediments exceeds the volume of the pipes segment below the flow separator.

5.3.7 Removal of absorbed pollutants

When analyzing the removal of absorbed pollutants in this case, only the removal of heavy metals is investigated. According to literature (§ 3.1), it was assumed that a certain fraction of the heavy metals is considered to be absorbed mainly to the fine particles. All particles are assumed to have a spherical shape, where the entire surface is assumed to be adsorptive and hence attract pollutants. The latter are assumed to be equally distributed over all the size ranges. Hereby, only the fraction smaller than 63 µm will be considered to absorb heavy metals. This is done since the specific surface of the bigger fractions is very limited as compared to the small particles. This assumption neglects that bigger particles might also adsorb heavy metals like for instance via iron coating on sandy particles.

To estimate the amount of heavy metals that can be retained by the removal of sedimented particles, several calculation steps have to be performed. First, the total caught load per particle size range (below 63 µm) is extracted from the model results. Knowing the mean particle size of each range, the overall surface area of the sphere per range is determined. Here, the formula shown in Eq. 5-8 is used. The latter is assumed to absorb the pollution under investigation.

$$A_{sphere} = \pi * {d_p}^2 \qquad \textit{Eq. 5-8}$$

where:

A_{sphere} = surface of the sphere [m^2]
d_p = mean particle size (diameter) [m]

Knowing the sphere area and the particle density, the number of particles for each size range can be estimated. First, the caught load is divided by the respective density, resulting in a volume of that size range. The latter is then divided by the sphere’s area to get to a total length of particles. Knowing the size of an individual particle, the length is divided by the particle size to obtain the number of particles of that range. Assuming that the entire spherical surface of the particles is adsorptive, the focus should be on the particle size range that represents the largest surface area, based on the amount and the size of particles.

6 Results

This chapter will introduce both the results from the laboratory analysis and the model, including the sensitivity analysis.

6.1 Laboratory results

The amount of sediments being trapped within the structure of the gully pots impacts the loads that arrive at the system. This parameter impacts the concentration being contributed from the pavers and green areas. In case the gully pots are clean, their capacity of storing sand particles and debris is relatively large. With an increasing amount of bed sediments in the sand trap, the amount being caught decreases and more ends up at the manholes installed thereafter as well as the SediSubstrator.

At first, the sediments and coarse floating material (tree leaves, cigarettes, cans, wood debris, etc.) have been visually observed in the manholes as well as gully pots. An impression of these observations can be seen in Appendix F.

In general, the material encountered in the composite gully pot sample when compared to the manholes, is coarser and more brownish in color. The sludge from the composita sample of the three manholes on the other hand is blackish and shinier. Within these manholes, the longer residence time for the bed sediments allow organic matter to break down. This can be identified by the dark, grey-black color as well as the gas bubbles that appear when touching the sludge layer. The variation in large debris encountered might be explained by looking at the water flow. The runoff will enter the system through the gully pots. Here, the installation is meant to trap sand on its bottom and any bigger floating matter by the flap installed at the outlet pipe. This flap should prevent the floating debris such as leaves, cigarettes, plastic etc. from flowing into the stormwater sewer. However, often this flap is dislocated during maintenance and no barrier for floating material will be present. Here, this material will continue its way towards the manholes. Figure 6-1 represents a gully with a missing flap. It can be seen that there is no floating debris on the water surface. The sediments from this location are smaller when compared to other gullies, since bigger parts such as leaves, wooden debris etc. will continue towards the manholes with the stormwater discharge.

Figure 6-1 *left: bed sediment from the gully pot with missing flap; right: gully pot without flap.*

According to Nijman (2019), for normal Dutch rainfall events the intensity of the rainfall is large enough to even mobilize the sludge that is retained within the sand trap in the gully pots several times a year. Furthermore, the depth of the sludge layer in these locations will reach an equilibrium over time. Hence, any sand and/or sludge that will be still in the gully pot at this point of equilibrium, will be flushed to the stormwater sewer until the sand trap of the gully pots are cleaned or partly flushed out.

Throughout the entire drainage system, the particles in the stormwater will be separated on the basis of settling velocity, hence particle size and density. The results of the particle size distribution analysis (figure 6-2) also confirm this assumption. The coarsest material is found in the gully pot, followed by the rest of the stormwater system. In addition, it could be determined visually during sampling, that more coarse particles and sand remain in the sand trap of a gully pot when compared to the manholes.

Before determining the particle size distribution of the sample, residuals of pedestrian waste, gravel and debris are removed. The latter can be for instance branches, residuals from construction sites etc. While the fraction of waste encountered is similar in gully pots and manholes (5.8 and 6.2 %, respectively), the amount of debris differs a lot. From the gully pot samples, about 7.4 % debris are removed, while only 10 % of that amount was removed from the manhole's samples. The manholes bed sediment seems to have a higher organic content than gully pots (22 % compared to 12.2 %). This content of mineral is also reflected in the density of the sample. While the manholes appear to have a density of 1178 kg/m^3, the gully pots sediments have a density of 1353 mg/m^3. The results from both laboratory analysis can be found in Appendix E.

To analyze the composition of bed sediments from manholes and gully pots, two different methods have been used. While the laboratory in TU Delft uses laser diffraction, the Waterproef laboratory determines the size fraction with wet sieving. Furthermore, at Waterproef the fractions smaller than 16 µm will be analyzed with the sedigraph method. The latter counts the particles that fall within an X-Ray beam and correlate that to a relative mass distribution. Comparing the sieving to the laser diffraction method, the latter allows a higher degree of separation between the individual fractions with less effort. As stated by Arriaga et al. (2006) the results of both techniques usually differ, which are shown in

Appendix F (figure F-23). While the laser diffraction device covers a large range of particles in a single measurement, sieves range from tens to hundreds of micrometers in mesh size. The performance of the sieving for particles smaller than 45 µm is poor. Since the fraction smaller than 16 µm was additionally analyzed using the sedigraph method, the numbers from the Waterproef laboratory within that size range is assumed to be more precise.

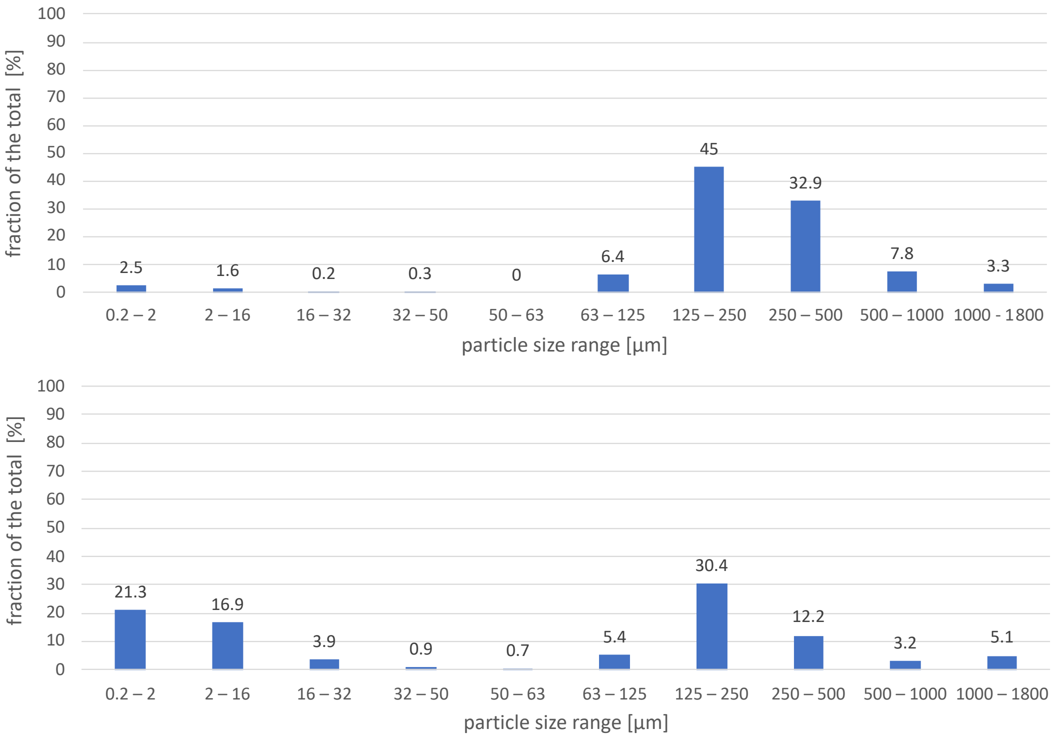

Figure 6-2 *top: particle size distribution (PSD) gully pot; bottom: PSD manhole.*

Comparing the two particle size distribution histograms of the composite samples (figure 6-2) a difference in the particle size distribution can be seen for both locations. It is clear that the size range of sand particles between 125 to 250 µm represent the biggest fraction of the total sediments. This seems evident since the area is currently been rebuilt and a lot of construction activities are surrounding the sampling locations. Furthermore, sand is used as a foundation to construct the Rooseveltlaan during the recent works and thus vastly present in the area. While the amount of sand particles is slightly higher in the gully pots, the fraction of silt and coarser clay is hardly present. It seems that this fine fraction between 2 and 32 µm continues to the location further downstream. There, the very fines represent a high fraction of the total. The reason for this might be the extremely small settling velocities, making it hard for them to settle within the gully pots and therefore they continue with the flow. Since the observed bed load can be in the system for a while, the coarser sediments are potentially a formation of aggregates of smaller particles.

The settling velocity was only determined for one gully pot sample due to a malfunction of the measuring device. From the frequency distribution depicted in Appendix F (figure F-24) it can be seen that 50 % of the particles in weight within the sample, settle with a velocity smaller than 0.06 m/s, while only 10 % settle faster than 0.1 m/s. Comparing these settling velocities to those computed using the settling formula by Ferguson & Church (table 5-5), this fraction can be assigned to the particles bigger in size than 250 µm. About 80 % of the total mass manage to settle with a velocity of 0.02 m/s or faster. These particles seem to be within the size range of 63 and 250 µm. The remaining 20 % on contrary have a relatively slow settling velocity between 0.02 m/s and 0.001 m/s.

6.2 Model results

The final output of the model represents an estimation of the overall removal efficiency of the installed SediSubstrator. Along with that, the frequency of maintenance for the cleaning of the facility can be estimated. This is done by determining the accumulation of settled sediments within the storage volume below the flow separator. Once the entire volume is filled, the system requires cleaning.

Several parameters described in detail in § 5.2 and § 5.3 are used as input to reach to the final results. However, most of them are values taken from literature and are not yet verified in the study area. Therefore, those that appear to have the biggest impact on the outcome, will be tested in a sensitivity analysis. Instead of reporting a final result of one set of input values, a range of potential outcomes with varying input values will be presented and discussed.

Finally, this sensitivity analysis can provide insight into which parameters affect the overall outcome the most and therefore should be verified in the field.

6.2.1 Statistical analysis of the precipitation data

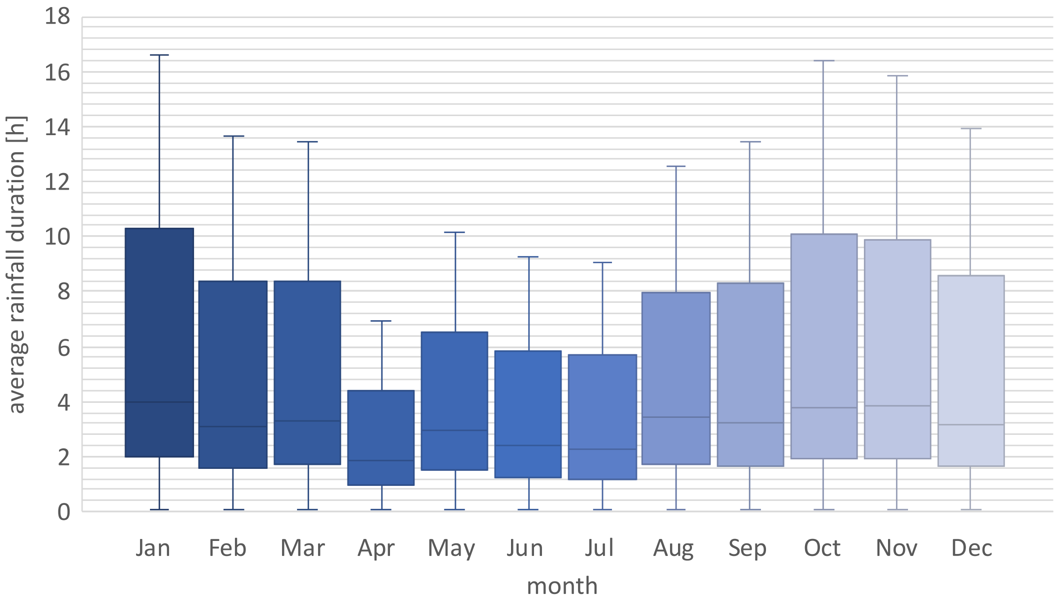

Figure 6-3 *Observed rainfall duration for each month in 2016 – 2019 at the wastewater treatment plant of Amstelveen.*

Analyzing the precipitation data, in general, only 4.1 % of the 5-minutes timesteps of the year 2019 were rainy. 95 % of all the time, the precipitation that falls on the roofs is intense enough to contribute to the total runoff. The green areas are assumed to have such a strong infiltration capacity that they only contribute to the runoff 0.02 % of the time that it rains. It indicates that the average rainfall duration in the past four years is around 3 hours (figure 6-3), considering the assumptions mentioned in § 5.2.1. While the minimum rainfall duration is assessed to be 5 minutes, the longest events seem to take up to 16.6 h (12.6 h on average).

Figure 6-4 illustrates the frequency distribution of the rainfall intensities during the 5 minutes intervals. The smallest measurable intensity of 0.1 mm/ 5min seems to be by far the most frequent one encountered in the data series. This is followed by the mean rainfall intensity of 0.2 mm in 5 minutes.

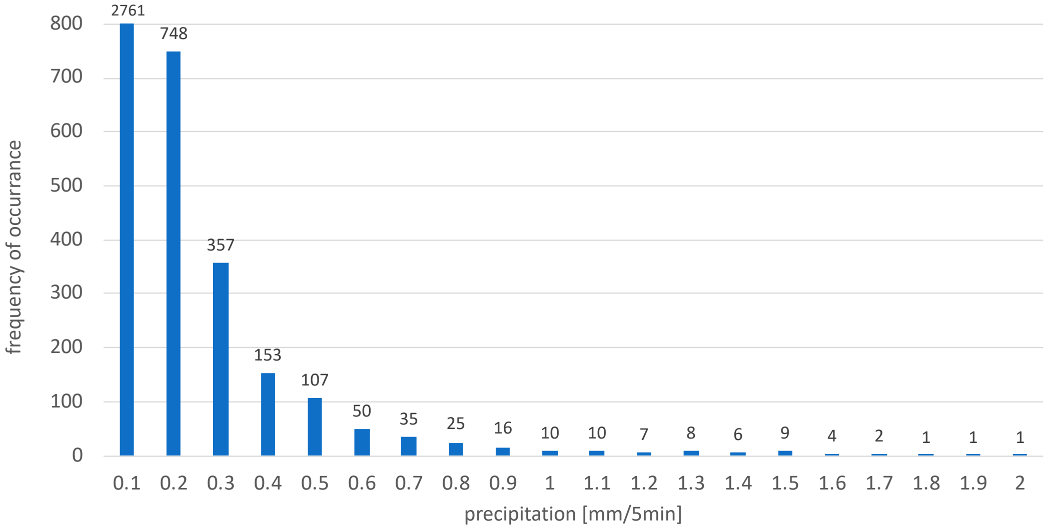

Figure 6-4 *Frequency distribution of the rainfall intensities for each 5 minutes interval in one year.*

Figure 6-5 on the other hand depicts the frequency distribution of dry minutes at a time. Again, the smallest analyzed interval of 5 minutes is the most encountered duration. However, here it must be mentioned that often, dry periods are interrupted by short rainfall events of 5 minutes with low intensities.

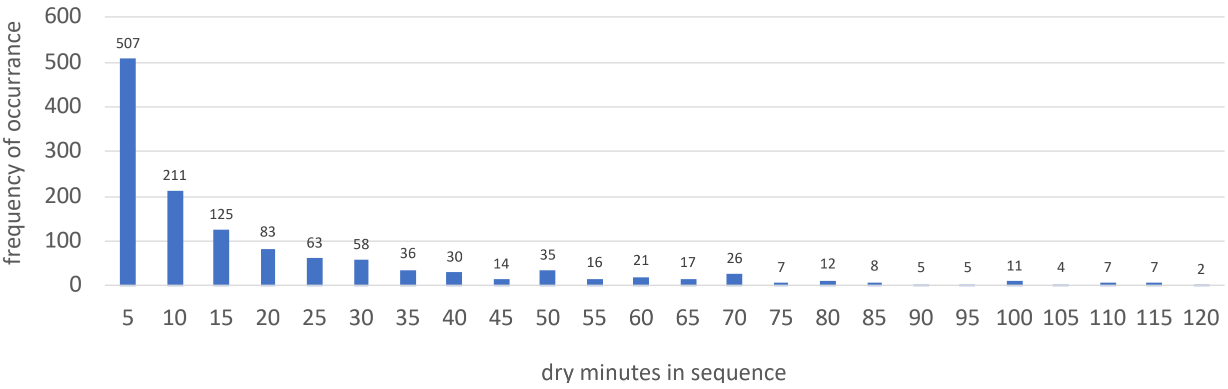

Figure 6-5 *Frequency distribution of the dry minutes in sequence between two flow-phases in one year.*

Analyzing the rainfall-runoff model and the computed runoff volumes, the biggest volumes for one rainfall event encountered within a year were about 150,000 liters (150 m^3). This volume was generated by approximately 25 mm of rainfall that fell on the connected surfaces during a period of about 4 h.

During this event, the incremental volumes ranged in between 350 and 20,650 liters within 5 minutes. This event represents a typical intense storm during summer months, generating a big amount of stormwater discharge in a short period of time. To be sure that the sampling device can deal with such big events, respective sampling volumes and frequencies have to be chosen. Depending on the incremental volume considered to take flow-weighted samples, the number of samples that should be taken throughout the event is determined as stated in § 5.2.1. The results are summarized in table 6-1.

Table 6-1 *Minimum and maximum number of samples needed throughout an event.*

Total stormwater discharge volume [l]	Incremental volume [l]	Number of samples	Sampling volume [ml]	Total sampled volume [l]
150000	300	500	50	25.0
150000	500	300	70	21.0
150000	700	214	90	20.0
150000	1000	150	130	19.5
150000	5000	30	600	18.0
150000	10000	15	1300	19.5

The minimum rainfall events and the related stormwater discharges on the other hand are important since these determine the volumes sampled for the laboratory analysis. In order to determine the total suspended solids in a stormwater sample, at least three bottles of 1 liter need to be filled. The minimum incremental volumes for the shortest events are 10 liters in case the connected surfaces were completely dry, compared to 350 liters if the depression storage was already filled.

Since a high variability in sediment concentration is expected in the area, taking small samples in short intervals generates a better understanding of the loads in the stormwater. This means, that for instance taking a sample every 500 liters of stormwater discharge that passes the flowmeter, needs a total amount of 300 samples of 70 ml volume to fill up 80 % of the storage vessel of 25 l. The sampling volumes are dimensioned in such way, that they will fill up the entire storage container only up to about 80 %. In this way, even bigger events than 25 mm can still be sampled in the same storage volume.

6.2.2 Comparison of the model simulation to the laboratory experiment by Boogaard (2015)

In order to better understand and validate the results of the model simulation, the latter has been checked using laboratory measurements by Boogaard (2015) as input values. This study tested the removal efficiency (figure 6-6) of the SediPipe XL (600/24) under a constant inflow of specific volumes (5, 10, 20 35 and 60 l/s). This device has the same construction as the SediSubstrator simulated in the model. The only difference is the length, which is 24 m as well as the particles used in the stormwater. The stormwater particles are represented by Millisil W4, having a specific density of 2650 kg/m^3 and a precisely set particle size distribution. Furthermore, the suspended sediment concentration was chosen to be 50 mg/l in this study.

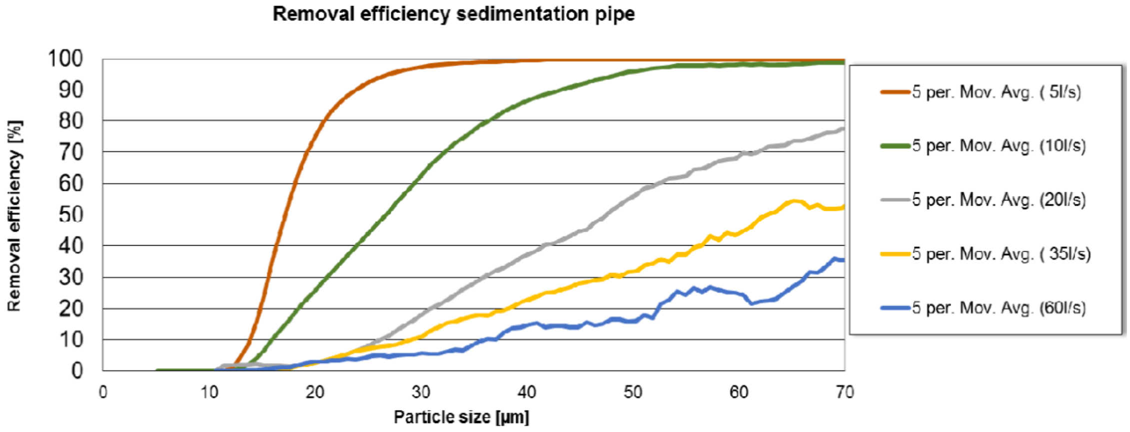

Figure 6-6 *Removal efficiency of the SediPipe XL (600/24) under laboratory conditions (Boogaard,2015).*

All of the mentioned parameters were introduced in the model to see whether the final results of the model simulation can be compared to those measured in the study by Boogaard (2015). Looking into the results shown in figure 6-7, it can be seen that the model simulates comparable treatment efficiencies. This especially applies for low flow rates (5 and 10 l/s), where the laboratory study as well as the model simulation determined very similar efficiencies. Particles bigger that 20 µm are removed with an efficiency higher than 80 % at inflow volumes of 5 l/s in both compared studies. Furthermore, the conclusion by Boogaard (2015), to avoid flows higher than 10 l/s to be able to remove the fine fraction smaller than 60 µm can be confirmed by the model simulation.

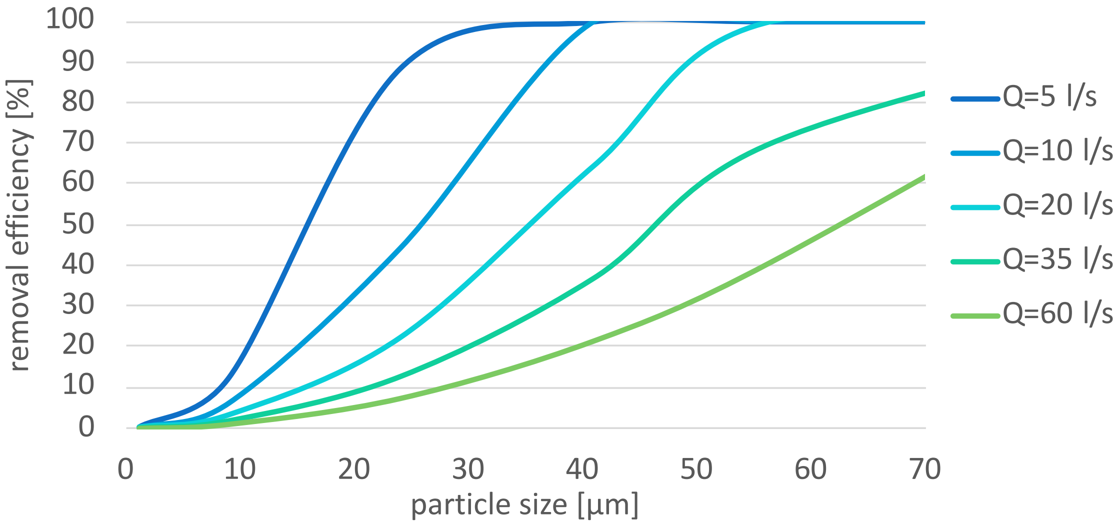

Figure 6-7 *Removal efficiency of the SediPipe XL (600/24) simulated by the model.*

For flows bigger than 10 l/s the removal efficiencies simulated by the model deviate from those measured in the laboratory. However, it can be seen that even those measured by Boogaard (2015) seem to show noise in the measurement results.

