CHARACTERIZING THE BEHAVIOR OF STORMWATER SEDIMENT AND ITS IMPACT ON THE PERFORMANCE OF THE STORM SEWER

ANNEMIEKE HOORNICK
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Characterizing the behavior of stormwater sediment and its impact on the performance of the storm sewer

A field study in Amsterdam

by

Annemieke Hoornick

Student number:	4489608	
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Thesis committee:	Prof. dr. ir. J. Langeveld	TU Delft
	Prof. dr. J. P. van der Hoek	TU Delft
	Ing. M. N. W. Nijman	Waternet

TU Delft

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Summary

Stormwater runoff transports solids from the streets into the storm sewer and receiving waterbodies, soil and groundwater. This can lead to sediment accumulation, decreased hydraulic capacity and water pollution. Urban stormwater management is needed in addressing these issues. However, the selection of appropriate treatment methods and the understanding of sediment behavior within the system are challenging due to limited information. The implementation of stormwater treatment facilities is often based on projections derived from laboratory tests using Millisil W4 as a reference material. However, previous research has observed discrepancies between the removal efficiency in situ and the laboratory tests which could be attributed to the differences between the characteristics of the material used in the tests and the actual solids present in the sewer system. This research aims to address these gaps by investigating sediment characteristics and dynamics. The findings will provide insights to support Waternet in developing effective stormwater management strategies to mitigate flood and pollution risks in Amsterdam.

Various methods were employed to collect sediment samples from different locations within the storm sewer, including runoff samples from gully pots, sediment bed samples from sand traps and from the bottom of manholes. Laboratory analysis was conducted to characterize the sediment in terms of physical and chemical properties. Settling and resuspension parameters were calculated from the laboratory results in order to compare the behavior of the sediment among the samples. The findings of this study revealed that the sediment characteristics varied throughout different locations within the system, with finer material observed near the storm sewer outfall (SSO) with lower settling velocities. The resuspension analysis indicated a higher likelihood of sediment resuspension near the system SSO compared to upstream locations. Comparing the particle size distribution of the sediment bed near the SSO with the reference material Millisil W4 showed similarities, but significant differences were observed in density. The settling velocity of the sediment particles in the manholes seemed comparable to Millisil W4, while the settling velocity of the runoff samples showed higher values. The resuspension parameter of Millisil W4 were comparable to the runoff samples but lower than the sediment bed samples meaning that Millisil W4 