6.3 Sensitivity Analysis

A sensitivity analysis has been performed for some input values used in the model. The values are chosen because they are expected to have a large effect on the final results, so they should be verified in the field. In particular the effect on the sedimentation efficiency of the installed system and the related cleaning interval will be compared. The sensitivity of the model to the change of the parameters assumed according to literature is assessed to determine the importance to prove these in the study area. Therefore, a variation of those parameters can give an impression on the impact on the final results and hence the necessity to verify the assumptions in the field.

6.3.1 Particle sizes and settling velocities

The SediSubstrator installed works according the principle of sedimentation. Therefore, parameters that impact the settling velocity of the stormwater particles are important to be assessed. Hereby, the temperature of the water, the particles size (diameter) as well as the density of the particles play an important role.

Since the particle size and the density of the different particles are analyzed in several studies before, the assumed values are considered relatively reliable. According to the settling velocities computed for each size range, the minerals will settle within the height of the sedimentation pipe (0.49 m) in approximately one second to 6 days. This huge difference in settling time depends mainly, as explained by the formula of Ferguson & Church, on the density as well as dimension of the particles. Since the diameter of the particle is considered exponentially, the bigger particles will settle much faster than the small ones. Comparing the times for the organic fraction to settle, these particles need in between one second and 28 days. This difference is coming from the difference in particle density. However, since the diameter of the particle influence the outcome exponentially compared to the density, this change in settling time is more pronounced in the small sized fraction. Considering these settling times, it can be seen that only sand particles (> 50 μm) will be able to settle in the total height of 0.49 m within 5 minutes. Any particles smaller than that need longer residence times to be able to reach the bottom.

The temperature of the stormwater discharge on the other hand might vary within location as well as throughout the year. Therefore, a change in such is assessed for its impact on the settling velocities and the total outcome of the model. Using 10 °C as a default value, the settling velocities of the different particle size ranges are as just stated. A decrease in temperature to 4 °C will increase the dynamic viscosity and so results in lower settling velocities. Compared to the default, mineral particles will settle in between one second and 7 days, while organics take up to 34 days to settle. However, all in all still the same fractions manage to reach the bottom of the sedimentation pipe, hence the flow separator, within 5 minutes. When increasing the temperature to 15 °C on contrary, the smallest minerals will settle one day faster than the default while the smallest organic fraction takes up to 24 days. Still, the same fraction of particles will settle within the facility in 5 minutes.

Concluding, it can be seen that a decrease in temperature has a slightly bigger impact on the settling velocity of the particles than an increase. This might be explained with the bigger change in dynamic viscosity. Again, mainly the small sized fraction is actually impacted by the change in temperature. Therefore, this change has hardly any impact on the overall outcome of the system when looking in the total caught load. Keeping all other input parameters constant, the change in temperature will only result in one kilo more of sediments being caught per year. This difference represents about 1.5 % of the total caught load. However, speaking about the pollutants adsorbed to the finest fraction, a change in temperature is more crucial since this fraction is the most impacted by this change. An increase in temperature, allows the smaller fraction to deposit better within the same amount of time when compared to colder temperatures. Hence, such circumstances seem favorable for the removal of adsorbed stormwater pollutants.

6.3.2 Sedimentation efficiency

Whether the particles of the different size ranges are able to settle or not within the sedimentation path, depends not only on the earlier assessed settling velocity, but is also influenced by the dimensions of the system and the incoming stormwater discharge. All these parameters determine the number of particles that settle during flow- as well as batch-phase. The systems dimensions are well known. However, the discharge depends on the actual precipitation in the area and the loss processes occurring on the connected surfaces.

As explained in § 3.5.2, the incoming flow, hence, the surface load, will impact the ability of sediments to settle during the flow-phase. Considering an average rainfall intensity of 0.2 mm in 5 minutes, only runoff generated from roofs will contribute to the stormwater discharge and result in about 2.5 l/s. This means that only the two smallest fractions of mineral particles (< 16 μm) and the three smallest fractions of organics (< 32 μm) will not settle with an efficiency of 100 %. All the fractions bigger than these will be able to settle effectively. In case of heavier rainfall intensities (e.g. 0.5 mm/5 min) and hence more runoff entering the system, the probability to settle decreases for most of the particle sizes < 63 μm. In this case, discharge volumes of about 11 l/s can be expected, resulting in particles below 63 μm to not end up at the bottom of the sedimentation pipe. This behavior can be seen in figures 6-8 and 6-9.

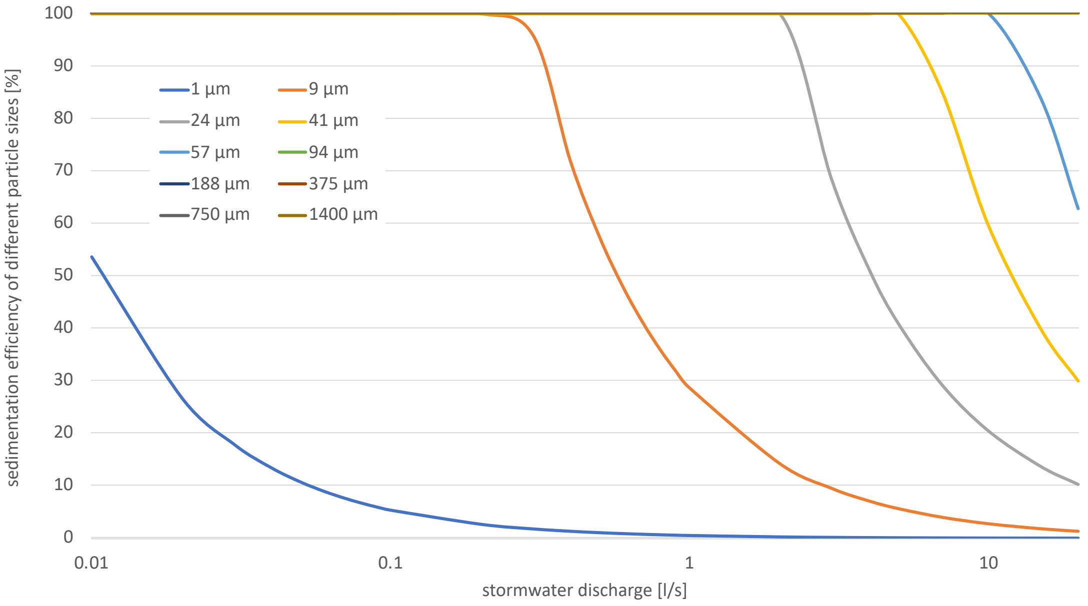

Figure 6-8 *Sedimentation efficiency for mineral particles from different size ranges at various discharge volumes.*

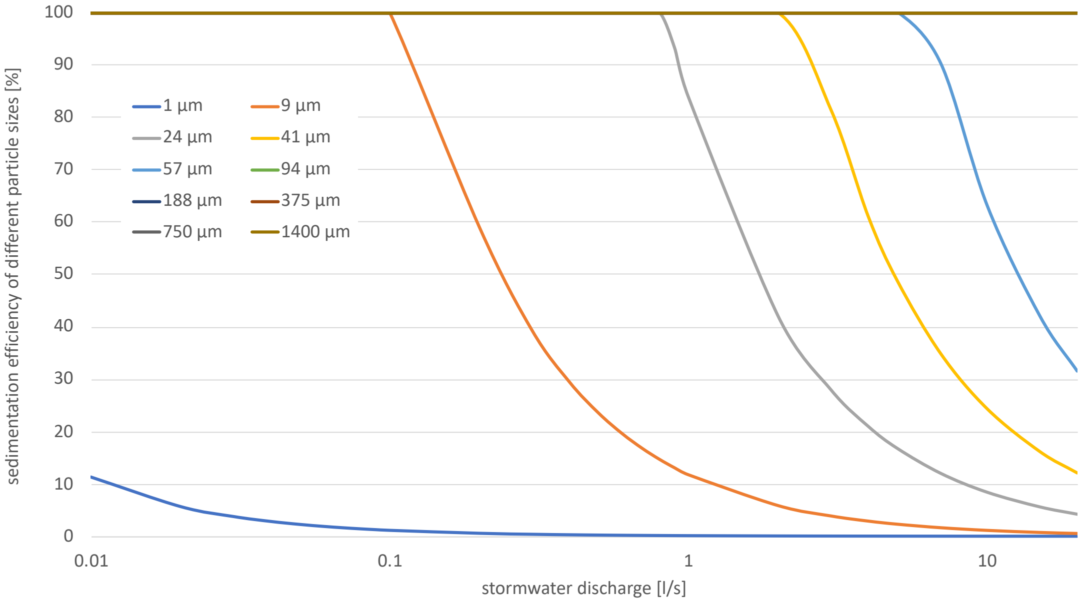

Figure 6-9 *Sedimentation efficiency for organic particles from different size ranges at various discharge volumes.*

These very small fractions, that hardly settle with any rainfall intensity, need periods of no stormwater discharge to be able to settle within the sedimentation pipe. During such a batch-phase, the entire volume of the sedimentation path will be filled with the last part of the rain. In this case, the flow conditions are stagnant, and the particles will have better conditions to settle. Then, only the respective settling velocity of the particles is crucial to determine their probability to settle. While really fine particles need long residence times, hence long dry periods, the coarser fraction will be already settling within shorter time frames. Looking at figures 6-10 & 6-11 it can be seen that within 5 minutes of batch-phase, all the mineral particles > 50 µm and the organics > 63 µm will settle completely in the sedimentation pipe. After 25 minutes, all of the particles besides those smaller than 16 µm will be settled. This means, that the duration of the dry periods has a huge impact on the settling behavior of the particles encountered in the stagnant water.

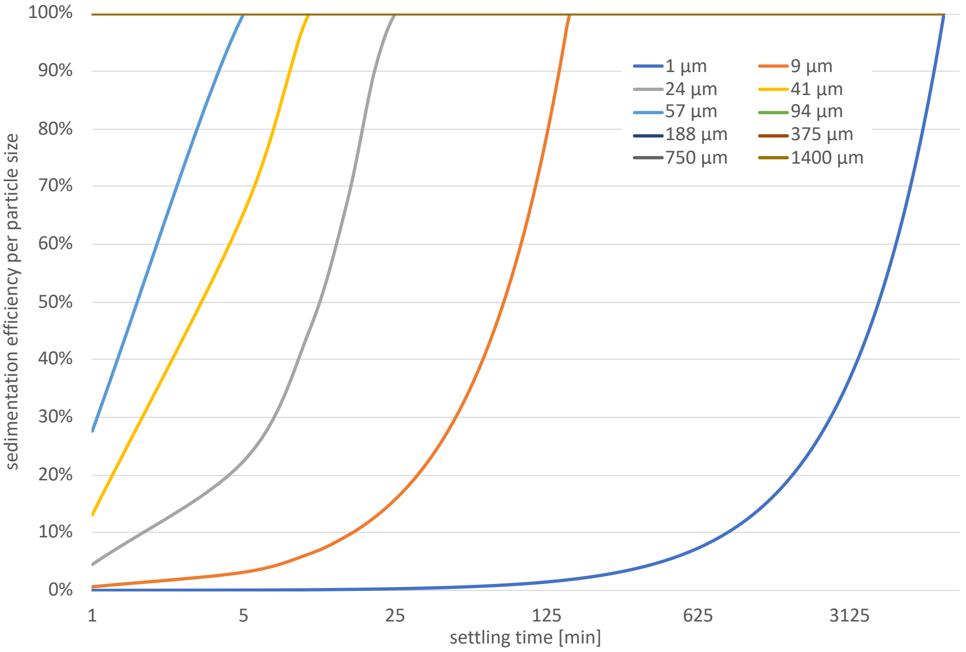

Figure 6-10 *Sedimentation efficiency for minerals per particle size range in specific timeframes.*

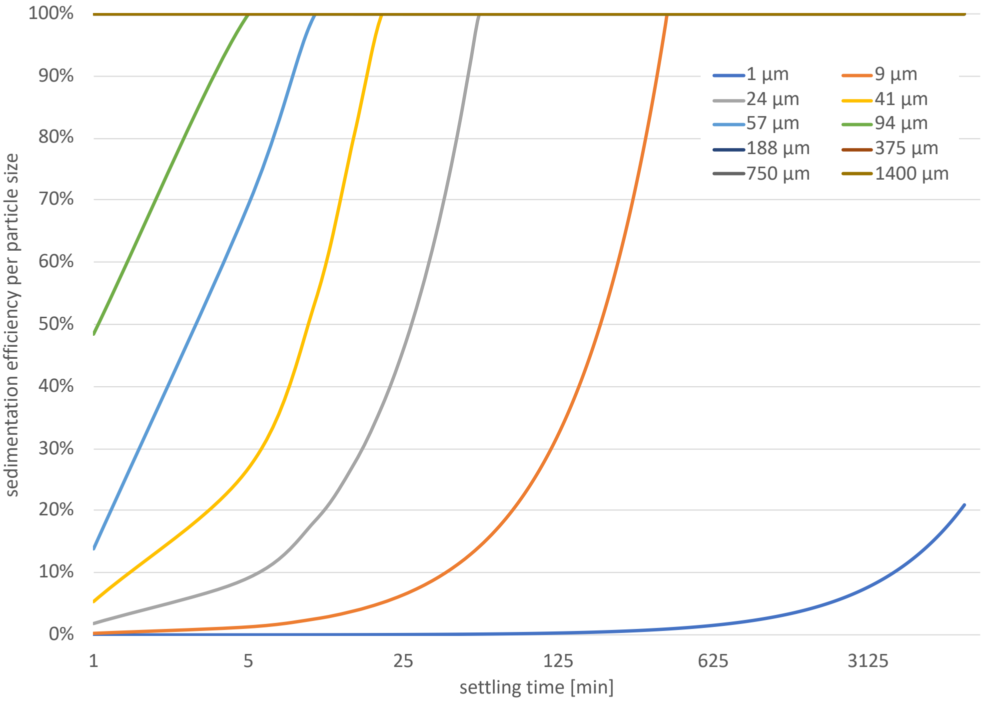

Figure 6-11 *Sedimentation efficiency for organics per particle size range in specific timeframes.*

Analyzing the computed runoff data series, figure 6-5 shows the frequency distribution of the dry periods in between moments where stormwater discharges enters the SediSubstrator. It can be clearly seen that most of the times, 5 minutes of stagnant conditions at a time can be encountered. This duration only allows particles > 63 μm to settle. Instead, periods of more than 2 h at a time of stagnant conditions hardly ever occur. This results in the particles < 16 μm to stay in suspension and leave the sedimentation path.

In this specific model, the fraction of minerals and organics is about 81 and 19 %, respectively. This ratio of mineral versus organic fraction furthermore enhances the particles to settle and more load being caught. On contrary, if the organic fraction is increased, the same load will be caught less effectively.

6.3.3 Runoff volume and treatment efficiencies

As already mentioned before, the load to be caught strongly depends on the rainfall intensity as well as the impact of longer dry periods, and so the flow velocity through the system. The larger the stormwater discharge volume that flows into the system per timestep, the lower the chance for the particles of different size ranges to settle.

Using the sedimentation efficiency and the precipitation data in Amsterdam for the year 2019, the load of sediments accumulating in the treatment facility can be estimated. Based on the inflowing discharge volume, the overall treatment efficiency of the system ranges in between 51 and 84 %, with an average of 67 %. When testing the sensitivity of the model on the change in volume, it can be seen, that an increase in discharge will decrease the overall treatment efficiency (figure 6-12).

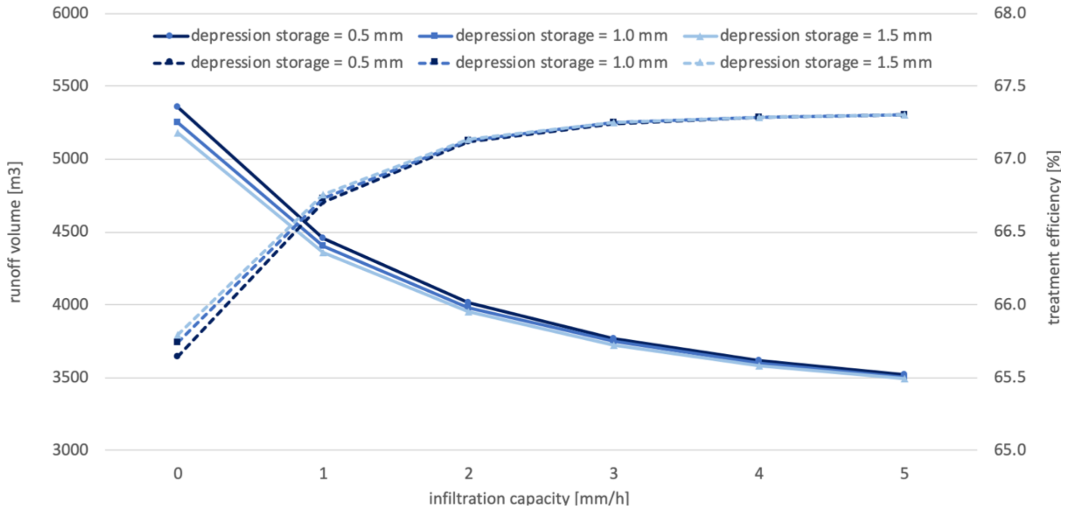

Figure 6-12 *Impact of the annual runoff volume (solid line) on the treatment efficiency (dashed line) of the system.*

This increase in runoff is achieved by decreasing the loss processes caused by the pavers. These loss processes are modified by changing the infiltration capacity and/or the depression storage threshold of these surfaces. Figure 6-12 illustrates two different behaviors. On the one hand it can be seen that the change in infiltration capacity of the pavers has more impact on the generated runoff than the change in depression storage threshold. This is depicted by the steep shape of the curve. Comparing the change in depression storage instead, the three different solid lines in the graph seem to be relatively parallel and the gap in between is small. Therefore, it can be concluded that the variation of this threshold hardly impacts the overall outcome. The reason for this is the way of emptying the storage. Since the infiltration rate per 5-minute time-step is far larger than the evaporation at the same time, the impact of the latter is less pronounced. Furthermore, evaporation is assumed only to take place in dry periods, while the infiltration capacity is assumed to stay the same even during rain.

The second conclusion of this graph is the decreasing impact of the infiltration capacity on the runoff volume. In general, an increase in infiltration capacity will lead to a reduction in runoff being generated from the pavers. However, with a constant increase in infiltration capacity, the decrease in runoff volume gets less pronounced. This behavior can be especially observed in case the capacity exceeds approximately 3 – 4 mm/h. Everything bigger than that will not impact the systems reaction equally strong anymore. This is because on average, rainfall intensities bigger than 3 mm/h only occur roughly 8 times a year while those bigger than 4 mm/h even only about twice. Therefore, the impact of big infiltration capacities will not necessarily cause the system to react differently even if an increase in capacity is being introduced.

The impact of the variation of the loss processes introduced by the pavers on their contribution to the total runoff can be seen in figure 6-12. For the pavers, this contribution to the total runoff depends on two things. One of them being the evapotranspiration and infiltration considered as well as the way the depression storage is assumed to be emptied by the same processes.

From the graph in figure 6-12 it can be concluded, that depending on the thresholds assumed, the contribution by pavers varies from 4 to 37 % or 10 to 82 %, considering evaporation and infiltration or evaporation only, respectively. It can be clearly seen that again the infiltration capacity impacts the contribution by the pavers stronger than the depression storage. Again, any infiltration capacity higher than 3 to 4 mm/h does not influence the change that strong anymore. Additionally, it can be concluded, that once the depression storage is bigger than 0.5 mm, the decrease in runoff production gets smaller as well.

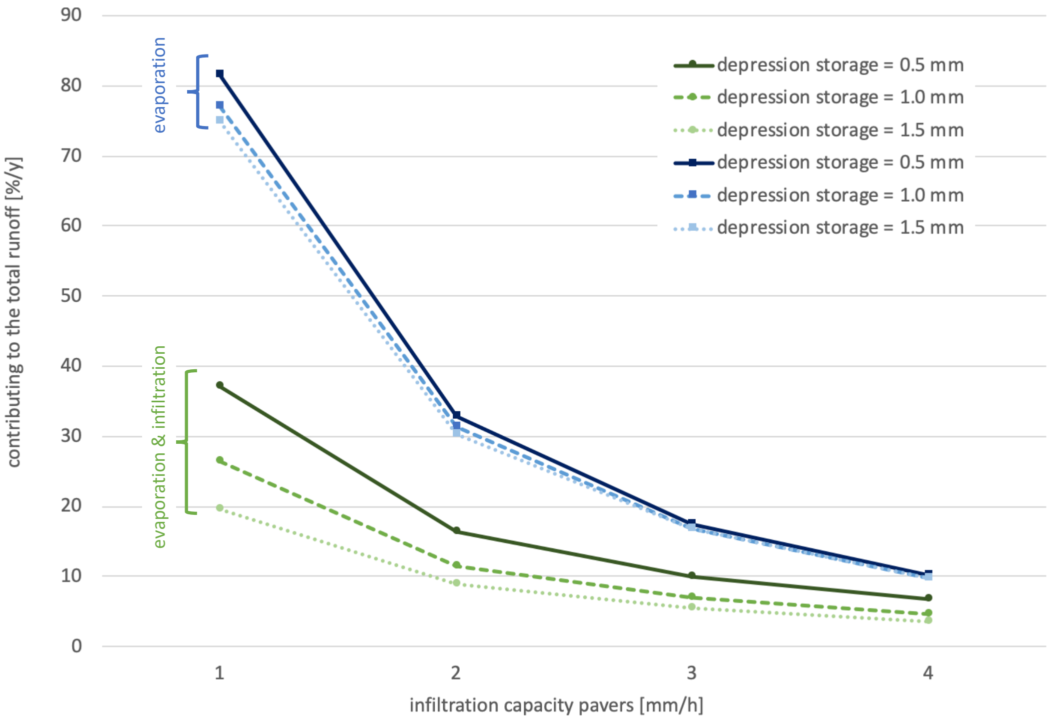

Figure 6-13 *Contribution to the annual runoff by the pavers; green: depression storage being emptied by evaporation & infiltration; blue: emptying by evaporation only.*

When focusing on the approach to empty the depression storage, two scenarios are compared. The depth in depression storage is either reduced due to evaporation and infiltration compared to evaporation only. While the green lines in the graph represent the impact of evaporation and infiltration on the emptying, the blue lines only consider evaporation. In case only evaporation is considered, the pavers contribute to the total runoff about 10 to 80 % of the time. The variation in contribution mainly depends on the infiltration capacity of the pavers once water runs off from the depressions. The change in the depth of the depression storage has less of an impact. In this scenario, the variation from 1 to 2 mm/h considered for the infiltration capacity impact the runoff generation strongly. Compared to that, any capacity higher than that will influence the result less strong. In case the depression storage is emptied by both, evaporation and infiltration, the contribution to the total runoff is more than halved. Furthermore, the impact of a change in infiltration capacity is less pronounced. Instead, the variation of the depression storage depth has more impact compared to the first scenario.

Finally, the graphs in figure 6-12, 6-13 and 6-14 highlight the impact of the generated runoff volume on the overall treatment efficiency of the system at that specific timestep. While small rainfall intensities and hence small stormwater discharges result in bigger treatment efficiencies, the contrary will reduce the efficiency of the system. However, the effect on the average annual treatment efficiency is less pronounced, since all compared scenarios are based on the same annual precipitation timeseries.

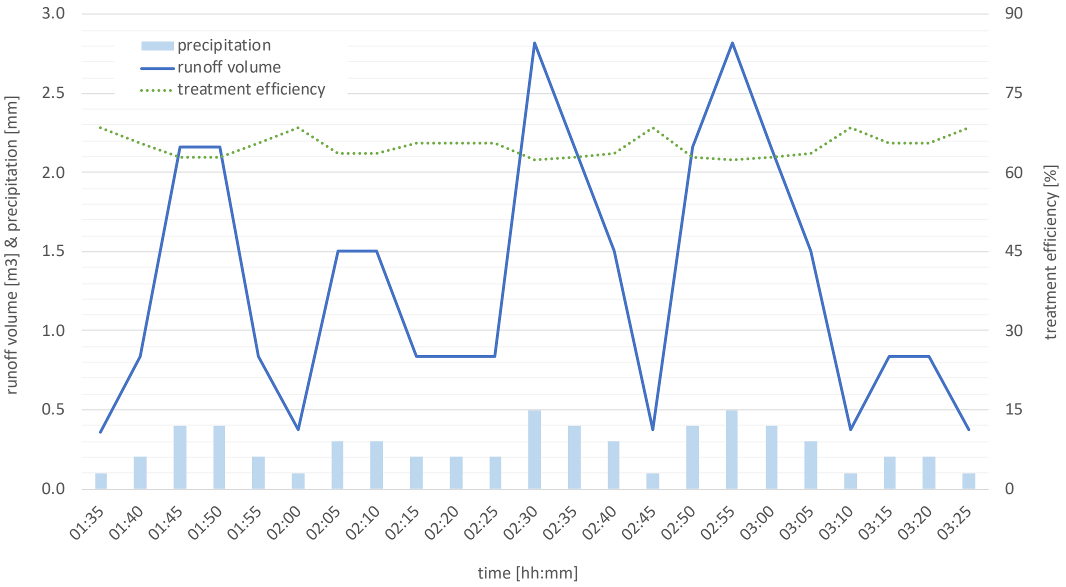

Figure 6-14 *Impact of the runoff volume per timestep on the treatment efficiency of the system of one rainfall event.*

6.3.4 Particle size distribution

The settling velocities of the particles itself is impacted the most by the particles size. Therefore, the composition of the sediment load reaching the treatment facility will impact the overall outcome as well. In case a higher fraction of small particles is present in the system, the related sedimentation efficiencies will result in less particles being caught. Instead, higher loads will leave the system and need to be eventually removed in a treatment step in sequence. Meanwhile, this also means that the storage volume of the treatment facility will be filled up less fast and cleaning is required less frequent. Contrary, if more coarse particles are present, sediments will accumulate faster and the cleaning of the system is necessary more often.

Figure 6-15 shows, that this parameter plays a crucial role when it comes to the overall results of the system. Using the measured values from the bed sediment analysis, about 40 % are smaller than 63 µm (table 5-1). In case even more small particles (< 63 µm) are present, the efficiency fluctuates strongly. Depending on the incoming volume, the average annual efficiency during flow-phase ranges in between 17 and 78 %. In case the majority of particles is bigger than 63 µm, the efficiency only varies in between 68 and 92 %. The reason for this difference in behavior is the impact of the particle size on the settling time. During the batch-phase, the impact of the particle size distribution is crucial as well since the settling velocity mainly depends on the particle size as well as its density. In case 80 % particles of the particles are > 63 µm, 25 % more sediments will settle during this period. Contrary, if the majority of particles are < 63 µm, 35 % less will be caught. Further impacts of this effect on the settling of the particles can be seen in § 6.3.2 and § 6.3.6.

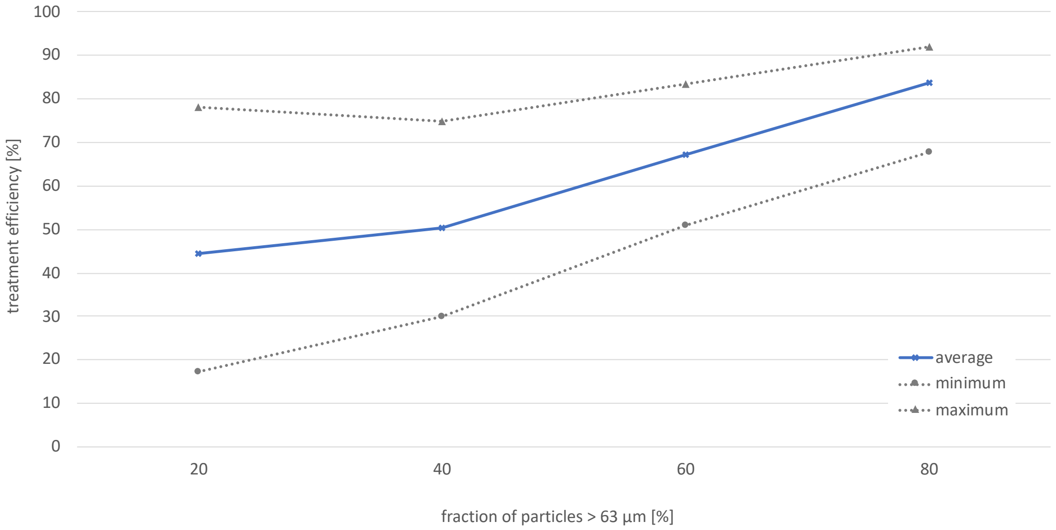

Figure 6-15 *Impact of the particle size distribution on the average annual treatment efficiency of the system excluding the batch effect.*

6.3.5 Incoming sediment loads from the roofs

Besides the composition of the particle's sizes distribution and the stormwater discharge volume, the incoming load itself also impacts the particles being caught within an entire year. Hereby, the model is being run with an increase in loads in two different ways. On one hand, the overall average inflowing load can be increased as a total. Hence a linearly increased concentration of particles is assumed to enter the system. Additionally, to that, the fraction originating from the roofs, that contributes to the entire incoming load, can be varied. This implies that the roofs contribute more or less to the overall inflowing sediment concentration. Since the roof area represents about 42 % of the total connected area, a change in its contribution plays a crucial role. An increase in the overall incoming concentration, while maintaining the contribution of the roof's constant, leads to a linear increase in caught load and hence outgoing load. Similar, an increase in contribution from the roofs, while keeping the overall concentration constant, leads to an increase as well.

However, the contribution of loads by the compared scenarios, meaning an increasing overall concentration versus increasing contribution from the roofs, is slightly different. An increasing fraction coming from the roofs means a higher concentration within the same runoff volume originating from there. This increase in concentration from the roofs has a slightly decreasing impact to the overall average incoming concentration to the system. Meaning the bigger the contributing fraction, the smaller the impact to the total. This can be explained by the effect of dilution. If the runoff coming from the roofs only contains small sediment loads, the overall incoming concentration will be more diluted. This results in a relatively smaller incoming concentration when compared to bigger loads.

6.3.6 Sediment loads caught during the flow-phase and the batch-phase

The caught sediment loads are composed be the amount being sedimented during the flow-phase as well as the batch-phase. Depending on the variation of the input values of the loss processes (especially for the pavers), the overall caught load results in about 41 to 67 kg of sludge being caught within one year during flow-phase. This represents about 64 % of the total incoming load. In addition to that, the batch-phase results in a sedimentation of about 7 kg of sediments during stagnant flow conditions, resulting in approximately 75 % of the incoming load being removed as a total. Comparing this volume of sediments to the available storage volume, cleaning will be necessary in every 2.5 to 4.1 years. The accumulation of the caught sediment over the entire year of 2019 can be seen in figure 6-16.

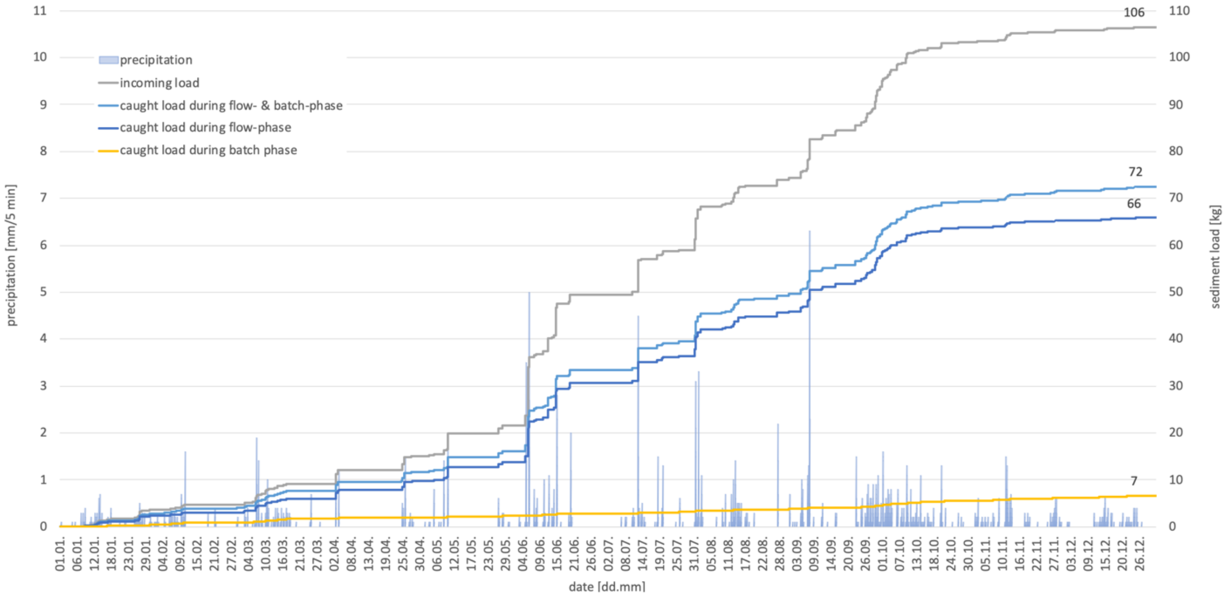

Figure 6-16 *Cumulative annual sediment load within the sedimentation pipe (simulation of 2019).*

It can be clearly seen that during high rainfall intensities the incoming sediment load increases significantly. However, due to the fast flow conditions during that period, the caught load does not increase with the same intensity. This is because most of the sediments will not have enough time to settle under these flow-conditions. The annual caught load during the batch-phase seems to be around 10 % of the load caught by the flow-phase. This can be explained by the particle size distribution assumed in the sediment load. About 35 % of the load is assumed to be smaller than 16 μm. According to the findings in § 6.3.2, these particles are not able to settle within a batch-period of one hour as well as for the average discharge volumes of about 2.5 l/s. In case bigger amounts of coarser particles instead of fines are expected, the caught load will increase.

6.4 Removal of stormwater pollutants

Table 6-2 shows the total load caught per particles size range over the duration of one year. It can be seen that the smaller particles will be caught less effectively. Therefore, the total caught load of these is smaller compared to the bigger fraction. However, due to the density and the size of the different particles, the smaller fractions are represented by more particles in number than the bigger ones.

***Table 6-2** Caught load, volume and adsorptive surface of the different particle size ranges.*

Particle size range [µm]	Total caught load [kg]	Total load leaving the SediSubstrator [kg]	Number of caught particles [-]	Area of each sphere [µm²]	Total caught adsorptive area [m²]	Pollutant removal efficiency [%]
0.2 - 2	0.02	20.79	1.8080E+12	3.8013E-06	6.87	0.1
2 – 16	0.80	15.41	1.3909E+11	0.000250	35.40	5
16 – 32	0.89	2.75	8.0798E+09	0.001810	14.62	31
32 – 50	0.45	0.52	8.1695E+08	0.005281	4.31	82
50 - 63	0.36	0.20	2.3384E+08	0.010029	2.35	100
63 - 125	4.11	0.73	5.8500E+08	0.027759	16.45	100
125 - 250	25.61	0.29	4.5774E+08	0.110447	51.22	100
250 - 500	21.66	0.00	4.8519E+07	0.441786	21.72	100
500 - 1000	7.78	0.00	3.3215E+06	1.767146	3.91	100
> 1000	4.24	0.00	3.4677E+06	6.157522	1.14	100

Assuming that all the different particles sizes smaller than 63 µm adsorb the same amount of pollution to its adsorptive surface, the fraction with the highest adsorptive surface represents the most important one to be removed. Each surface is assumed to be a sphere. In this case, the second smallest fraction (2 - 16 µm) seems to contain the biggest surface amongst the small fractions. Compared to the smallest considered fraction (0.2 - 2 µm) the number is about 5 times larger. Instead, the surface of the biggest adsorptive fraction (50 - 63 µm) is found to be 15 times smaller than the most adsorptive one. Furthermore, it can be seen that most of the small sized particles will not be caught and instead leave the system. This means that most of the adsorbed pollutants will also leave the sedimentation path with the untreated stormwater discharge.

Comparing the adsorptive surface of the caught load to the incoming load, it can be concluded that only for particles > 50 µm the entire adsorptive surface is being caught within the sedimentation path of the SediSubstrator. Instead, for those particles < 50 µm the efficiency differs. The size range between 2 and 16 µm, that represents the biggest surface, only seems to be removed with an efficiency of 5 %. The smallest fraction will hardly be removed at all, while approximately a third of the fraction in between 16 and 32 µm is removed. The fraction ranging in between 32 and 50 µm seems to be removed with an efficiency of about 82 %. This implies that most of the stormwater pollutants will not be treated by the facility and end up in the system installed thereafter. In this case, an effective functioning of the filter cartridge in the end shaft of the SediSubstrator is crucial to remove these particles including its attached pollutants. Appendix C shows an idea of another material to be used in the filter cartridges.

When talking about the overall treatment efficiency of the facility, the effectiveness seems to be good. However, this applies only for the caught load which includes mainly the large stormwater particles. Focusing on the removal of pollutants, a good treatment efficiency does not imply an effective removal of adsorbed pollutants. In fact, in the simulated case, most of the pollutants will leave the sedimentation path of the SediSubstrator without treatment in order to make a good statement about the effective removal of the pollutants by the SediSubstrator, the performance of the filter cartridge needs to be further assessed.

7 Discussion

The discussion will highlight the most relevant findings of the sensitivity analysis and the laboratory analysis and compare them to available literature. The methodology and its limitations will be discussed. Finally, a link to practical implementation in the field will be created by proposing a sampling setup according to the findings.

7.1 Evaluation of the theoretical and practical analysis

7.1.1 Particle size distribution

Since the stormwater treatment facility works on the principle of sedimentation, the parameters that impact the settling velocity of the particles are crucial. Hereby, the size of the particles impacts the settling velocity the most. Therefore, the composition of the particles within the samples is important to be determined to improve the model results and predict the efficiency in a theoretical way. As determined in the sensitivity analysis, especially the small particles sizes have a big impact on the overall removal efficiency. Knowing the amount of each size fraction, the load of particles that can be caught by the system can be determined.

Both methods have in common that the biggest fraction of the entire sample is between 125 – 250 µm. This distribution is similar to the one observed by Boogaard (2015). Boogaard (2015) illustrated that about half of the particles in the stormwater in Amsterdam are smaller than 50 µm. The bed sediment sample analyzed in this study contained about 40 % of particles in the same size range. The difference in fraction might again be due to the difference in particles being assessed. In case actual stormwater discharge would be analyzed, the results could differ from the reported ones. This would allow better comparison to other studies performed on stormwater discharge in the Netherlands.

Comparing the coarser fraction in both locations, the debris is mainly encountered in the gully pots. Only 10 % of it seems to reach the manholes (Appendix E). The fraction of fine sands, silt and clay appears to be trapped less efficiently within the gully pots, allowing roughly 68 % of the fraction between 125 – 250 µm to enter the manholes. The particles bigger in size than 250 µm are withhold by the gully pots structure by about 60 % (figure 6-2). This means that in case the gully pots are cleaned on a regular basis and the flap is positioned in the appropriate manner, the chance of the particles to be trapped increases. In this way, the total sediment load arriving at the manholes can be reduced by about 20 %, assuming that the sand trap of the gully pot will capture these particles > 250 µm and that the gully pots are cleaned regularly. Rietveld et al. (2019) emphasized that cleaning the gully pots four times a year can reduce the annual loads. Each cleaning is estimated to roughly remove 80 kg/ha. This would result in a relief of the stormwater treatment facility, since the annual load arriving at the system will be lowered.

Sampling was performed at the two mentioned locations in order to compare the difference in particle size distribution. This was done because the sediment loads used in the model simulation were taken from measurements taken in gully pots. Since the composition is assumed to change along the way to the start shaft of the SediSubstrator, it has been compared to the sediments encountered in manholes. The latter are assumed to be the closest location to the start shaft. Analyzing the difference in the sediment composition when comparing the gully pots and the manholes, the loads used in the model simulation taken from the gully pots can be adjusted to those expected in the SediSubstrator accordingly, by reducing the amount by a certain fraction.

7.1.2 Sediment load in stormwater

Interpreting the sensitivity analysis, it can be seen that the particle size distribution as well as the TSS of the stormwater is relevant. So far, the TSS concentration has been taken from a different location in the Netherlands (Rietveld et al., n.d.) and should be replaced by data from the actual project location. The particle size distribution on the other hand was based on the sampling performed in the study area. Since these results were comparable to other sediment compositions sampled in Amsterdam (Nijman, 2019), they were assumed to be representative enough for the first model simulation. However, both parameters influence the total amount of sediments being caught and should therefore be a more detailed assessment in the field is necessary. In this way, a more accurate estimation of the treatment efficiency can be determined by the model. Furthermore, the change in TSS when comparing the concentration of sediment entering and leaving the system, gives insight on the actual efficiency of the facility. Therefore, the stormwater discharge should be sampled at both, inlet and outlet of the sedimentation pipe to determine the average TSS concentration of stormwater. Since it is mainly important to determine the total amount of particles entering and leaving the system during an entire event, composite instead of discrete sampling is recommended. Since the incoming concentrations are mainly originating from the roofs, they are expected to be relatively low. Hence, small sampling volumes in short flow-weighted intervals may be sufficient to predict the removal efficiency. Depending on the sampling device used, the volume and interval can be determined. This is elaborated in § 6.2.1.

7.1.3 Runoff volumes and treatment efficiencies

Analyzing the removal efficiency in more detail, the rainfall pattern can further impact the settling behavior of different particles sizes. However, the volumes strongly depend on the loss processes considered for the runoff generation. According to the thresholds assumed, the different surfaces will generate a specific runoff volume.

The variation of the threshold values as well as the approach used to empty the depression storage will result in a large or hardly any runoff coming from the pavers. In case a depression storage of 0.5 mm, an infiltration capacity of 2 mm/h and only evaporation to reduce the storage is assumed, the contribution by the pavers is 33 %. Since the infiltration capacity impacts the runoff generation more, an increase in such will reduce these values. However, for infiltration capacities above 2 mm/h, the impact on the overall efficiency of the installed system is relatively small. Compared to that, in case evaporation as well as infiltration will reduce the depression storage depth, the contribution is approximately halved (16 %). However, either way the total contribution by the pavers to the total runoff is usually less than a third. Furthermore, in case these surface areas do contribute at all, the amount is most of the times only approximately 12 % (max. 40 %) of the total runoff volume at that timestep. Therefore, the difference in between both emptying scenarios on the total annual runoff volume is only about 5 %.

These runoff volumes will further impact the surface load and hence the sedimentation efficiency of particles during the flow-phase. Both values are in direct relationship and therefore important to be assessed in an accurate way. Analyzing the rainfall data from 2019, it can be seen that the smallest expected volumes to reach the SediSubstrator are about 0.03 l/s (10 liters in 5 minutes). These low volumes only occur in case the depression storage of the roofs is assumed to be empty. In case some water is already present, the volume rapidly increases to the 30-fold amount. Actually, 70 % of the times the stormwater discharge volume exceeds 1.25 l/s (370 l in 5 minutes). Since the just discussed volumes are only contributed by roofs (A=3700 m^2) only small loads of particles are assumed to be in this water from the roofs. In case the depression storage is (partially) filled and the rainfall intensity exceeds approximately 2.5 mm/h, also the pavers (A=2900 m^2) will contribute to the runoff volume. Then, the minimum flow to be expected is 4.6 l/s (1380 l in 5 minutes).

The average discharge volumes encountered in the model are between 2.5 and 3 l/s, which implies that most of the particles > 32 µm can settle successfully. Boogaard (2015) also observed that discharge rates smaller than 10 l/s will results in 50 % removal of the fraction smaller than 60 µm. In general, the simulated overall treatment efficiency of the sedimentation path of the SediSubstrator in flow-phase over one year was on average 67 %, ranging in between 51 and 84 %. However, when analyzing the rainfall data of the past four years it can be seen that only 4.1 % of the assessed time steps will result in stormwater discharge towards the sewer system. This means, that several dry moments in between rainfall events are encountered. In that case the just mentioned efficiency estimated by the conceptual model during the flow phase is underestimated. This is because of the so called batch effect (Weiß & Schütz, 2019), where stagnant conditions are present in the system. During these, more sediments will be able to settle within the residence time, depending on the duration. Including the sedimentation of stormwater sediments in the batch-phase actually increases the average treatment efficiency to 76 %, reaching maximum values of 100 % in case short rainfall events are followed by long dry periods. This results in about 10 % more sediments being caught over time. Knowing the average stormwater discharge arriving at the system (0.00125 m^3/s), this volume represents only about 0.04 % of the entire sedimentation path's volume (2.97 m^3) that can be filled. These stormwater volumes arrive at the SediSubstrator about 33 % of the time it rains. Actually, about 40 minutes of constant discharge of the mentioned volume would be needed to completely renew the entire volume of water within the sedimentation pipe. However, such rainfall durations of 40 minutes at a time causing constant discharge, only occur about 0.1 % of the year. In case the dimensions of the SediSubstrator would be bigger, even longer periods of constant discharge would be needed to completely fill the volume with fresh water.

While during the flow-phase the treatment efficiency strongly depends on the stormwater discharge, the duration of the dry periods and the volume of the sedimentation path of the SediSubstrator determines the efficiency of the batch-phase. This implies that sedimentation pipes with a big diameter and length can have a strong impact on the sediment load to be caught during the batch-phase. Sedimentation pipes with very big dimensions allow a lot of stormwater volume to be temporarily stored and so big amounts of sediments to settle. This highlights that the batch effect indeed is a relevant phenomenon to be considered when simulating the sedimentation of stormwater particles in the sedimentation path of the SediSubstrator. The importance of dry periods is furthermore highlighted by Vaze & Chiew (2003) for another reason. They mentioned that the highest pollution loads are to be expected in case moderate rainfall events occur in combination with preceding dry periods. Furumai et al. (2002) on the other hand observed that small flow will detach only few particles when compared to stronger rainfall events. This potential fluctuation in the overall influent sediment concentration will also impact the total amount of sediments being caught. This makes it challenging to predict the expected loads arriving at the system under investigation. However, it emphasizes the relevance to determine these in the field to understand what needs to be monitored.

Comparing the results of the simulated sedimentation efficiencies using silica (Millisil W4) of different particle size ranges to those measured in the laboratory study by Boogaard (2015), similar results can be achieved. For flow rates of 5 l/s both studies estimated a removal efficiency for particles bigger than 20 µm of about 80 %. Furthermore, at flows bigger than 10 l/s (approx. 0.5 mm/ 5min), even particles > 60 µm will not settle successfully anymore. Such rainfall intensities of 0.5 mm in 5 minutes only occur about 2.5 % of the times with rain (figure 6-4). However, since constant flow conditions were simulated, the effect of the batch-phase is not included in these results of the sedimentation efficiency. Therefore, the sedimentation efficiencies of the sedimentation path of the SediSubstrator for the different particles size ranges of both studies might be underestimated if compared to field conditions.

7.1.4 Reduction in pollution

The reduction of pollutants goes along with the removal of caught particle loads of the adsorbing size-fractions. The fraction that is the most crucial to be removed can be estimated by assuming that the adsorbed pollutants are evenly distributed over the surface and the adsorptive surface of each particle can by approximated with the surface of its sphere. Looking into the available adsorptive surface for each particle size range, the medium sand sized particles (125 – 250 µm) appear to have the biggest. Hoewever, this fraction is not assumed to adsorb many pollutants and furthermore is effectively removed by sedimentation most of the times. Instead, the fraction between 2 – 16 µm has only 30 % less available adsorptive surface and is indeed considered to adsorb many pollutants. Additionally, this fraction seems to be hardly removed at average flow rates and needs at least two hours of stagnant flow conditions to settle successfully. This means that after an entire year about 95 % of this size range with the biggest adsorptive surface leaves the sedimentation path and is not treated. Similar to that, the pollutants adsorbed by particles between 16 and 32 µm will only be removed with an efficiency of 30 %. Therefore, from an environmental point of view, these should be the target fractions to be removed. Fuchs et al. (2019) emphazised this by stating that 74 to 88 % of the heavy metals (Zn, Cu and Pb) are absorbed by the particles of a size smaller than 63 µm. The same was observed by Bathi et al. (2009), Morquecho et al. (2005) and Pitt (2002).

The SediSubstrator uses a filter cartridge in the end shaft of the system, that is assumed to remove many more fines than simulated by the model. The impact of this filter should be analyzed in the field and the assumption of the positive impact on the pollutants removal should be verified.

7.2 The methodological approach

This thesis followed a stepwise approach in order to simulate the functioning of the SediSubstrator to be installed in the study area. The overall aim was to understand the most relevant parameters to be assessed in the field to measure the actual sediment removal efficiency in the field.

To understand the characteristics of stormwater that can be determined and grasp the exact behavior of the stormwater treatment facility, literature was studied in detail. This provided the basic knowledge to allow the further steps of the methodology to be executed.

Having the findings from literature in mind, actual sampling was performed in the field. The aim was to determine the stormwater particle composition in the field. As a result, the latter would be used as input parameter in the model. However, only bed sediment was sampled since no stormwater discharge was available during the sampling period. Therefore, it needs to be highlighted, that the sediments analyzed in the laboratory do not directly represent the sediments that reach the SediSubstrator. The stormwater discharge will contain a different composition than the bed sediment. Furthermore, only the particle size distribution and not the loads within stormwater were determined. Instead, loads measured in Rotterdam by a different study were used as input in the model. However, the loads expected in the study area can differ. Factors such as the traffic situation, the cleaning of the streets and gully pots, the surface characteristics and runoff processes will determine the actual sediment loads (Andral et al., 1999; Huber & Helmreich, 2016). Since these will impact the final result of the conceptual model, they should be assessed in the field. Additionally, the contribution of particles from the roofs to the total incoming load should be assessed separately in the field.

In general, the model results seem to depict a realistic behavior of the treatment facility. However, most of the input values are based on assumptions. Since the impact of some of the assumptions on the final results is relatively strong, these should be given particular attention for verification in the field. These assumptions are in particular the particle size distribution, the incoming sediment load and the stormwater discharge volume, depending on the runoff generation. Additionally, the model does not include the functioning of the filter cartridge in the end shaft. Even though it is assumed that the latter will increase the removal efficiency of fines, not enough information is available on the exact amount. Therefore, an estimation of the clogging of the AquaBASE using the model was not possible. Looking into the removal of pollutants, many assumptions were made. Therefore, it is recommended to determine actual numbers in the field before making a final statement.

So far, the only model encountered in literature that estimates the removal efficiency of the SediPipe was built by Weiß & Schütz (2019). However, no results from the model simulation on the caught loads and the removal efficiency have been published so far. This model assumes a parallel plug flow for the stormwater in the horizontal sedimentation pipe, that is “pushed through” the facility according to the inflow volume. Instead of determining a surface load for each discharge volume, Weiß & Schütz (2019) use the residence time of specific water volumes along the length of the pipe. This residence time represents the time which the water volume has spent in the sedimentation pipe and during which sediments had time settle. Finally, an integration over the total time will result in the volume of sediments to be removed and thereby the respective overall removal efficiency. Both models rely on residence-time-based approaches. In contrary to Weiß & Schütz (2019) this divided the stormwater inflow into a flow- and batch-phase instead of considering plug flow. This way, the caught load is computed per 5 minutes time-step instead of the entire residence time of a certain water volume.

7.3 Sampling and monitoring setup for the SediSubstrator

The sampling and monitoring setup need to be well prepared. The first step is to define the exact objectives, to determine what needs to be achieved by the setup. It is necessary to define the parameters to be assessed and the appropriate equipment to do so. To get good results, these devices should be placed in locations that best represent the parameter to be identified. Furthermore, a sampling frequency as well as volumes that can represent the site-specific conditions best, should be chosen.

Precipitation

There are several precipitation measuring stations around the study area that can provide the representative precipitation data to be used. Some of them are installed by Waternet, others by KNMI. Since there are a few stations nearby the study area, the data from these can be used to get representative precipitation data. The closest rainfall recording stations around the study area can be seen in Appendix G (figure G-1).

The rainfall can vary spatially and represents an important input parameter. Therefore, it is advised to install an additional measuring device in the study area. Usually, these devices are installed on public property to allow access at any time. Therefore, the Montessori Public Elementary School Maas and Waal located right in the east of the study area could provide the circumstances needed for the placement of a tipping bucket. The use of a tipping bucket is recommended since it guarantees more accurate results compared to conventional depth gauges, as mentioned in § 3.4.3.

Stormwater discharge

The generated stormwater discharge that enters the system should be monitored using an electromagnetic flowmeter for applications with partially filled pipes. Hereby, the measuring device by KROHNE called TIDALFLUX 2300 could be used. This flowmeter does not require any obstacles to be placed within the pipe to enforce a certain level of filling. In this way, no sediments will be unnaturally trapped along the pipe and instead the entire flow will end up in the start shaft of the SediSubstrator. In case the pipe will be filled with less than the required 10 %, the system will display an error. Exact specifications of the device are given in Appendix G (figure G-2).

The smallest discharge volumes to be expected at the system are about 1.2 l/s. As soon as the pavers will contribute to the stormwater discharge as well, meaning the rainfall intensity exceeds 2.5 mm/h, the volume increases to 2.15 l/s. Since the proposed device is capable to measure flow in the range of minimum 0.01 l/s until 27,800 l/s, it seems to be appropriate tool for this research.

Stormwater sediments

It is proposed that the stormwater sediments are sampled in an automatic way using an automated sampler. For this, the portable sampler Aquacell P2-MULTIFORM provided by Aquamatic may be used. The automated sampler should be placed at least at the inlet and outlet of the SediSubstrator. The exact locations will be indicated in § 7.3.2. Further details about the automated sampler are given in Appendix G (figure G-3).

This inlet position of the suction hose of the sampler will be placed within the water column of the start shaft as well as before and after the filter cartridge. This way, only suspended sediments will be sampled, while bed sediments are taken in when being in suspension in the water column.

Turbidity

A turbidity sensor should be installed to assess potential resuspension. For future studies, it is recommended to use the VisoTurb 700 IQ by the provider Xylem Analytics for measuring the turbidity. This sensor is equipped with an ultrasound cleaning system that removes fouling and so assures accurate measurements. To guarantee the right angle for accurate results, the device is advised to be fixed to the flow separator, in a distance of minimum 10 cm from the bottom. This way the sapphire disc can face the flow direction. More detailed specifications on the installation of the turbidity sensor is given in Appendix G (figure G-4).

Pressure, temperature & electrical conductivity

The LTC Levelogger Edge by Solinst is advised to be used to measure the level (pressure), the temperature as well as the electrical conductivity all in one probe. This device is able to take measurements with a minimum interval of 2 seconds. The level and temperature measurements can be conducted with an accuracy of about ± 0.05 %, while it is 1 % for the electrical conductivity in the range of 5,000 µS/cm –80,000 µS/cm. Further information on the system and the installation can be found in Appendix G (figure G-5).

7.3.2 Sampling points

It is important that the parameters are measured in representative locations. It is important that the devices can be easily installed, maintained and in a later moment, the monitoring results can be read out. It needs to be assured that the measuring equipment can fit within the chosen locations. If not, additional facilities need to be created to place the measuring devices there. Proposed locations for various measuring devices can be seen in figure 7-1. Appendix G provides additional detailed information about each sampling point separately.

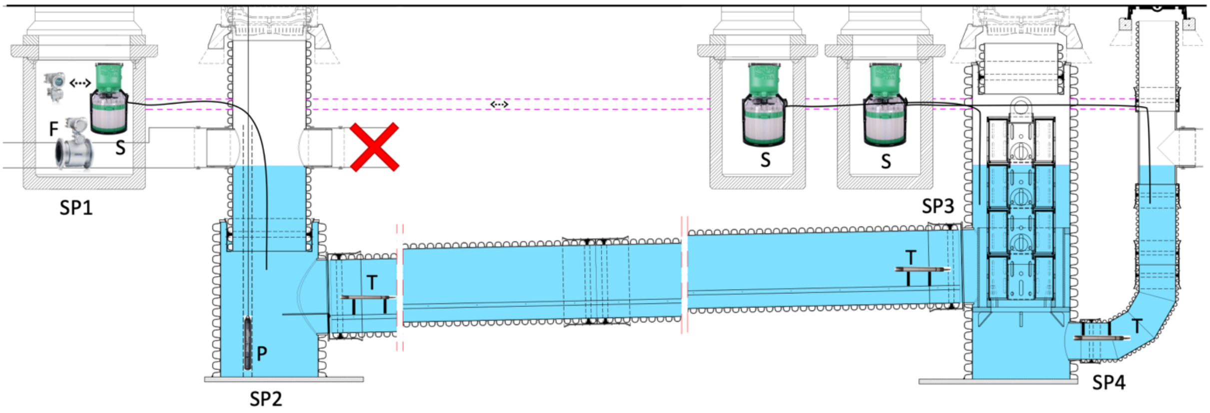

***Figure 7-1** Sampling point (SP) of the different devices: flowmeter (F), automated sampler (S), turbidity sensor (T), pressure transducer & EC meter & temperature sensor (P), mantle tube (dashed pink line).*

7.3.3 Sampling frequency and volumes

The selection of the sampling frequency is based on the estimated flows determined in the model. The minimum rainfall events and their related discharge volumes will define the available stormwater samples to be analyzed in the laboratory. Therefore, at least 3 liters are necessary to determine the suspended sediments concentration and its characteristics in the water. For small rainfall intensities, a minimum of around 10 liters can be expected to arrive at the SediSubstrator within 5 minutes in case the connected surfaces were completely dry. If not, meaning the depression storage is fully filled, the inflow volumes increase to 350 liters in the same timeframe. The maximum rainfall events on the other hand define the sampling frequency and volumes that need to be taken. In order to guarantee a representative monitoring of the variability of the sediment concentration in the stormwater, it is advised to take small volumes in short intervals. Depending on the volume of the available storage container, volumes of about 50 to 100 ml should be taken every 300 to 700 liters of stormwater discharge volume. In case more frequent sampling or bigger sampling volumes are desired, the storage container needs to be replaced throughout the measurements. The weather forecast should be checked on beforehand in order to potentially adjust the sampling frequency according to the predicted rainfall duration. In this way, it can be also seen if due to e.g. long predicted durations or heavy events, the storage containers might need to be replaced throughout the sampling.

7.3.4 Targeted rainfall events

In order to get representative results, it is important to gather information about different rainfall intensities. Therefore, every rainfall event that accumulates enough runoff must be measured. Since parts of the rainfall is lost on its way to the sewer system and will not be translated to stormwater discharge, only rainfall events that are more intense than approximately 1.2 mm in one hour are relevant to be considered. Events smaller than that will not cause any runoff and the water will gradually evaporate or infiltrate from the surfaces.

7.3.5 The implementation of the SediSubstrator in the field

The implementation of a SediSubstrator in the Rooseveltlaan is challenging, due to the hydrological conditions in the area. The groundwater levels are only 0.5 m below street level and furthermore the area represents a bottleneck in case of heavy storm events (figure C-1, Appendix C). Therefore, the design of the facility had to be adjusted in such way, that it will not be deeper than 3 m in the ground. Another reason for this limitation was the expensive excavation works related to the installation of the facility. In terms of the dimensions of the SediSubstrator, the length was another limiting parameter. The current drainage system (figure G-6, Appendix G) as well as the possibility to re-open already newly built street sections, reduced the maximum possible length to about 12 m. To allow the chosen maximum length, the SediSubstrator needs to be placed parallel to the ventweg.

7.4 Uncertainties and errors

There are several uncertainties and errors that may have been introduced throughout the sampling and the analysis of the data.

Bed sediment sampling

Due to the lack of heavy storm events, only bed load samples have been taken and analyzed. This does not allow a complete understanding of the entire stormwater particle composition. Therefore, several assumptions regarding the actual composition of the stormwater discharge needed to be made. Furthermore, the samples have been grabbed by using a shovel with an extended arm. This allows to reach the bottom of the manhole; however, it may have caused parts of the bed sediment to fall off while lifting the device. Additionally, sediments may have been lost while placing the sample inside the sampling bottles. This might have introduced a partial loss of a certain particle size range during sampling.

Handling of the samples

In between sampling and the analysis in the laboratory, the samples are stored in bottles while being transported. The samples were only mixed before and after the sieving of the samples. This might have resulted in cohesive binding of smaller particles or building of aggregates which effects particle size and shape.

Laboratory analysis

Since the laboratory devices required filtering of the samples beforehand, size ranges greater than 1.8 mm were excluded from further analysis. Furthermore, the sample is introduced to the laser diffraction device using a pipette. Since the device used to determine the particle size distribution only requires 1 to 3 drops of a sample, the rest will stay within the pipette itself. Therefore, it cannot be guaranteed that the smaller and bigger particles were introduced to the measuring device in equal portions.

When using the settling velocity device, further errors might have occurred due to the procedure. First, the introduction of the particles to the water column has to be communicated to the sensor by activating a switch. While introducing the sample manually from the top, the switch has to be activated by stepping on it by foot. In case this is not performed at the exact same time, the settling velocities might be under- or overestimated. Lastly, the experiment will be stopped once the signal of the cumulative weight stays approximately constant. In case the experiment is stopped too early, important data could be lost.

7.5 Limitations

COVID-19 pandemic

The unexpected occurrence of the COVID-19 pandemic changed the initial scope of the thesis. Due to the freeze in production as well as delayed delivery of the stormwater treatment device, the effectiveness of the system could not be tested in the field. Instead, the best possible setup to do so in future has been elaborated in this research.

Lack of rainfall events

Due to the lack of relevant rainfall events during the indented sampling period, the assessment of the stormwater discharge properties could not be performed. To compensate for this, bed sediments in the study area were assessed. In this way, the procedure of sampling, laboratory analysis as well as the interpretation of the results could be practiced appropriately.

Software used to process data

The software Microsoft Excel for Mac (version 16.39) was used to build the model and analyze the precipitation data series for one entire year. However, this software solution turned out to reach its limitations due to the size of the dataset. In this case, more than 100,000 lines of calculations were used over several spreadsheets. This significantly slowed down the processing and computing of results.

Functioning of the settling velocity device

To determine the settling velocity of the different samples, the experiment should be repeated several times. However, due to the malfunctioning of the signal, this was not possible. Furthermore, the lack of the time remaining, did not allow the experiments to be repeated on new samples. Therefore, the results from the settling velocity device are not reliable enough.

8 Conclusions and recommendations

8.1 Conclusions

This thesis aimed to propose an adequate sampling and monitoring strategy to determine the removal efficiency of the SediSubstrator L in future. To do so, international and local literature was used to identify the most important parameters to be assessed. Using these in combination with field data, a model has been built to simulate the removal of stormwater sediments from the stormwater discharge. Finally, the sensitivity of the model to several parameters delivered a selection of those having the strongest impact on the final results.

From the results obtained by the sensitivity analysis it can be concluded that there are three main parameters influencing the treatment efficiency the most. Once verified in the field, they can be adjusted in the model itself.

The results from the analysis indicate that the first parameter to be measured in the field is the *stormwater runoff discharge*. The runoff impacts not only the amount of sediments being flushed towards the SediSubstrator but also the stormwater discharge volume and so the flow velocity through the horizontal sedimentation pipe. The latter will determine the efficiency of the stormwater sediments to settle and to be removed from the system during flow-phase. The generation of runoff itself depends on the loss processes in the catchment. Evapotranspiration, interception, infiltration, wetting losses as well as losses by depression storage reduce the amount of actual precipitation reaching the SediSubstrator. Depending on the surface topology, a combination of these processes needs to be considered. Based on the assumptions in the model, it can be concluded that especially the infiltration rate of the pavers impacts the total runoff volume. In fact, rainfall intensities stronger than 2.5 mm/h are needed to significantly generate runoff from the pavers. According to the rainfall data from 2016 to 2019, intensities of that magnitude only occur about 3 to 6 % of the times. Since the results depend on the loss process thresholds assumed, these should be determined in the field to understand the actual impact. The stormwater discharge volumes arriving at the system can be assessed using the flowmeter proposed in § 7.3.1. In this way, the measured precipitation combined with the connected surfaces can be compared to the determined volumes. The difference in volume can then be related to the loss processes and used to calibrate the model.

Based on the sensitivity analysis performed, the second parameter to impact the treatment efficiency of the SediSubstrator is the *influent sediment load*. This parameter can be already assessed prior to the efficiency testing. In this way, the model can be calibrated on this input value. The importance to sample and analyze the incoming sediment load is shown by the linear relationship of the caught versus the influent load. So far, the data used as input of the model is based on field experiments of other study areas and literature. However, these values can vary strongly from location to location according to differences in e.g. traffic, land use, rainfall intensities etc. Furthermore, typically road runoff is being assessed while the contribution from other surfaces such as roofs is rather unexplored. Since all surfaces contribute to the total inflowing sediment load, the difference in contribution should be assessed in the field. To determine the overall treatment efficiency of the system, it is sufficient to assess the sediment load before and after the sedimentation pipe of the SediSubstrator. Based on literature, it is concluded that flow-weighted composite sampling provides sufficient insight on the difference in load and so the treatment efficiency.

The *composition of the stormwater particles* affects the amount being removed by the SediSubstrator. This parameter can be already assessed simultaneously with the sediment load. Since this facility works on the principle of sedimentation, the particles size and density are crucial. However, using the equation by Ferguson & Church to estimate the settling velocity, it can be concluded that the impact by the particle size is the most pronounced one. It is advised to analyze the particle size distribution of the stormwater discharge as well as the specific density of the particles to better understand its composition. The results from the sensitivity analysis showed that indeed an increasing number of particles bigger in size than 63 μm positively contributes to the overall removal efficiency of sediment loads. However, in terms of adsorbed pollutants, the high removal efficiency of particles bigger than 63 μm does not imply the removal of stormwater pollutants. In fact, since these are mainly adsorbed to the fine particles > 63 μm, most of the pollutants will escape the system. In case many particles smaller than 63 μm are present in the stormwater discharge, it needs to be assured that especially the fraction in between 2 and 16 μm is being caught, since these seem to represent the biggest adsorptive surface compared to other fractions. By installing the SediSubstrator with the SediSorp filter cartridge in the end shaft, a reduction of the small sizes particles after the sedimentation process is expected to be achieved. Due to the lack of information on both, the construction and on the expected sediment load of the incoming water, the filter function was not included in the model simulation. The exact performance of the filter should be tested in the field to understand the impact on the stormwater quality. Additionally, the functioning of the filter could be included in the model simulation in a future step.

The model shows that the SediSubstrator seems to catch about 48 to 74 kilograms of sediments per year by sedimentation. As predicted by Fränkische Rohrwerke, this implies cleaning intervals each 2.5 to 4.1 years. This number corresponds with the service intervals communicated by Fränkische Rohrwerke of 1 to 4 years.

The methodology used, gave a good understanding of the parameters to be assessed in the field and therefore allowed to answer the research questions. Furthermore, the measurement setup to monitor the selected parameters was deduced from the simulated results. This will allow to monitor the stormwater treatment system in future and add information to the few testing's that have been performed on SediSubstrators under field conditions. However, actual stormwater sediment sampling under field conditions should be performed in future to improve the model results. In this way assumptions can be verified and, if necessary, adjusted.

Summing up, this thesis delivers a measuring setup to start evaluating the treatment efficiency of the SediSubstrator L in the field. The results can be further compared to the results simulated by the model. Once similar, the model can be used to estimate the performace of the treatment facility for a longer time-series. In this way, the interval of cleaning can be predicted while avoiding high monitoring costs. The calibrated model can be used to improve the design e.g. to make an assessment of the length of the SediSubstrator in which the cost vs. the treatment efficiency is compared.

8.2 Recommendations for further research

8.2.1 Improvement of the model

The model built for the purpose of this thesis uses simplified calculations to estimate the treatment efficiency of the SediSubstrator. However, since the precipitation data series is based on short time intervals of 5 minutes, the dataset has more than 100,000 rows. This results in many calculation steps with cross references and hence a big file size with long calculation times Therefore, the improvement of the model is recommended to speed up the calculation process. Since only about 4 % of all considered timesteps include precipitation, and thus important numbers, the rest could be eliminated. In the case of the year 2019, this could for instance reduce the row numbers by approximately 93 % (7,225 rows compared to 105,108). Doing so, it needs to be assured that important information about the emptying of the depression storage in between is not lost. Here, it is advised to take advantage of the relationship of evapotranspiration over time. By reducing the number of rows, more than only a one-year time series can be introduced. To be representative, many more years should be included in the model in a future simulation. By doing so, even more of these cells without precipitation data would be present. Hereby, a bigger interval for the rainfall data of e.g. 15 minutes seems to improve the problem. However, over the timespan of many years, even longer intervals will result in too many rows without actual precipitation data. Furthermore, also the phenomenon of the batch effect should be still considered during the dry periods. Another approach would be to use a different software, like Python, to build the model. In this way, similar results to the reduction in calculation steps can be achieved.

Lastly, the most important input data of the model should be improved as well by replacing values assumed from literature with actual field measurements. This allows a better representation of the conditions in the study area.

8.2.2 Stormwater sediment sampling

As stated throughout the report, the determination of stormwater sediments is an important task to understand the exact composition in the study area. Due to the given circumstances it was not possible to perform sampling on stormwater sediments. Instead, only bed sediment samples were taken. It is recommended to take samples from stormwater discharge to determine the sediment load as well as particle size distribution in the field. These samples are advised to be taken at the outlet of gully pots as well as the manhole installed right before the SediSubstrator. In this way it can be determined, what load continues from the gully pots further downstream. Hereby it is important to identify the cleaning interval of the gully pots to understand the rate of filling of these. At both locations, sampling should be performed as composite sampling over an entire rainfall event. Several events should be considered in order to get an average sediment load and composition as reference. The intake of the sampling should be placed approximately at the center of the outlet pipe of the gully pot or manhole. Furthermore, samples taken from the roof runoff should be analyzed as well. The latter can be taken at the rain gutter or at a location where the connection of the rain gutter and the sewer system is made.

8.2.3 Testing the SediSubstrator under field-conditions

Once the SediSubstrator is installed, the measurement setup should be tested. It is recommended to make sure all the devices work properly and if necessary, adjustments of the arrangement should be made. As soon as everything is in place and properly working, the parameters identified to assess the treatment facility should be monitored for one entire year. Based on the measurements, the model can be calibrated, to allow to simulate long time-series. With a calibrated model also the design of the Sedi-Substrator can be improved.

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Appendices

A - Drainage situation in the study area

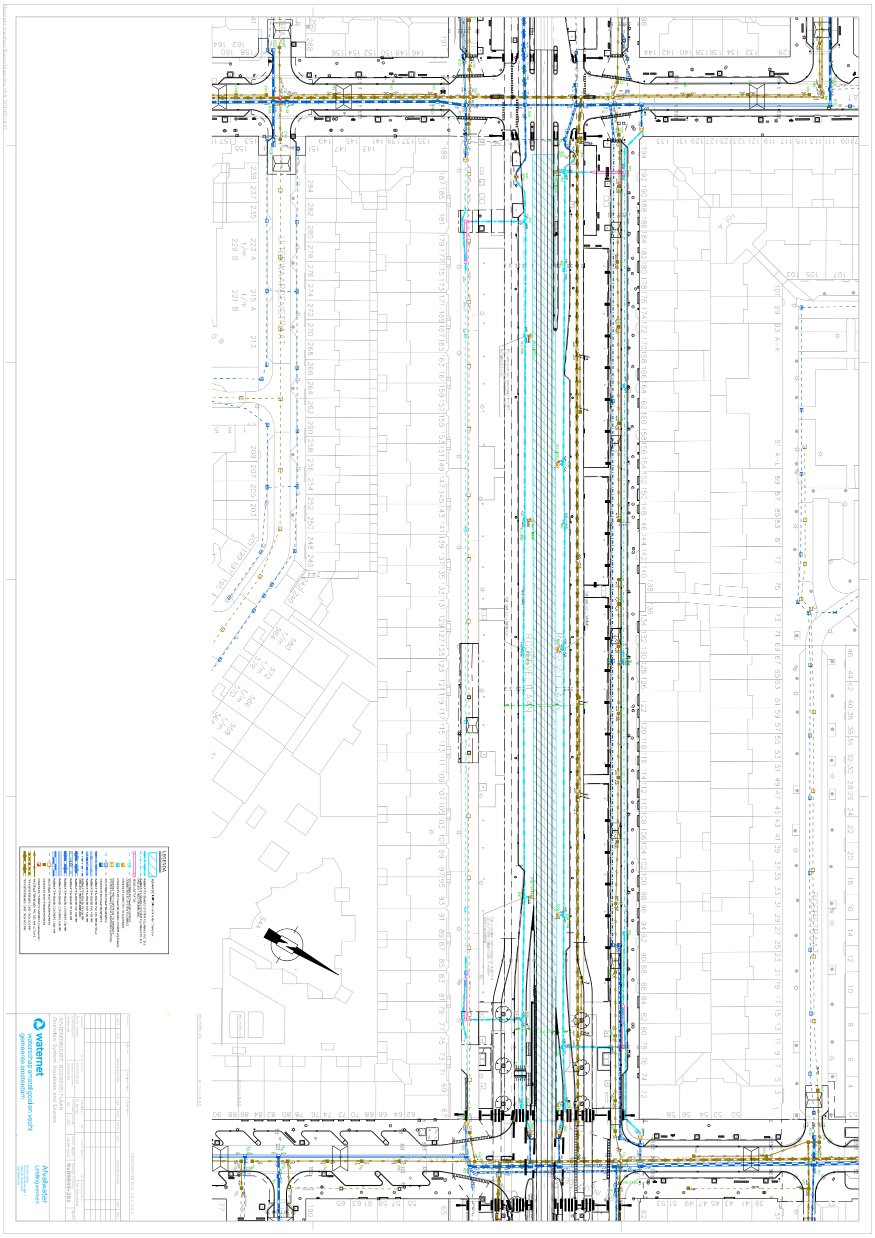


Figure A-1 *Drainage situation of the study area.*

B - Additions to the literature review

I. Main sources of pollutants encountered in urban stormwater

The main pollutants to be found in the stormwater are heavy metals, PAH, pesticides, nutrients and bacteria (Boogaard et al., 2015). In general, there are two main sources of these, namely the atmosperic pollution and then pollution from the surfaces (Reinhold, 2002).

The accumulation of the atmospheric pollution is mainly caused by gaseous substances. These are often derived from combustion processes in the power generation. Furthermore, the dust load from industry or wind erosion contributes to this kind of pollution. Parts of this atmospheric dust already precipitates during the dry weather phase and contributes to the accumulation of particles on surfaces. Here, in particular aromatic hydrocarbons and pesticides are important contributors to the wet deposition. The dry deposition can be seen as the sedimentation of gaseous and particulate pollutants on the earth's surface and the adsorption of contaminants on surfaces. Especially, organic and inorganic pollutants such as polycyclic aromatic hydrocarbons (PAH) or heavy metals are here of particular interest (Reinhold, 2002).

Surface contaminations on the other hand are mainly caused by the processes on the top drainage surface areas. These mainly depend on the area-specific uses. They can be composed of waste from urban and road traffic. A large part of surface pollution is caused by emissions from motor traffic, especially road surfaces. This is where combustion residues, abrasion from tyres, brake linings as well as losses of fuels and lubricants are deposited. The amount of traffic-related pollution depends on the volume and characteristics of traffic. Furthermore, during winter, the road maintenance leads to an increase chlorides. Traffic is indeed the main origin of heavy metals and PAH. For instance zinc is mainly generated by tyres. Pitt et al. (2004) summarized that heavy metals and PAH mainly derive from pavements, while nutrients have their origin in landscaped areas. Pollution on the surfaces can further originate from various sources such as construction activities, animal wastes, pedestrians trash, weathering of buildings or vegetation (Rietveld et al., n.d.).

II. Stormwater sediment sampling approaches

Automated sampler

Automatic water samplers are devices that are commonly used for stormwater sampling and therefore used by many different studies (He et al., 2010; Horwatich & Bannerman, 2008; Kidner & Roesner, 2007; Melcher, 2019; Reinhold, 2002; Rommel & Helmreich, 2018; Wichern et al., 2017). Hereby, rainfall runoff is collected with these sampling devices, retrieved at any other (later) time, and finally analyzed in a laboratory. Autosampler use pumps which are connected to a tube to withdraw and deposit stormwater into sampler containers. They can be flexibly programmed. Clark et al. (2008) emphasized that autosamplers will deliver good results for particles < 250 µm, while problems occur if large amounts of sand-sized particles are present in the water sample. Erickson et al. (2013) already mentioned a decrease in accuracy with particles bigger than 88 µm. However, they reported that this technique is usually used to monitor stormwater since metals as well as nutrients can be assessed quite accurately. Such portable automated sampler encountered in literature were: Sigma 900 MAX portable sampler (Hach Company), Liquiport 2000 (Endress+Hauser), ISCO 3700 (Teledyne ISCO), WaterSam WS 316 (Edmund Bühler PP 84) and many more.

Manual sampling

In contrary to the automated sampling, a manual approach can be used. This involves someone to physically take samples at the location throughout a rainfall event. The sampling will start at the beginning of the event and last until it is over (Law et al., 2008). The advantages and the disadvantages of the respective methods are given in table 0-1.

Table B-1 Advantages and disadvantages of the sampling techniques adapted from Law et al. (2008).

Type	Advantages	Disadvantages
Manual	Low capital cost	Probability of increased variability due to sample handling
	Not a composite	Inconsistency in collection
	Point in time characterization	High cost of labor
	Adaptable to various situations	Repetitious and monotonous task for personnel
	Note unusual conditions	Potentially hazardous situations
	No maintenance	
	Collection of extra samples possible	
Automatic	Consistent samples	Inflexibility
	Probability of decreased variability caused by sample handling	Restricted in size to the general specifications
	Minimal labor requirement for sampling	Sample contamination potential
	Has capability to collect multiple bottle samples for visual estimate of variability and analysis of individual bottles	Considerable maintenance for batteries and cleaning; susceptible to plugging by solids
	Flexible programming capabilities	Potential subject to damage by vandals

III. Analytical methods

Particle size analysis

In general, there are two main approaches to determine the particle size in the laboratory (Goncalves & Van Seters, 2012). The first methods are based on examination of the sample with specific devices. The second method uses a combination of such with prior wet sieving of the sample instead. The particle size analyzing devices are based on different principles. The first one uses laser diffraction, where a laser beam scans the sample and due to the reflection of the light, the particles can be detected. This size of the particle is in a direct proportional relationship with the angle of scattering and is defined as diameter of the particle that projects the same area (Andral et al., 1999). Hence, the intensity of the distribution of the beam gives information to identify the particle size distribution of the sample. The measuring range of such devices is between 0.01 µm up to 2 mm. These devices are also referred to as Coulter Counter analyzer (Andral et al., 1999) and were used in studies such as Goncalves & Van Seters (2012) and Koo (2014). These light diffraction techniques are faster than traditional wet-sieving approaches, however results amongst these two do not precisely agree (Arriaga et al., 2006).

The second technique to identify the particle size in samples is the digital micro-imaging. This method uses the principle of filtration and settlement of the particles when passing though filter media of 0.4 microns (Goncalves & Van Seters, 2012). The settled particles are then recorded with photomicrographs and further inspected with an optical microscope at different magnifications. By using an image processing software to specify the edges of the particles, the size of each particles and their number can be determined. This is done based on the number of pixels that are occupied by these in the photo. In this way, the number of particles for each size range can be identified.

Another strategy for stormwater particle analysis is suggested by Burton & Pitt (2002). This approach was used by several studies amongst others by Andral et al. (1999), Dierschke (2014), Horwatich & Bannerman (2008) and Selbig et al. (2016). In a two-step approach, the samples are first wet sieved for particle diameters of 32, 63, 125, 250, and 500 μm. The study performed by Andral et al. (1999) used four filters with decreasing pore size of 1000, 500, 100 and 50 μm. The sieved mass of all the different size ranges is further dried at 105 °C for about 24 hours and weighed. In this way the loss in weight of the dried sieving-residues can be measured and the mass is assessed. The particles smaller than 32 μm, are further processed and divided into even smaller ranges by laser scattering or Coulter Counter. Here, the percentage of the sediments by mass with diameters smaller than 14, 8, 5 and 2 μm are determined (Horwatich & Bannerman, 2008). Dierschke (2014) used a pure wet-sieved approach to determine the number of particles in stormwater of a certain size.

The same technique was recommended by Erickson et al. (2013) to be used for samples where coarser particles are encountered. Dierschke (2014) proposed to prior use a 1- or 2-mm sieve to remove the coarse sediments. In this way, very coarse visible pollution such as cigarette butts or parts of wood can be removed manually. The resulting sieve residues should then be dried, weighed and documented for later discussion of the results. The following determination of the finer fraction of solids of the runoff sample is carried out in three steps. First, the sample is homogenized and then sieved and filtered through a filter of 45 μm. For stormwater, which often contains only low concentrations of a few mg/l, mainly glass fiber, membrane or paper filters with smaller pore sizes are used. This results in a potential range of mesh sizes between 0.3 to 25 μm, often even 0.45 μm (Dierschke, 2014). In case the determination of organic matter is desired, the filter is burned at 550 °C and therefore its material must burn ash-free. Erickson et al. (2013) further recommended to use the hydrometer method to get detailed information about the size distribution of the particles. This method should be a subsequent step of the wet-sieving, providing more information on the silt and clay-sized particles. Kidner & Roesner (2007) stated that this is the preferred way to analyze stormwater solids. First, the total concentration of solids in the sample is analyzed (SSC analysis), followed by the TSS analysis.

The total sediment load is then determined by the combination of the results from both, the coarse and the fine fraction. This concentration is usually given in mg/l. To depict the distribution of particles according to their size, a cumulative distribution curve can be constructed. This is done by plotting the percentage of sediment by weight being smaller than a given mesh size, against the sieve or particle diameter (Lin, 2003).

In order to get the mean concentration of suspended sediments in the runoff sample the following formula shown in equation 0-1 can be used:

$$C_{avg} = \frac{\left(\frac{S_m}{1000} * C_s\right)}{V} \qquad \textit{Eq. B-1}$$

where:

C_{avg} = concentration of the sieved particles [mg/l]
S_m = dried mass of the sieved particles [g]
C_s = concentration of the constituent in sieved particles [mg/kg]
V = volume of the sieved sample [l]

Particle shape

Rodriguez et al. (2013) recognized that several authors developed various methods to identify the shape of a particle. The latter includes the form and roundness. While spherical particles are identified by their size, meaning diameter, irregular shaped particles have a variety of definitions. Here, particles can be only characterized by adding information about the particle shape as well (Olson, 2011). Furthermore, Ma (2001) stated that since particle size and shape are related, both parameters impact many processes. Compared to the size of particles, for the determination of the shape, not only the radial but also azimuthal intensity distribution is crucial.

Over the past years, different techniques to measure this parameter have been introduced. One of them, mainly used in times before computers were used, is the sieving methodology. Here, the flakiness and elongation of particles is determined. This technique however is limited by the particle size due to practicality and thus not suitable for fines. Rodriguez et al. (2013) specified the particle size range to be suitable for this method to be within 4 to 63 mm. This approach is composed by a twofold sieving process, that finally leads to the flakiness index of a particle. First, the particles are sieved on size and then bar sieving is applied. The latter helps to find the shortest axis diameter. Another technique demonstrated by Rodriguez et al. (2013) is the chart comparison where a qualitative chart of images with six roundness and two sphericity characteristics is used to determine the shape of the particle. Here, a disadvantage is the subjectivity of the observer, when comparing particle to these images.

More recently, the analysis of images through computers has been introduced, which can be applied to the older sieving method (Rodriguez et al., 2013). Carter & Yan (2005) mentioned that this approach allows the simultaneous detection of particle size and shape. They highlighted that a variation in shapes results in a different surface area of the 3D image. In this way important information about the surface area as an area available for reaction to take place is delivered. Shapes can be described either by using a 2D or a 3D analysis. While the 2D analysis focuses on the outline of the particles, the 3D analysis delivers 3D scan or images in a two orthogonal way. This method can save on time since automatization is possible. There are various methods to process these photographs, amongst these the most advanced one is 3D laser scanning. While Rodriguez et al. (2013) emphasizes that the orientation is rather irrelevant in case a big amount of random particles are involved. The accuracy on the contrary, is impacted by the resolution. The higher the latter, the more accurate the results. The downside however is the time required to achieve this.

Based on his review, Rodriguez et al. (2013) could not conclude whether a 2D or 3D descriptor is better. However, he clearly stated that the analysis through images results in fast and repeatable results even though this tool is objective.

Olson (2011) and Rodriguez et al. (2013) categorized particles into three sub-quantities that describe them into more detail. All of these three categories describe the shape of the particle but in different scales. The largest scale the particles are described according to their form (Olson, 2011) or sphericity (Rodriguez et al., 2013). This scale reflects the geometric proportions of the particle and will be referred to as spherical, platy, elongated etc. The next smaller scale rather highlights irregularities, focusing on roundness and the particles angularity. Finally, the smallest scale, focusses on the surface condition, hence the roughness or smoothness.

Particle density

For most of the studies (Boogaard, 2015; Ferguson & Church, 2004; Li et al., 2006; Lin, 2003) it is assumed that all particles have a density to that of quartz of 2650 kg/m^3 and of spherical shape. However, Lin (2003) stated that this is not representative since there is a variety of sediment sources in urban areas that influence the density. This variation in density as well as the percentage of mineral content, linearly impacts the velocity of sedimentation of the particles (Andral et al., 1999).

Therefore, the density of the sediments in stormwater is often determined in the laboratory. Hereby, the analysis is done with a helium pycnometer, using the inert gas helium (Andral et al., 1999; Lin, 2003). This device determines the actual volume of each fraction under investigation by measuring difference in pressure. To do so, a specific known reference volume (V_R) of the gas under pressure is directed towards a sample cell containing the sediments. Throughout the process, the pressure is measured, and the differences are recorded. In this way, the volume of the solids can be obtained by using the following formula (Eq. 0-2)

$$V_s = V_C - V_R * [\frac{P_1}{P_2} - 1] \qquad \textit{Eq. B-2}$$

where:

V_s = sample volume in the pycnometer [m^3]
V_C = cell volume in the pycnometer [m^3]
V_R = reference volume in the pycnometer [m^3]
P_1 = initial pressure in pycnometer [psi]
P_2 = final pressure in pycnometer [psi]

Following this step, the density of the particle can be computed by using the following equation (Eq. 0-3):

$$\rho_s = \frac{M_s}{V_s} \qquad \textit{Eq. B-3}$$

where:

ρ_s = particle density [kg/m³]
V_s = sample volume in the pycnometer [m³]
M_s = mass of the sample determined prior to the pycnometer [kg]

According to Lin (2003) the density of sediments smaller than 425 μm was relatively consistent within the range of 2200 – 2600 kg/m³ . The findings of several other studies are summarized in table 0-2.

Table B-2 *Stormwater sediments size ranges and their respective density range.*

Size range [µm]	Density [kg/m3]	Sampling and experimental methods	References
< 50	2380 - 2650	Manually collected from channel	Andral et al., 1999
50 – 100	2530 - 2860		
100 - 500	2500 - 2820	Wet filtration – oven drying at 105°C	
500 – 1000	2510 – 2700		
All sizes	2200 - 2270	Manually collected from traps installed in the bottom of a detention basin	Jacopin et al., 1999

Heavy metals

According to Erickson et al. (2013) lead, zinc, copper, and cadmium are the most common metals encountered in stormwater. There are two different types of metals in stormwater. One of them is the total concentration, being present in unfiltered samples. The second concentration is the dissolved, where the sample is filtered through 0.45 µm filters. In this state the metals are biologically available. Erickson et al. (2013) recommends detecting both, total and dissolved metals, by first releasing the metals that are bound to particles with a strong acid or oxidants. Once these metals are dissolved, they appear in solution and can be further analyzed by atomic adsorption spectrometry or inductively coupled plasma mass/emission spectrometry (ICP-MS or ICP-ES). While the method using atomic adsorption analyses one element after the other, the ICP-MS has the advantage to measure various components at once. The latter was successfully used in many different studies amongst other by Allabashi et al. (2019), Boogaard (2015), Furumai et al. (2002), Gunawardana et al. (2012) and Morquecho et al. (2005).

ICP-MS is used for the analysis of trace elements in solution in the concentration range between µg/l to ng/l. The method allows the simultaneous determination of all metals and some non-metals from acidified, aqueous solutions. The maximum possible total dissolved concentration is of about 1 g/l. In this analysis, the sample is introduced into an inductively coupled argon plasma via a pneumatic atomization system. At a temperature of 5000-10000°C in the plasma, the sample droplets are decomposed, vaporized, atomized and ionized very fast while plasma is built. The ions, that are generated in the plasma, are then accelerated in the direction of the mass spectrometer's analyzer. There the individual elements and their isotopes are measured. To determine the element content of a solution quantitatively, the instrument is calibrated with synthetic solutions of known content. The final results are then checked by using commercially available reference solutions.

Nutrients

When referring to nutrients in stormwater, literature talks about phosphorous (P) and nitrogen (N), both present in many forms. Phosphorous in stormwater is typically referred to as total P, which can be further divided into a particulate and dissolved fraction. This is done by filtering the sample through a 0.45 μm filter. Similar to phosphorus, also nitrogen is available in stormwater as total N. Hereby, according to Erickson et al. (2013), the common forms include particulate N, dissolved organic N (DON), nitrate (NO3-), nitrite (NO2-) and ammonium (NH4+). From these forms, nitrate is the most soluble, resulting often in contamination of water bodies (Erickson et al., 2013) .

Total P can be assessed by techniques using strong acid digestion on unfiltered samples and determining the concentration of P using a colorimetric method. This method was for instance used by Vaze & Chiew (2003) in combination with spectroquant P and N test kits. They stated that these two methods are widely used all around the world in water and wastewater analysis and achieve highly accurate results. Dissolved as well as particulate P are determined in filtered samples. In order to choose the right technique, it is important to know which form of P is encountered. These forms of P also influence the efficiency in removal of these. While the removal by sedimentation or filtration is able to capture particulate P, dissolved P will not be captured. Furthermore Erickson et al. (2013) mentioned that within stormwater treatment facilities, the form of P can change and transform, resulting in the need to assess fractions.

For nitrogen on the other hand, there is not a standard technique to analyze the substances. Usually, organic nitrogen (particulate N and DON) is converted to ammonium by digesting the samples using the Kjeldahl digestion (Erickson et al., 2013). This will give a certain concentration of ammonium which will be referred to as total Kjeldahl nitrogen (TKN). The TKN is hence composed by the organic N and the previously present ammonium in the sample. To finally get a number of total N, the TKN is added to the nitrate and nitrite.

IV. Flow measurement devices

Primary flow measurement

A primary flow measurement device is a method to determine the flow rate by using a flow control structure. In this way a geometric relationship between the depth and the rate of the flow is created. The depth of the flow, also called head, as well as the flow rate can be further used to mathematically compute the volume through the system. Salguero (2015) mentioned that such primary devices can be seen as heart of a continuous flow measurement. Important examples of such primary devices are illustrated by Church et al. (1999), Salguero (2015), Kilpatrick & Kaehrle (1986) and US EPA (1992). These include for instance weirs and flumes that use a stage-flow relation to continuously monitor the flow. While weirs are structures imbedded in the channel and cause water to overflow their crest, flumes convey water through their geometrical structure. Additionally, venturi and orifice type meters using the relationship of pressure and flow can be seen as primary devices. Other important primary methods are the electromagnetic (or magnetic-inductive) and acoustic methods, that use the change in voltage or sound waves, respectively. The latter appears to have problems measuring if suspended solids, debris or air bubbles are present and may interrupt the pipe of the sound signal (Church et al., 1999). Kilpatrick & Kaehrle (1986) expressed the concern that stage and head measurements in combination with flowmeters are not appropriate methods for stormwater sewers. The reason for this is the limited available space. In several studies (Kilpatrick & Kaehrle, 1986; Kilpatrick et al., 1985; Rommel & Helmreich, 2018; Wichern et al., 2017), the magnetic-inductive flowmeter has proven to be an appropriate device to measure flows.

Secondary flow measurement

Secondary devices, on the other hand, typically measure flow rate and volumes automatically. They are commonly used in combination with a primary device since they can provide data about the changes in flow depth (head). Using mathematical relationships, the collected data about the head can be transformed into flow rates and flow volumes (US EPA, 1992). These devices include all sensors used to determine and process the particular hydraulic response of the primary device (Salguero, 2015). Salguero (2015) mentions that sensors such as ultra-sonic transmitters, floats, pressure transducers, capacitance probes, differential pressure cells, electromagnetic cells, etc. to be typically used. Electronic sensors rely on the relationship of electric voltage and flow rates. Instead, acoustic (sonic) sensors measure the time of travel of a sound that is emitted and reflected back from the water surface. The latter does not need any contact and hence does not disturb the water flow.

V. Impacting factors on the settling velocity

Comparing the settling velocities computed by Stoke and Ferguson & Church

Figure B-1 by Erickson et al. (2013) depicts the difference in the settling velocities computed by the just mentioned approaches. Hereby, the particle density or sand (=2.65 g/cm^3) and the respective value for C (=1) as well as a temperature of 25°C was used.

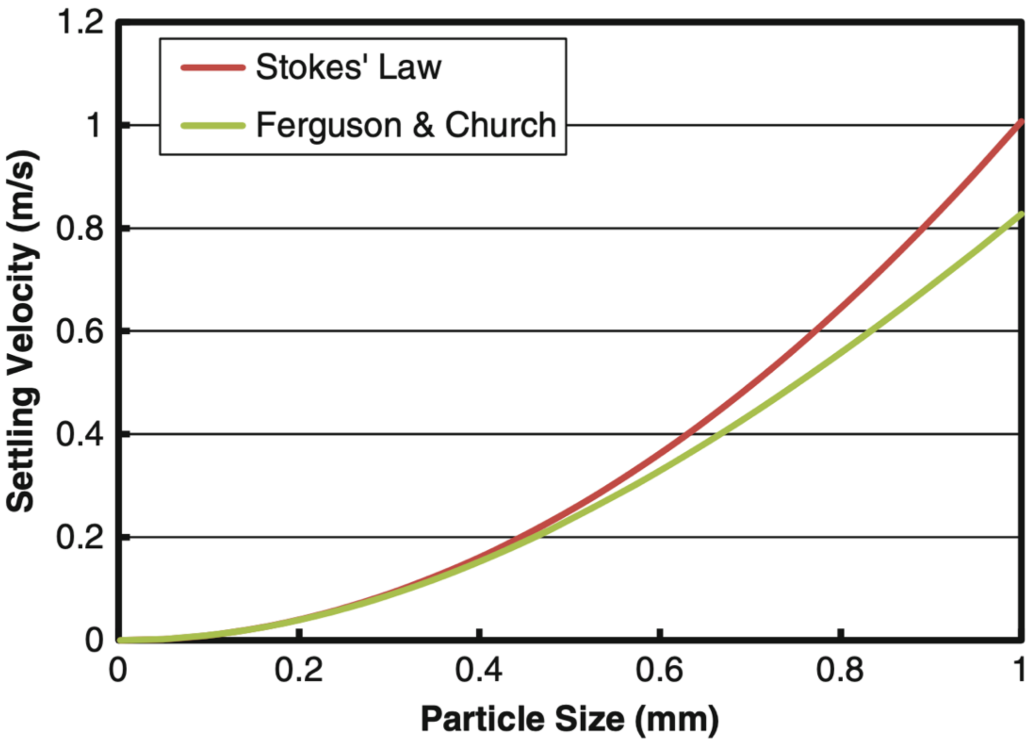


Figure B-1 *Comparison of settling velocity determined by Stokes' Law and Ferguson and Church.*

The impact of the flow conditions on the settling velocity

The turbulent flow conditions of stormwater result in a balance of sediments in motion and settled state. In general, the settling process of particles is disturbed by these turbulent eddies and so reduced (Erickson et al., 2013). In contrast, under plug flow conditions, no particles mixing inside the treatment facilities is assumed. According to Erickson et al. (2013) stormwater experiences conditions somewhere between turbulent and plug flow. Figure B-2 compares the impact of different flow conditions on the settling and hence removal efficiency for two different rainfall intensities. While case 1 uses a rainfall intensity of 15.5 mm/h, case 2 uses 40.1 mm/h. In both cases the sand was used to determine both, particle density and C (2.65 and 1, respectively) while the temperature was set to be 25°C.

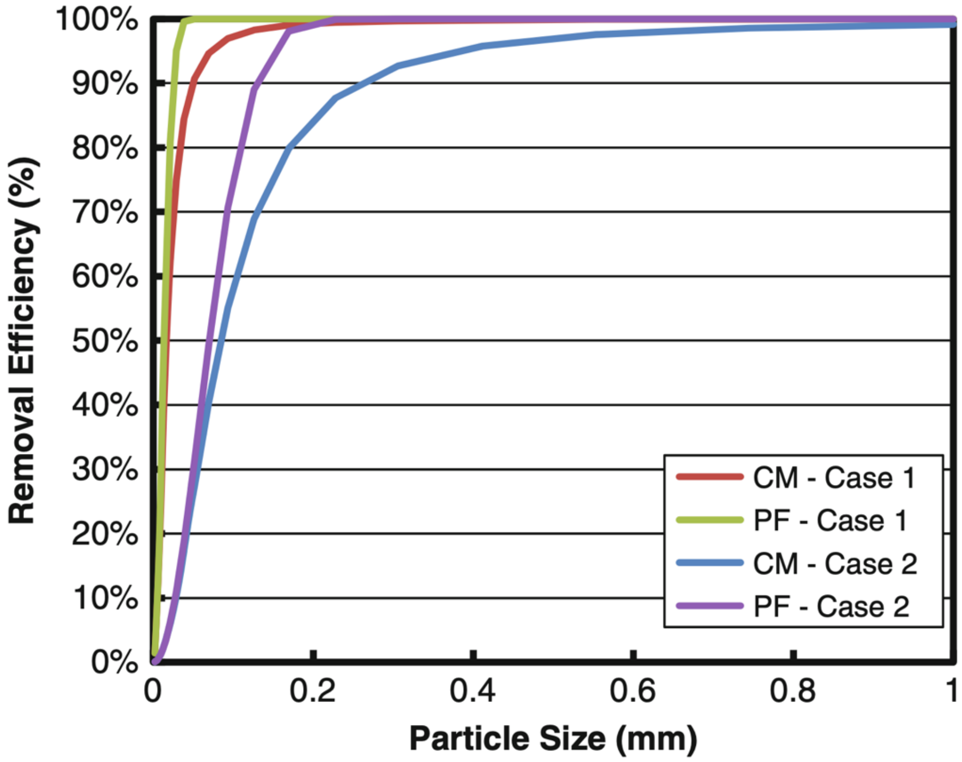


Figure B-2 *Impact of mixing on the removal efficiencies (CM=completely mixed; PF=plug flow) by Erickson et al. (2013).*

Comparing both cases, it can be seen that the plug flow condition results in better removal efficiencies. Furthermore, smaller rainfall intensities also positively impact the particle removal by the system.

C - Site description and installed facilities

I. Amsterdam Rainproof measures

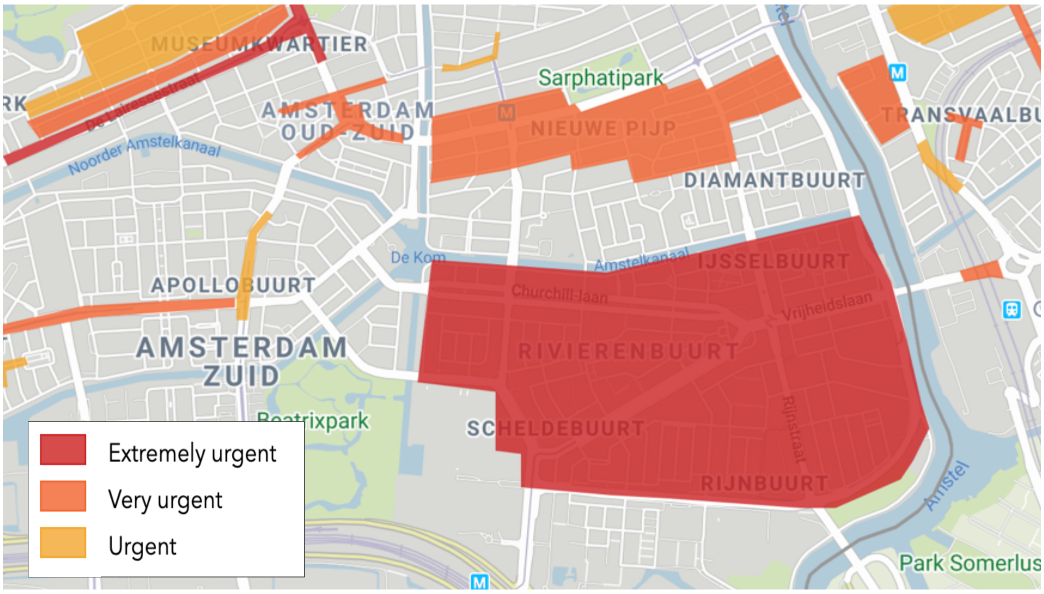


Figure C-1 Bottlenecks in Amsterdam-Zuid according to Amsterdam Rainproof.

Over the past years, the Rivierenbuurt is being gradually equipped with several rainproof measures. This is done to adapt the area to the expected increase in pro-longed and more intense showers. Figure C-1 illustrates the encountered bottlenecks in this area of Amsterdam, highlighting the urgency of taking action in the district in investigation. In the course of this, sustainable drainage solutions such as bioswales, permeable pavements, green areas or infiltration facilities have been installed to drain and store the excess water. The study area between Maasstraat and Waalstraat is equipped with an infiltration facility, allowing water from the area to be stored and later infiltrated through a layer of coarse material (figure C-3). After that, the water will be discharges into the closest surface water, namely the river Amstel in the east of the area as well as the surface water behind the RAI. In this way, the inspected road segment and its connected area are decoupled from the remaining conventional drainage system installed in the district.

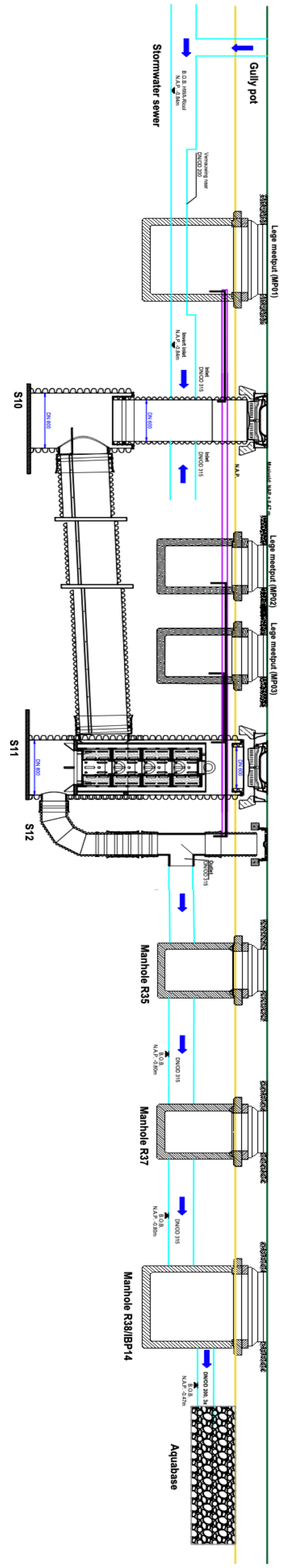


Figure C-2 *Schematic overview of the water flow through the system.*

About 25.6 ha of connected surface area, composed by the roofs, the ventweg, the greean areas, the bike lane as well as the main road, will be inclusively infiltrated through the infiltration system AquaBASE. Only the water from the tram tracks will not be drained towards this facility. Instead, this water is directly drained to the foul sewer, since it is polluted by heavy metals and oil and should not be infiltrated.

In case the water levels are too high, this drainage system would cause flooding on the streets and houses. Therefore, eight emergency overflows are installed. These allow the water to spill from this decentralized system to the surrounding stormwater system. The two systems are separated by an adjustable weir, that makes sure the water only flows towards the neighboring sewer system if it exceeds a certain level. In this way, under normal conditions, all the water within the study area will be drained towards the AquaBASE. Here it can be temporarily stored, infiltrated and eventually discharged via the groundwater to the surface water. During dry periods on the other hand, the height of the weir can be lowered, allowing water from the surrounding area to enter and restore the low groundwater levels in the area of study.

AquaBASE

The infiltration system installed in the study area is called *AquaBASE* and provided by the eponymous Dutch company. The AquaBASE (figure C-3) is installed underneath the tram tracks only in the part of the Rooseveltlaan that stretches in between the Maasstraat and the Waalstraat. The system creates a stable hollow space, that allows for water to be stored and subsequentially infiltrated while keeping a high load-bearing capacity in the structure. The providing company promises an initial infiltration speed of about 770 l/s/ha. The stability of the system is achieved by a patented geotextile (TenCate Accorder®) consisting of approximately 5.5 cm high compartments and a parallelogram-shaped surface. On top of this geotextile, a layer of aggregate minerals (EcoBASE A5) of 8 to 32 mm diameter is placed. With a porosity of 34 %, this hollow space gives plenty of volume to store and buffer water. The surface of the geotextile is able to lock up the collapsed mineral aggregate better. In this way the construction layer is more rigid and provides better resistance to permanent deformation. Around these two layers, a fleece (TenCate Polyfelt®) is used to separate the various components of the AquaBASE system and to prevent the rinsing of fine particles. In this way the AquaBASE can retain its hollow space. On top of that, another layer (EcoBASE B3) of approximately 5 cm is applied as basis for the actual surface of the road. This layer consists of 2 to 8 mm big material and provides another hollow space of 33 %.

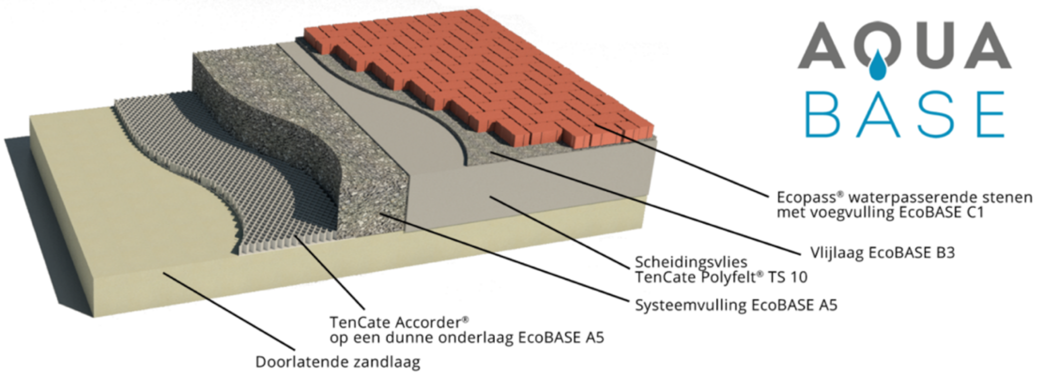


Figure C-3 *Schematic visualization of the components of the AquaBASE (AquaBASE).*

In our case, the AquaBASE is installed directly underneath the tram tracks (figure C-4). This means that the top surface is made out of concrete and does not allow any infiltration. Hence, the water that will be introduced to the infiltration facility will be only coming in by the drainage pipes from the sides. These pipes drain the stormwater from the connected surface area towards the system. The AquaBASE in the Rooseveltlaan has a length of 290 m, a width of 7 m and a depth of 0.55 m. Considering its porosity, the AquaBASE has a storage capacity of approximately 380 m^3.

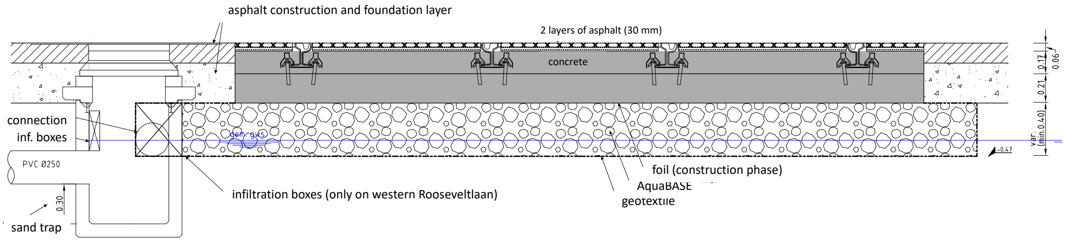
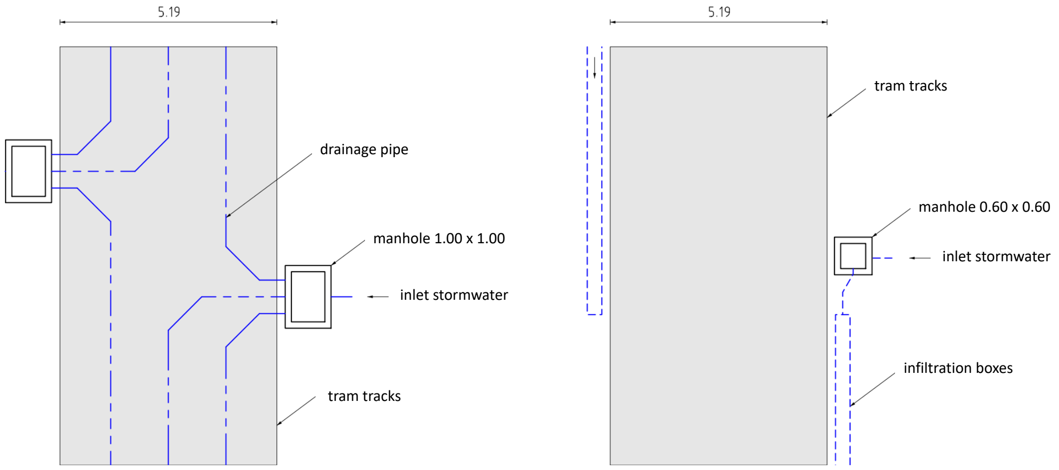


Figure C-4 *Cross-section of the tram tracks in the Rooseveltlaan.*

Connection to the AquaBASE

There are two different inflow designs (figure C-5) in this section of the road. On the western side of the road, the stormwater first enters infiltration boxes. The inlet pipe towards these have a diameter of 250 mm. These boxes then evenly spread the flow over their length and from there drain into the AquaBASE. The manholes that are connected to these infiltration boxes are squared with sides of 0.60 m. On the eastern side of the Rooseveltlaan, three drainage pipes with a diameter of 200 mm directly feed the gravel layer. Again, this guarantees a good distribution even inside the AquaBASE. The manholes installed in front of these three drains are rectangular and have the dimension of 1.00 x 1.00 m.



connection with the AquaBASE
through drainage pipes

connection with the AquaBASE
through infiltration boxes

Figure C-5 *Bird's-eye view of the connection between the manholes and the AquaBASE.*

Design of the pre-treatment

This section will elaborate on the pre-treatment steps that will be installed in the stormwater system. It will elaborate on the SediSubstrator as pre-treatment using the sedimentation process.

SediSubstrator L in the study area

In the study area, a SediSubstrator L will be installed at four different locations to filter out parts of the incoming pollution from the stormwater. This treatment facility exists in different sizes, varying in length from 6 to 24 m and in diameter of 600 mm. This specific product is chosen, because the laboratory test of Boogaard (2015) showed that only larger sedimentation devices such as the Sedipipe (similar principle tu SediSubstrator) can catch particles over 60 µm with an efficiency higher than 80 %. To achieve even better results and filter out the fines remaining in suspension by filtration, the SediSubstrator L is chosen. The reason for this choice is the filter option provided by within the cartridges in the end shaft.

The water that is flowing through these treatment facilities is drained from the roofs, sidewalks, green areas as well as the ventweg. It will first enter the gully pots on the sides of the ventweg, before it flows through the stormwater sewer into the SediSubstrator. The sedimentation pipes are installed right before the manholes that feed the AquaBASE. The stormwater that will accumulate on the main road and the bike lane instead, is directly drained to the manholes that feed the infiltration system. This water is not pre-treated by the SediSubstrator.

Adjustments of the SediSubstrator design

In order to be suitable for the study area, some adjustments on the original design of the SediSubstrator are needed. This is mainly due to the installation depth of about 4 m, which represents a rather deep installation for subsoil infrastructure in this area in Amsterdam. Too deep installation heights will require enormous excavation work and may cause damage to the wooden pile foundations. The latter might be caused due to the temporary change in groundwater level. Therefore, the installation depth was shortened in collaboration with Fränkische Rohrwerke and extends now to a maximum of 3 m in depth. This represents an installation depth of -2.54 and -3.106 m NAP for the start and end shaft, respectively. Furthermore, to still allow the filter cartridges to be used, the whole construction of these was shifted upwards inside the end-shaft of the SediSubstrator. To allow for more space for the cartridges, the overall diameter of the shaft will be enlarged to from DN600 to DN800. Only the very top part will build with a diameter of DN600 to guarantee standard manhole covers to be used. Additionally, to that, the top cartridge will not be sealed in the top. This allows the water to overflow the filter material in case the pressure builds up too much. Lastly, the inlet as well as the outlet pipe from the start and end shaft, respectively, will be placed in the same height as the current stormwater drainage with respect to the surface level. In this specific case, this represents a total depth of -0.84 m NAP. The adjustments of the system can be seen in figure C-6.

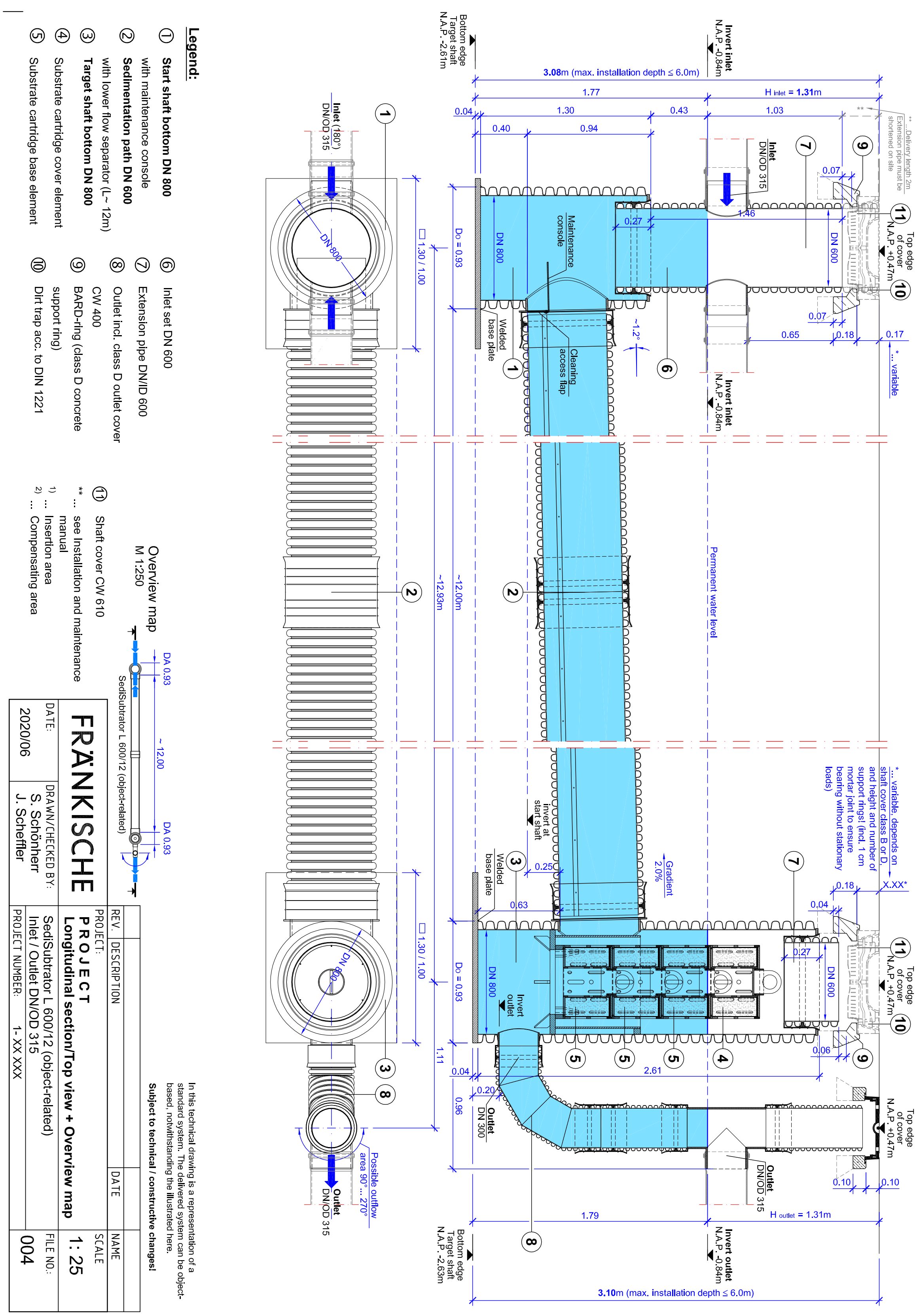


Figure C-6 SediSubstrator design in the study area, adjusted system by Fränkische Rohrwerke.

Filter material of the SediSubstrator cartridges

As mentioned earlier in this subchapter, the last part of the SediSubstrator L treatment facility works on the principle of filtration. Here, a filter material made from iron hydroxide is in charge of removing fine particles and adsorb its attached pollution. The material, called SediSorp, is stored in cartridges in the shape of a donut. Several of these cartridges are stacked above each other allowing a big surface area to treat the water. The whole cartridge construction (figure C-7) is placed inside the end shaft of the system inside a cladding tube. The latter actually has two functions. Firstly, it ensures that the water from the sedimentation pipe itself first flows against a vertical baffle wall from where it then gets evenly hydraulically distributed within the cladding tube. In this way, it can be ensured that the cartridges are equally charged with the pollution circumference from all sides. The particles will be distributed on the entire filter surface instead of mainly impacting the stream facing side. Furthermore, this cladding ensures a centric introduction of the cartridge when they are being inserted from the top of the shaft.

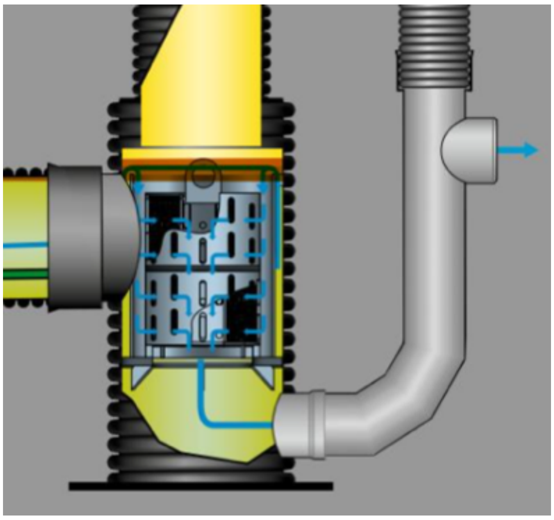


Figure C-7 *End shaft with filter cartridges within the SediSubstrator L (Fränkische Rohrwerke).*

The main aim of Amsterdam is to filter out the stormwater sediments to prevent clogging of the drainage system. The original design instead, customized to the German preferences, additionally focusses on the absorption of pollutants such as heavy metals itself. Therefore, the filter material can be replaced by other materials to achieve these objectives. This could be done by removing the SediSorp material and replacing it by any material that seems to fit. However, it needs to be assured that the entire drainage system can cope with the hydraulic resistance introduced by such changes. The estimated hydraulic resistance of the SediSorp material can be seen in figure C-8. An idea for a different filter material and the special effects that can be potentially achieved by its use will be given below.

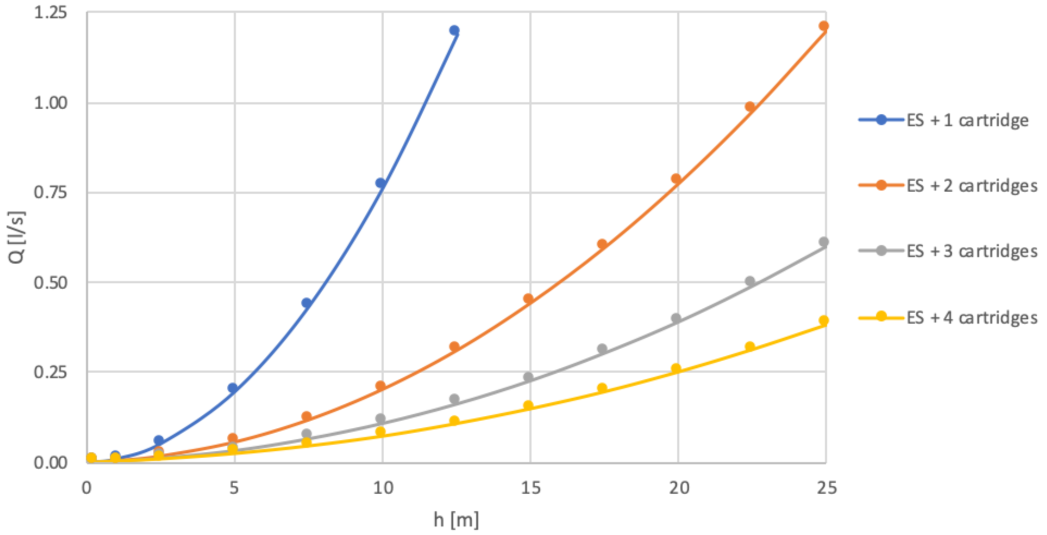


Figure C-8 *Q-h relationship within the end shaft for different scenarios (Fränkische Rohrwerke).*

Alternative filter material: Fuzzy filter balls

As mentioned in § 4.1.2 the SediSorp filter material can be replaced by any other material. An alternative filter media that could be used are filter balls, used in different sectors such as the wastewater industry or to clean the water from swimming pools. Several providers such as Bosmann (FuzzyFilter), FilterBalls and many more sell these balls made from fiber media (figure C-9). These filter balls can be removed once clogged, back-washed and reused. Due to their light and porous structure, they can be compressed and so achieve a better filter capacity. The level of compression is achieved by filling the cartridges with more or less balls and hence can be adjusted to the needs.

Figure C-9 *left: FuzzyFilter (Bosmann); right: FilterBalls (FilterBalls).*

The principle of the usage of filter balls as a filter media within the cartridges in the end shaft of the SediSubstrator L is illustrated in the schematic images below (figure C-10 & C-11 & C-12). Modular cartridges are installed in the end shaft of the SediSubstrator. The round cartridges are well perforated at all sides, allowing the water to flow through easily. The hollow center, which is perforated as well, guides the filtered water downwards to the bottom of the SediSubstrator. From there, the treated water will continue its way in the drainage system.

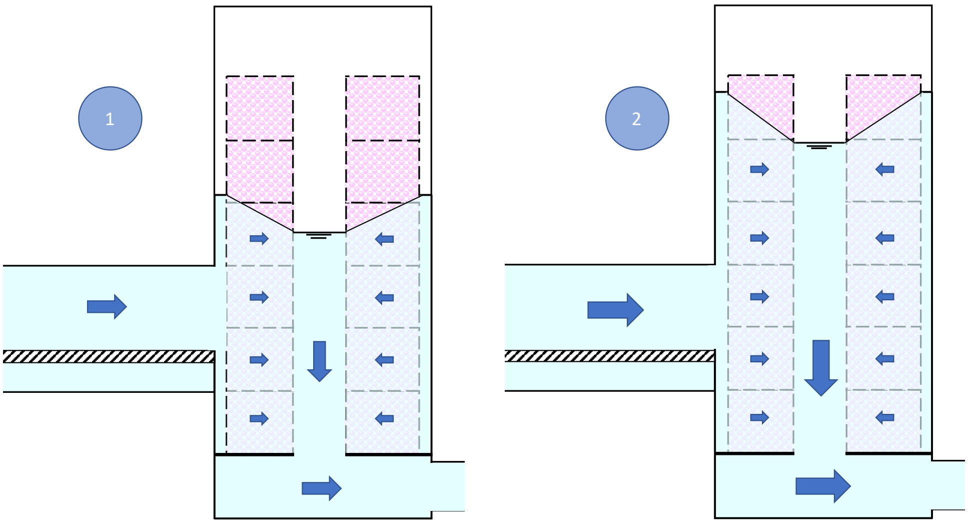


__Figure C-10__ End shaft with stacked cartridges, filled with filter balls.

The compression of the balls is variable and should be priory determined experimentally. The higher the compression of the filter material, the finer sediments can be retained. However, simultaneously this will also lead to more resistance for water flowing through the filter. Furthermore, there is an option to vary the compression of the various stacked filter cartridges. For instance, the material within the lower cartridges could be compressed more intensively compared to the top cartridges. The water from the sedimentation pipe of the SediSubstrator will flow into the vertical end shaft. Then, it continues its way through the perforated cartridges where the compressed filter balls retain suspended solids and so clarify the water. In case the stormwater discharge volumes exceed the capacity of the filter system, the water outside the cartridges will rise higher than these. Here, this excess water will have the opportunity to directly flow through the hollow center of the cartridges from above, without passing the filter material. In this way, an emergency overflow is available, aiming for no backwater of flooding to be caused by the increase in resistance by the filter media. In case there is no stormwater discharge for a longer period, the captured organic material can be potentially oxidized within the filter media.

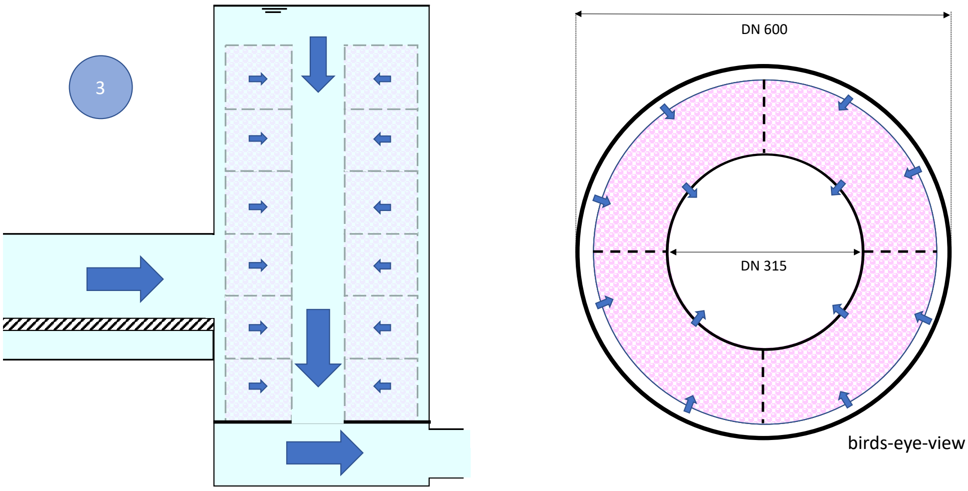


__Figure C-21__ left: End shaft during high stormwater discharge volumes, functioning of the emergency overflow; right: birds-eye view of the donut shaped filter cartridges.

The cartridges should be replaced regularly, to clean the filter balls. To do so, the cartridges should be removed from the end shaft first, be back-washed and replaced once clean.

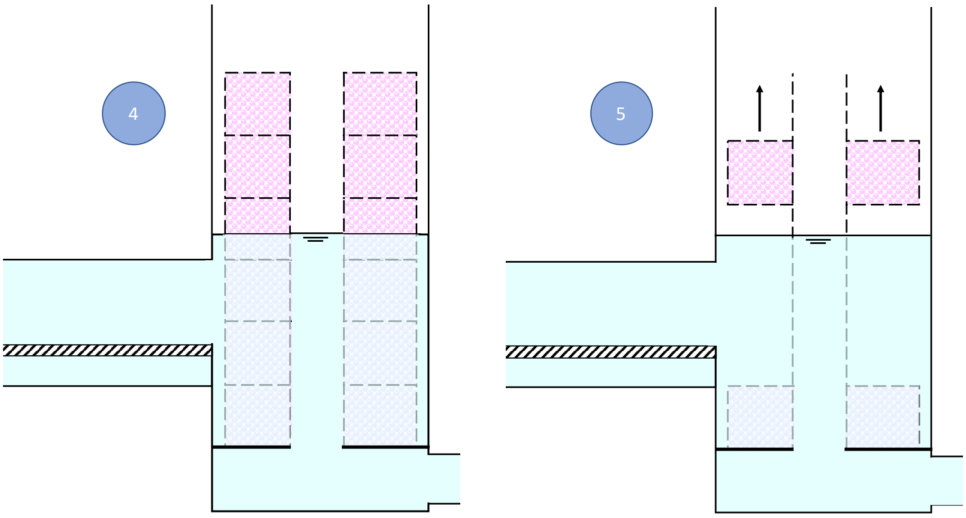


Figure C-32 *Removal of the clogged filter cartridges to back-wash the filter balls.*

D - Bed sediment sampling & laboratory analysis

Figure D-1 *left: location manhole; middle & right: location gully pot.*

Figure D-2 *right: sampling location of the stagnant water in manholes (Google Maps); left: targeted manhole.*

Figure D-3 *Blocking of the road to take samples following the Waternet safety protocols.*

Figure D-4 *left: shovel; middle: sampling bottle (550ml); right: sampling bottle (1l).*

Pre-treatment of the samples

To perform either of the two analysis, the sample needs to be first pre-treated (figure D-5) by removing the particles that are bigger in size than 2 mm. This is to protect the devices from damage caused by larger sand particles and debris and to avoid disturbances of the measurement. Therefore, the sample will be sieved through a sieve with a mesh size of 1.8 mm to be on the save side. All the particles above this size will not be analyzed for the particle size and settling velocity. Parts of this sample will then be analyzed in the Blue wave device. The determination of the particle size distribution will be repeated three times, since the device itself already loops the sample through the laser unit three times.

Figure D-5 *left: sieves 0.075 and 1.8 mm; right: pre-treatment of the samples by sieving.*

The rest of the sample will be again sieved through a sieve with 75 µm big openings. This mesh size was the smallest available sieve at the Waterlab. The sieving through such a small filter is necessary to take out the smallest sediments that are assumed not to settle within a timeframe of one hour. Any particles smaller than 75 µm will be discharged. The filtered sample will be finally analysed for the settling behaviour. For more representative results, the settling velocity will be assessed 3 to 4 times in a row.

Functioning of the settling velocity apparatus

The apparatus determines the settling velocity by weighing the particles that fall within a certain time inside a water-column of a specific height. The apparatus is composed by a transparent pipe with a diameter of 0.16 m and a height of approximately 2 m, positioned in a vertical way. While the sludge sample is introduced from the top, is will be discharged at the bottom at the end of the experiment. The lid of the transparent pipe is equipped with a weighing device that sends a signal to the connected software in a specific frequency. This signal represents the time a particle takes to reach the attached unit at the bottom, the weighing pan, as well as the incremental measured weight. The latter is a round plate with the same width as the inner diameter (0.15 m) of the pipe. It is connected via a long robust stick to the weighing unit at the lid. Additionally, to the already mentioned parts, a switch is connected to send a signal to the computer once the particles have been introduced to the water column.

Before starting the experiment, a computer needs to be connected to the apparatus in order to receive the test results. At the same time, the settling column can be already filled with water. This transparent pipe represents the water column within which each particle will settle within a certain time. In this case, process water is introduced until the top of the column, which is determined to be at a height of 1.88 m. Then, the weighing pan is introduced to the column. A screw mechanism attaches the stick of the weighing pan to the actual weighing unit. Finally, the lid is placed on top. The next step is to measure the temperature of the water column, since this impacts the settling velocity. Once the column is fully filled, all the devices are attached and the temperature is determined, the experiment can be started. First, the data acquisition software for Excel (PLX-DAQ), that is installed on the computer, needs to be activated and connected. Then, a cup of approximately 150 ml is filled with sludge from the sample. The content of this cup will be then tipped into the water column, helping the rather sticky sediments to detach by using a metal spoon. At the same time, the switch needs to be activated to send a signal to the computer. In this way the software knows that the measurement has started, and particles have been introduced at the top of the column. From that moment onwards, around 20 signals per second will be send from the weighing pan to the computer. The particles that will be introduced from the top will reach the weighing pan in a certain time. The accumulation of the settled mass will be registered and determined over time. As soon as the measured weight reaches a relatively constant value, the experiment can be ended.

Proceeding of the data

Every signal will send the (incremental) weight at that specific time to the system. This data will be processed using MATLAB, transforming it into a settling velocity with respect to the weight. First, the measured weight is translated into a relative mass by dividing the weight as a specific timestep by the weight at the end of the experiment, hence the total accumulated weight. The settling velocity instead is computed by dividing the height of the water column [m] by the settling time [s]. In this way, the relative mass can be plotted against the settling velocity [m/s].

Modified fouling index (MFI) device

The Modified (or membrane) Fouling Index (MFI) is a useful tool to determine the fouling rate of water on membranes (van Duijvenbode & Olsthoorn, 2002). The value is proportional to the amount of particles within the water and therefore gives insight into the tendency of physical clogging by suspended particles (van Zoeren, 1992). The MFI method is derived from the comparable Silt Density Index (SDI). It uses a specific filtration volume for each time unit throughout the experiment to determine the index. Compared to the SDI, where only the initial as well as the final volume are compared, this method gives a linear relationship between the MFI and the concentration of particles. The bigger the MFI, the greater the potential for physical clogging.

The water sample is pressurized using a pump (207 kPa) and is kept at this constant pressure. Since the pressure will be held constant, the occurrence of fouling will result in a decrease in initial flow. This analysis gives information about the clogging of the 0.45-micron pores.

Figure D-6 *left: Inspector SDI/MFI (Convergence); right: bucket with the water sample and hose.*

The analysis of the water sample using the MFI can provide information on the tendency of the water leaving the SediSubstrator to clog the infiltration system installed in sequence. Up to now, Waternet uses this device to determine the MFI for water that will be introduced into infiltration wells. In order to protect these from clogging, the MFI for this water is supposed to be below 3 s/l^2.

Results of the MFI measurement

The stagnant water being present in the manhole above the bed sediment was analyzed for the MFI as well as the amount of suspended solids (TSS = 14 mg/l). Using the MFI Inspector, the tendency of clogging by the analyzed water is determined. Compared to studies on the MFI performed by Waternet on pre-treated surface water, the values for the stagnant water of the manholes are noticeably higher. The pre-treated surface water is only suitable for infiltration through infiltration wells if the MFI is in between 3 to 5 s/l^2. These infiltration wells are located in rounded dune sand (150 µm) with a gravel pack around the filter screen of the well. The analyzed water from the manhole however, showed values in between 145 and 155 s/l^2. Comparing the material where the water is being infiltrated, the AquaBASE is composed by gravel of 2 to 32 mm in diameter. This composition is for sure not entirely comparable, however the accumulation of fines can also lead to clogging of the coarser gravel layer of the AquaBASE. A comparison of the clean and clogged filter membrane can be seen in Appendix F.

All in all, the MFI Inspector is a fast and cheap method to determine the tendency of clogging. However, it is not the most appropriate device to be used with stormwater. The membrane of 45 microns clogs almost immediately and does not give a useful insight on the water properties itself.

E - Results from the laboratory

Analyserapport

Waternet, TOP
Watertechnologie
T.a.v. mevrouw I. Goess-Enzenberg
Postbus 94370
1090 GJ AMSTERDAM

Datum:	**Rapportnummer:**	**Uw Kenmerk:**
20-07-2020	362634	267806 / 278042
Project:	**Monstername door:**	**Uw projectcode:**
dooea001/1111, Rooseveltlaan, Amsterdam	Opdrachtgever	P00.9845/001/400

Geachte mevrouw Goess-Enzenberg,

Hierbij zend ik u de resultaten van analyses die op uw verzoek werden uitgevoerd.
Deze resultaten hebben alleen betrekking op de monsters, zoals die door u ter analyse werden aangeboden.

De werkzaamheden zijn, tenzij anders aangegeven, uitgevoerd overeenkomstig het document 'Producten en dienstencatalogus Stichting Waterproef'. Belangrijk voor de interpretatie van de resultaten is het gegeven dat analyseresultaten altijd een meetonzekerheid bezitten. Gegevens over de analysemethoden en meetonzekerheden worden u op aanvraag toegezonden.

De met een Q gemerkte analyses zijn geaccrediteerd door de Raad voor Accreditatie.

Dit rapport mag niet anders dan in zijn geheel worden gereproduceerd.

De resultaten op dit rapport zijn geautoriseerd namens de directeur van Stichting Waterproef
E. van Oorsouw.

Kopie aan:
Watertechnologie , t.a.v. de heer N. el Ayadi

Waterproef, laboratorium voor onderzoek van water en bodem.
Dijkgraaf Poschlaan 6 - Postbus 43 - 1135 ZG Edam
T 0299 39 17 00 - F 0299 39 17 17 - klantenservice@waterproef.nl

Volgnummer	**Puntcode**	**Monsteromschrijving***
591142	ox050001	Zuiveringsslib Mengmonster Kolken Rooseveltlaan
591143	ox050001	Zuiveringsslib Mengmonster HW-putten

Volgnummer	**591142**	**591143**
Monstertype*	Zuiveringsslib	Zuiveringsslib
Bemonsteringstype*	steekmonster	steekmonster
Monsternemer*	Isabelle/ Najim	Isabelle/ Najim
Datum bezoek*	01-07-2020	01-07-2020
Tijd bezoek*	07:00	07:00
Monstername datum*	01-07-2020	01-07-2020
Monstername tijd*	07:00	07:00
Acceptatiedatum	01-07-2020	01-07-2020

Fysisch- Chemische analyses						**Eenheid**
Carbonaat, volumetrisch		16		53		g/kg dg
Dichtheid van vaste matrix		1,3528		1,1779		g/ml
Indamprest van vaste matrix	Q	22,6		39,8		%
Gloeirest van de indamprest	Q	76		90		% van dg
Organisch stof gehalte		12,2	*a*	22,0	*a*	%ds
Voorbehandeling SCG kromme						
Afval		5,8		6,2		%
Grind		< 0,1		< 0,1		%
Grond		86,8		93,1		%
Puin		7,4		0,8		%
Korrelgrootte voor SCG						
Korrelgrootte <2 um, sedigraaf		< 2,5		21,3		% md
Korrelgrootte <16 um, sedigraaf		4,1		38,2		% md
Korrelgrootte <32 um		4,3		42,1		% md
Korrelgrootte <50 um		4,6		43,0		% md
Korrelgrootte <63 um		4,6		43,7		% md
Korrelgrootte <125 um		11,0		49,1		% md
Korrelgrootte <250 um		56,0		79,5		% md
Korrelgrootte <500 um		88,9		91,7		% md
Korrelgrootte <1000 um		96,7		94,9		% md

Opmerkingen

a Resultaat is gecorrigeerd met fractie 2 in % van droge stof, bepaald door Sedigraaf.

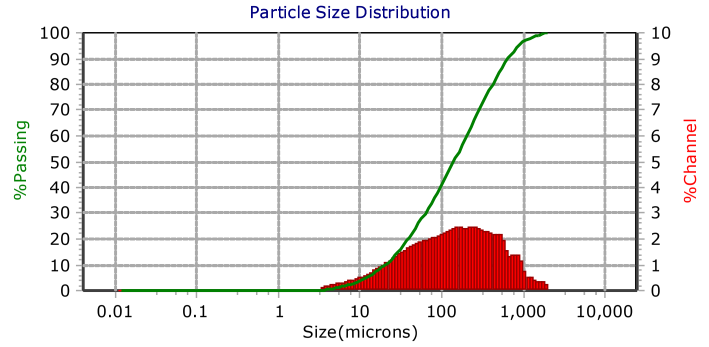
Microtrac
Total Solutions in Particle Characterization

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.2\Databases\MTDatabase.mdb

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
2000	0.23	100.00	95.97	2.11	40.02	4.63	0.21	0.74	0.2230	0.00	0.00
1826	0.33	99.77	88.00	2.06	37.91	4.24	0.20	0.53	0.2040	0.00	0.00
1674	0.33	99.44	80.70	2.03	35.85	3.89	0.20	0.33	0.1870	0.00	0.00
1535	0.36	99.11	74.00	1.99	33.82	3.57	0.13	0.13	0.1720	0.00	0.00
1408	0.42	98.75	67.86	1.96	31.83	3.27	0.00	0.00	0.1580	0.00	0.00
1291	0.49	98.33	62.23	1.92	29.87	2.999	0.00	0.00	0.1450	0.00	0.00
1184	0.54	97.84	57.06	1.87	27.95	2.750	0.00	0.00	0.1330	0.00	0.00
1086	0.74	97.30	52.33	1.82	26.08	2.522	0.00	0.00	0.1220	0.00	0.00
995.6	1.14	96.56	47.98	1.76	24.26	2.313	0.00	0.00	0.1110	0.00	0.00
913.0	1.35	95.42	44.00	1.69	22.50	2.121	0.00	0.00	0.1020	0.00	0.00
837.2	1.35	94.07	40.35	1.63	20.81	1.945	0.00	0.00	0.0940	0.00	0.00
767.7	1.35	92.72	37.00	1.55	19.18	1.783	0.00	0.00	0.0860	0.00	0.00
704.0	1.32	91.37	33.93	1.48	17.63	1.635	0.00	0.00	0.0790	0.00	0.00
645.6	1.52	90.05	31.11	1.40	16.15	1.499	0.00	0.00	0.0720	0.00	0.00
592.0	1.97	88.53	28.53	1.32	14.75	1.375	0.00	0.00	0.0660	0.00	0.00
542.9	2.19	86.56	26.16	1.24	13.43	1.261	0.00	0.00	0.0610	0.00	0.00
497.8	2.16	84.37	23.99	1.16	12.19	1.156	0.00	0.00	0.0560	0.00	0.00
456.5	2.18	82.21	22.00	1.08	11.03	1.060	0.00	0.00	0.0510	0.00	0.00
418.6	2.22	80.03	20.17	1.00	9.95	0.972	0.00	0.00	0.0470	0.00	0.00
383.9	2.26	77.81	18.50	0.92	8.95	0.892	0.00	0.00	0.0430	0.00	0.00
352.0	2.31	75.55	16.96	0.85	8.03	0.818	0.00	0.00	0.0390	0.00	0.00
322.8	2.35	73.24	15.56	0.78	7.18	0.750	0.00	0.00	0.0360	0.00	0.00
296.0	2.39	70.89	14.27	0.71	6.40	0.688	0.00	0.00	0.0330	0.00	0.00
271.4	2.44	68.50	13.08	0.65	5.69	0.630	0.00	0.00	0.0300	0.00	0.00
248.9	2.48	66.06	12.00	0.59	5.04	0.578	0.00	0.00	0.02790	0.00	0.00
228.2	2.47	63.58	11.00	0.54	4.45	0.530	0.00	0.00	0.02550	0.00	0.00
209.3	2.40	61.11	10.09	0.49	3.91	0.486	0.00	0.00	0.02340	0.00	0.00
191.9	2.39	58.71	9.25	0.45	3.42	0.446	0.00	0.00	0.02150	0.00	0.00
176.0	2.46	56.32	8.48	0.41	2.97	0.409	0.00	0.00	0.01970	0.00	0.00
161.4	2.45	53.86	7.78	0.38	2.56	0.375	0.00	0.00	0.01810	0.00	0.00
148.0	2.39	51.41	7.13	0.34	2.18	0.344	0.00	0.00	0.01660	0.00	0.00
135.7	2.34	49.02	6.54	0.31	1.84	0.315	0.00	0.00	0.01520	0.00	0.00
124.5	2.28	46.68	6.00	0.29	1.53	0.2890	0.00	0.00	0.01390	0.00	0.00
114.1	2.22	44.40	5.50	0.26	1.24	0.2650	0.00	0.00	0.01280	0.00	0.00
104.7	2.16	42.18	5.04	0.24	0.98	0.2430	0.00	0.00	0.01170	0.00	0.00



Summary	
Data	Value
MV(um):	254.8
MN(um):	6.39
MA(um):	50.17
CS:	1.20E-01
SD:	229.9
Mz:	220.7
σι:	247.8
Ski:	0.614
Kg:	1.218

Percentiles	
%Tile	Size(um)
10.00	20.25
20.00	38.67
30.00	62.60
40.00	95.90
50.00	140.7
60.00	201.1
70.00	286.7
80.00	418.1
90.00	643.8
95.00	888.7

Peaks Summary		
Dia(um)	Vol%	Width
140.7	100	459.7

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- Measurement Info -

Title	
Issabelle	
Identifiers	
Gullypot	
-	
Database Record	16305
Run Number	1 of 3
Date	7/1/2020
Time	3:17 PM
Acquired Date	7/1/2020
Acquired Time	3:17 PM
Serial Number	S6730
Sample Cell ID	0309
Calculated Data	
Above Residual	0
Below Residual	0
Loading Factor	0.7589
Trans. L1:L2	0.907:0.872
RMS Residual	0.145%
Recalculation Status	
DB-Meas : : Original :	

-SOP Info-

ISSABELLE_PSD(*)	
Timing	
Setzero Time	30 (sec)
Run Time	30 (sec)
Number of Runs	3
Multi-Run Delay	0 (min)
Delay First Meas.	Disabled
Analysis	
Sludge	
Refractive Index	N/A
Transparency	Absorb
Shape	Irregular
WATER	
Refractive Index	1.33
Options:	
Filter	Enabled
Analysis Gain	Default(2)
Analysis Mode	BLUEWAVE
Perspective	
Progression	Geom 8 Root
Distribution	Volume
Upper Edge(um)	2000
Lower Edge(um)	0.0107
Residuals	Enabled

Sample System(Wet)	
Number of Rinses	4
Flow Rate (%)	25%
Deaeration Cycles	3

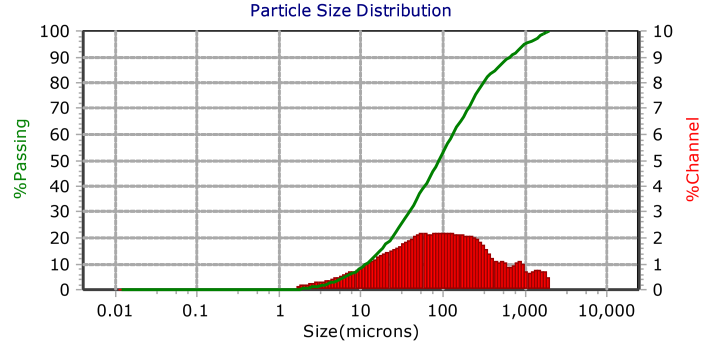
Microtrac
Total Solutions in Particle Characterization

- Particle Size Analysis -

C:\Microtrac\FLEX 11.1.0.2\Databases\MTDatabase.mdb

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
2000	0.46	100.00	95.97	2.17	51.99	4.63	0.40	3.08	0.2230	0.00	0.00
1826	0.70	99.54	88.00	2.19	49.82	4.24	0.36	2.68	0.2040	0.00	0.00
1674	0.70	98.84	80.70	2.17	47.63	3.89	0.33	2.32	0.1870	0.00	0.00
1535	0.72	98.14	74.00	2.09	45.46	3.57	0.31	1.99	0.1720	0.00	0.00
1408	0.72	97.42	67.86	2.09	43.37	3.27	0.28	1.68	0.1580	0.00	0.00
1291	0.69	96.70	62.23	2.16	41.28	2.999	0.26	1.40	0.1450	0.00	0.00
1184	0.61	96.01	57.06	2.15	39.12	2.750	0.23	1.14	0.1330	0.00	0.00
1086	0.70	95.40	52.33	2.09	36.97	2.522	0.22	0.91	0.1220	0.00	0.00
995.6	0.96	94.70	47.98	2.03	34.88	2.313	0.20	0.69	0.1110	0.00	0.00
913.0	1.07	93.74	44.00	1.96	32.85	2.121	0.18	0.49	0.1020	0.00	0.00
837.2	1.01	92.67	40.35	1.89	30.89	1.945	0.18	0.31	0.0940	0.00	0.00
767.7	0.94	91.66	37.00	1.81	29.00	1.783	0.13	0.13	0.0860	0.00	0.00
704.0	0.86	90.72	33.93	1.75	27.19	1.635	0.00	0.00	0.0790	0.00	0.00
645.6	0.88	89.86	31.11	1.68	25.44	1.499	0.00	0.00	0.0720	0.00	0.00
592.0	1.01	88.98	28.53	1.62	23.76	1.375	0.00	0.00	0.0660	0.00	0.00
542.9	1.06	87.97	26.16	1.56	22.14	1.261	0.00	0.00	0.0610	0.00	0.00
497.8	1.01	86.91	23.99	1.51	20.58	1.156	0.00	0.00	0.0560	0.00	0.00
456.5	1.06	85.90	22.00	1.44	19.07	1.060	0.00	0.00	0.0510	0.00	0.00
418.6	1.22	84.84	20.17	1.38	17.63	0.972	0.00	0.00	0.0470	0.00	0.00
383.9	1.38	83.62	18.50	1.31	16.25	0.892	0.00	0.00	0.0430	0.00	0.00
352.0	1.57	82.24	16.96	1.24	14.94	0.818	0.00	0.00	0.0390	0.00	0.00
322.8	1.72	80.67	15.56	1.16	13.70	0.750	0.00	0.00	0.0360	0.00	0.00
296.0	1.85	78.95	14.27	1.09	12.54	0.688	0.00	0.00	0.0330	0.00	0.00
271.4	1.94	77.10	13.08	1.01	11.45	0.630	0.00	0.00	0.0300	0.00	0.00
248.9	1.99	75.16	12.00	0.95	10.44	0.578	0.00	0.00	0.02790	0.00	0.00
228.2	2.03	73.17	11.00	0.88	9.49	0.530	0.00	0.00	0.02550	0.00	0.00
209.3	2.05	71.14	10.09	0.82	8.61	0.486	0.00	0.00	0.02340	0.00	0.00
191.9	2.08	69.09	9.25	0.76	7.79	0.446	0.00	0.00	0.02150	0.00	0.00
176.0	2.10	67.01	8.48	0.71	7.03	0.409	0.00	0.00	0.01970	0.00	0.00
161.4	2.13	64.91	7.78	0.66	6.32	0.375	0.00	0.00	0.01810	0.00	0.00
148.0	2.14	62.78	7.13	0.61	5.66	0.344	0.00	0.00	0.01660	0.00	0.00
135.7	2.16	60.64	6.54	0.56	5.05	0.315	0.00	0.00	0.01520	0.00	0.00
124.5	2.16	58.48	6.00	0.51	4.49	0.2890	0.00	0.00	0.01390	0.00	0.00
114.1	2.17	56.32	5.50	0.47	3.98	0.2650	0.00	0.00	0.01280	0.00	0.00
104.7	2.16	54.15	5.04	0.43	3.51	0.2430	0.00	0.00	0.01170	0.00	0.00



- Measurement Info -

Title	
Issabelle	
Identifiers	
Manhole	
-	
Database Record	16293
Run Number	1 of 3
Date	7/1/2020
Time	12:37 PM
Acquired Date	7/1/2020
Acquired Time	12:37 PM
Serial Number	S6730
Sample Cell ID	0309
Calculated Data	
Above Residual	0
Below Residual	0
Loading Factor	1.0236
Trans. L1:L2	0.813:0.797
RMS Residual	0.195%
Recalculation Status	
DB-Meas : : Original :	

-SOP Info-

ISSABELLE_PSD(*)	
Timing	
Setzero Time	30 (sec)
Run Time	30 (sec)
Number of Runs	3
Multi-Run Delay	0 (min)
Delay First Meas.	Disabled
Analysis	
Sludge	
Refractive Index	N/A
Transparency	Absorb
Shape	Irregular
WATER	
Refractive Index	1.33
Options:	
Filter	Enabled
Analysis Gain	Default(2)
Analysis Mode	BLUEWAVE
Perspective	
Progression	Geom 8 Root
Distribution	Volume
Upper Edge(um)	2000
Lower Edge(um)	0.0107
Residuals	Enabled

Summary	
Data	Value
MV(um):	227.8
MN(um):	3.14
MA(um):	28.52
CS:	2.10E-01
SD:	188.0
Mz:	167.0
σι:	249.3
Ski:	0.732
Kg:	1.938

Percentiles	
%Tile	Size(um)
10.00	11.54
20.00	23.22
30.00	38.76
40.00	59.11
50.00	88.65
60.00	132.3
70.00	199.4
80.00	311.9
90.00	655.1
95.00	1031

Peaks Summary		
Dia(um)	Vol%	Width
976.3	11	848.4
71.1	89	228.3

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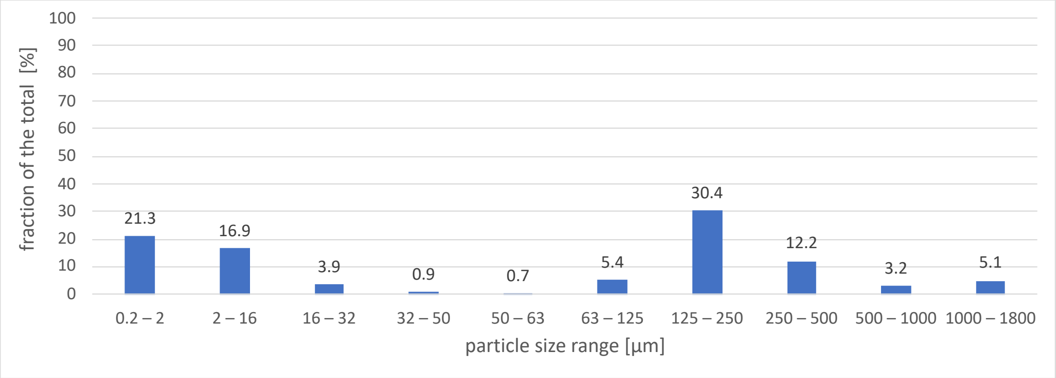
Sample System(Wet)	
Number of Rinses	4
Flow Rate (%)	25%
Deaeration Cycles	3

F - Results from the practical assessment

Figure F-1 *left: sludge sample from the gully pots; right: sludge sample from the manholes.*



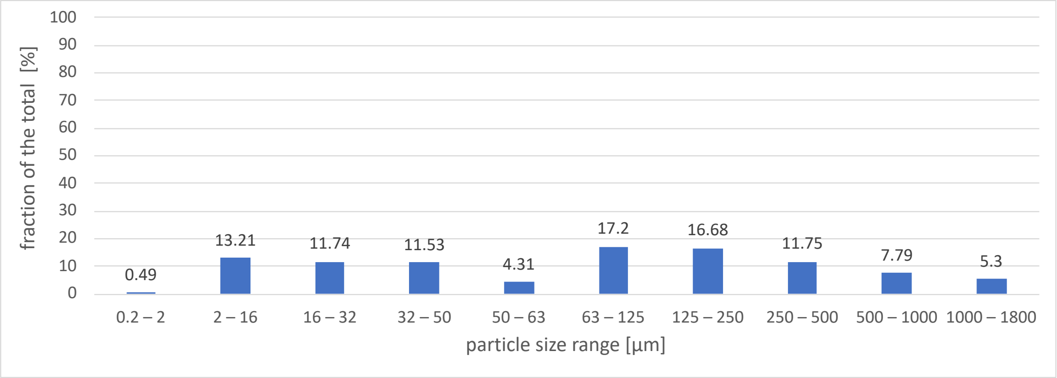


Figure F-2 *top: PSD according to Waterproef; bottom: PSD according to TU Delft.*

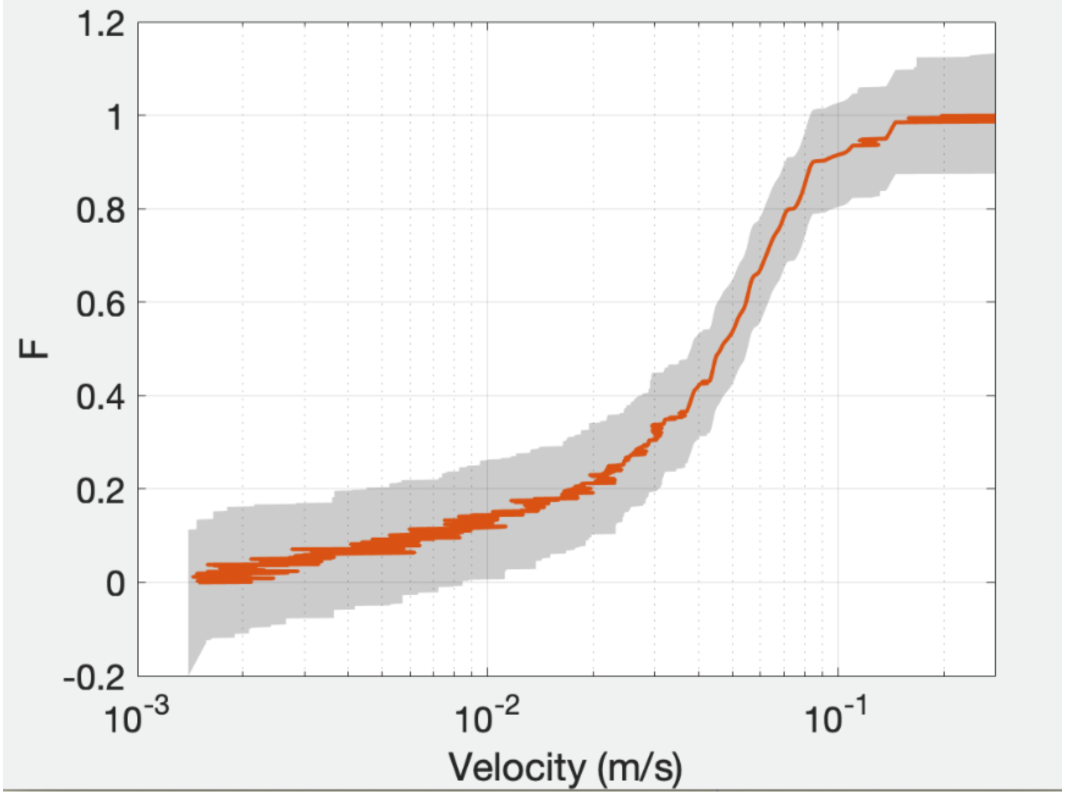


Figure F-3 *Settling velocities determined by the settling velocity device (F= 1 – relative mass); orange line: average measured values, grey line: upper and lower boundaries of measured values.*

Figure F-4 *left: filter membrane before filtration; right: filter membrane after filtration.*

G - Sampling and monitoring setup

Precipitation measurement

***Figure G-1** Location of the precipitation measuring devices around the study area (Google Maps)*; A: radar point by KNMI; B: tipping bucket at Rietveld Academie by Waternet; C:weighing rain gauge by Waternet.

TIDALFLUX 2300

The TIDALFLUX 2300 can be used for capacitive level measurement for water and wastewater. It is able to measure flows in partially filled pipes, starting to record signals already at levels of ≥10 % filling. The TIDALFLUX 2300 can measure without obstructions with an accuracy of ±1 %. To achieve this, it should be assured that the minimum flow velocity is approximately 1 m/s. It is available in different diameters, ranging from DN200 up to DN1600. In this specific study, the smallest diameter (DN200) is chosen, since smaller cross-sections allow more accurate results. Therefore, the existing stormwater pipe will be reduced from DN315 to DN200 using a PVC connecting piece provided by Wavin (figure G-2, right). This reduction in diameter needs to be done in a certain distance in front of the installation location of the flowmeter. The suggested distance by KROHNE is about ten times the diameter, which corresponds about 2 m in this case. After the flow has been measured, the diameter is increased back to the initial size. This is done to allow the sewer construction to be brought back to the original state in case the measuring equipment will be removed in the future.

Figure G-2 *left: TIDALFLUX 2300 by KROHNE; right: PVC connector to change the diameter of the pipe by Wavin.*

Aquacell P2-MULTIFORM

The Aquacell P2-MULTIFORM (figure G-3)can accommodate a choice of 4 different sample collection vessels, varying in size and volume. They range from a single 25 l container to 12 x 0.75 l glass bottles up to 12 (or 24) x 1 l PET bottles. The whole device is 0.78 m high, 0.46 m wide and deep and weighs 8.5 kg without container. The special construction using an open aluminum frame structure allows the collected samples to be easily visually inspected.

Figure G-3 *Aquacel (Aquamatic) and available sample container vessels.*

VisoTurb 700 IQ

This sensor should be equipped with a self-cleaning function to remove fouling or debris that could potentially attach to the device. In this way readings are allowed to happen throughout the measuring period. Furthermore, it needs to be assured, that the sensor is always surrounded by water. To guarantee representative results, the sensor should be placed where the water is as homogenous as possible. Otherwise there is a risk that the distribution of particles is not random because some particle might have settled already while others float on the top. Therefore, the first sensor should be placed at the height of the horizontal pipe of the SediSubstrator, the sedimentation pipe. The next one in sequence should be installed at the outlet location of the same pipe. Lastly, the third sensor is advised to be centered at the bottom part of the outlet pipe of the end shaft.

Several studies (Leutnant et al., 2016; Y. Liu et al., 2020) used online turbidity sensors to monitor this parameter. The VisoTurb 700 IQ (figure G-4) is recommended by the provider Xylem Analytics to be used for the measurement of the turbidity or of the suspended solids concentration (TSS) in wastewater systems. It is equipped with an ultrasound cleaning system where a sapphire disc provokes vibrations in the ultrasound range that prevent the growth of pollution as a result of the movement. Furthermore, the device aims to provide measurement results with a high accuracy but low maintenance costs. This online sensor determines the turbidity nephelometrically in accordance with EN ISO 7027, offering a measuring range of 0 – 4000 FNU.

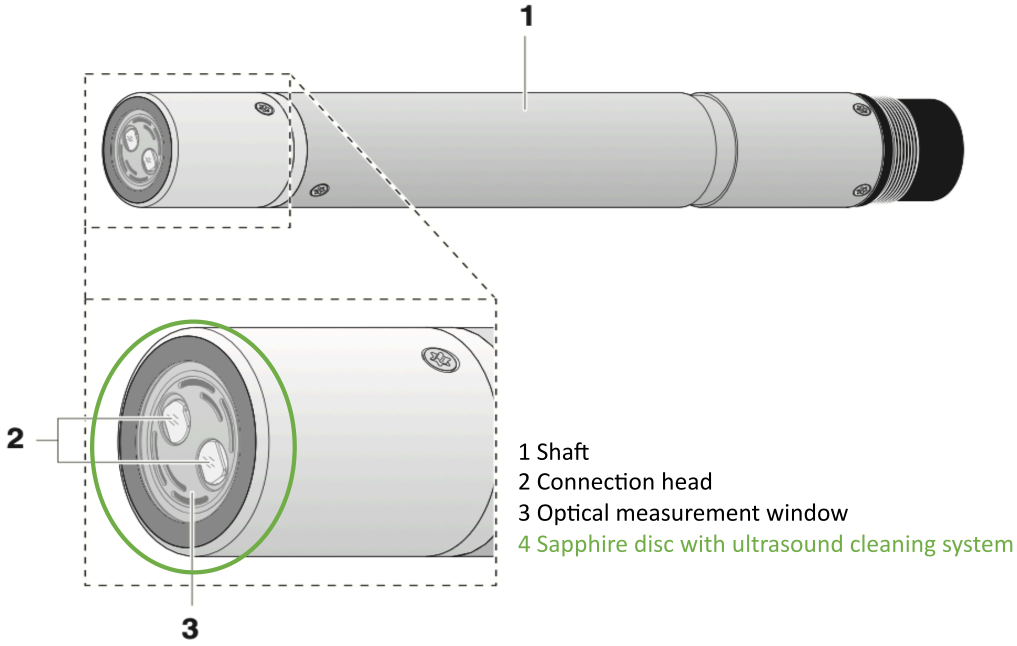


Figure G-4 *Structure of the VisoTurb® 700 IQ (SW) turbidity sensor (Xylem Analytics).*

To allow accurate measurements to be conducted, some requirements need to be fulfilled regarding the placement of the turbidity sensor. As stated in the manual provided by the manufacturer, it is imported to keep a minimum of 10 cm distance from the bottom and walls. The sapphire disc should be positioned in such way that the current of the water is directly flowing towards the disc, guaranteeing an angle of attack of about 20 to 45 °. Only in case large fibers or particles with large surfaces are excepted, it is suggested to turn the sensor facing downward of the flow. The sensor should be inclined in such way that as little light as possible is scattered or reflected by the walls or bottom. In order to keep the sensor stable, it is suggested to use attach it in such way that it cannot be damaged by bumping against obstacles or the walls. Here, the device could be fixed to the flow separator, in a distance of minimum 10 cm from the bottom, allowing the sapphire disc to face the flow.

LTC Levelogger Edge

Looking further into the measurement parameters, the Levelogger measures the absolute pressure. Hence, to obtain the actual pressure, total pressure needs to be reduced by the barometric pressure. The temperature on the other hand is assessed by using a platinum resistance temperature detector, which compensates for changes in temperature within the range of 0 to +50 °C. It is able to measure temperature in a range on -20 to 80 °C. The last parameter is the electric conductivity, measured with a platinum four-electrode sensor. The temperature is used to correct the electric conductivity.

Figure G-5 *left: LTC Levelogger Edge; right: measurement line with respect to the pressure access holes (Solinst).*

The Levelogger can be either hung from the top or be fixed within the system. The manual of the device recommends installing the sensor in a vertical way. The measurement line is located right above the pressure access holes and indicated in figure G-5. Moreover, it always needs to be assured that the Levelogger is submerged. Hereby, it should not exceed the pressures higher than 200 % of the full-scale level range. Therefore, the minimum and maximum expected water levels have to be estimated on beforehand. Furthermore, it needs to be considered that the logger is not placed at locations where turbulences are present or where head conditions change due to lifting by obstacles or change in velocity. This would lead to non-representative results. This could be avoided for instance by using a piezometer filter tube to simulate these conditions.

Sampling points

Following the flow of the water, the first measuring device is the tipping bucket. This rain gauge is installed in top of the Rietveld Academie and provides the study with precipitation measurements. The next measuring device in sequence is the flowmeter. Based on the measured flow, this instrument will send specific previously determined signals to the three automated samplers. The latter will take time-weighted samples at the start shaft of the SediSubstrator to determine the overall incoming sediment concentration. Only the suction hose of the automated sampler will be located inside the start shaft of the treatment facility. The main body of both devices is placed inside a dry manhole right beside the start shaft. This sampling point (SP) will be referred to as number 1. This dry manhole was built to provide the needed flow conditions for the flowmeter to measure as well as the demand in space to place the devices. Furthermore, turbidity, electric conductivity as well as pressure and temperature are measured in the start shaft of the SediSubstrator.

The sampling location in the start shaft will be referred to as SP 2. As it can be seen in figure G-6, the start shaft has two incoming pipes. In order to allow for accurate monitoring of the flow, the connecting stormwater pipe from the eastern side needs to be blocked. In this way, water will only enter the system from the western side. This allows bigger flows to be measured and furthermore only one flowmeter will be necessary. This adjustment can be seen in figure G-6.

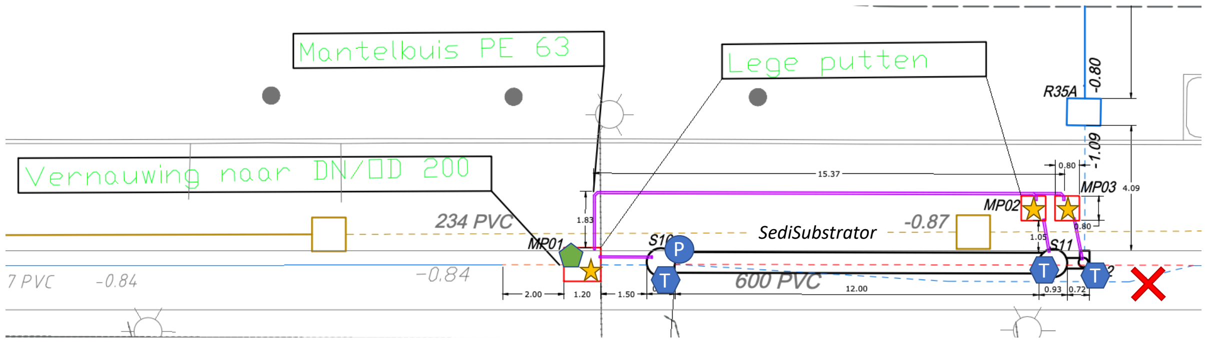


Figure G-6 *Sampling locations at the SediSubstrator in the south-eastern Rooseveltlaan; flowmeter (pentagon), automated sample (star), turbidity sensor (T), pressure transducer & EC meter & temperature sensor (P), pipe blockage (red cross).*

To be able to monitor the functioning and effectiveness of the sedimentation pipe itself, the next sampling location will be the end shaft of the SediSubstrator, right before the filter cartridge. This location is named SP 3 and will be composed of the suction hose of an automated sampler as well as a turbidity sensor.

The fourth sampling location (SP 4) is inside the outlet shaft of the end shaft. Here, the suction hose of a third automated sampler as well as a turbidity sensor will be placed. The main part of the two automated samplers that measure at the end of the sedimentation pipe, are located inside dry manholes as well. These dry manholes are installed close by the end shaft and provide the necessary space for the samplers to be installed. The sampling by automated samplers is crucial at each location where a change in sediment composition is expected. Therefore, they will be placed before and after the sedimentation pipe as well as after the filter cartridge.

To guarantee more stormwater to enter the SediSubstrator, the whole southern stormwater drainage system of the Rooseveltlaan will be connected to the installed facility. In this way higher flows can be expected, allowing a more accurate monitoring of the stormwater discharge. Furthermore, in this way the entire stormwater will be treated until another treatment facility will be installed on the western side of the southern ventweg as well.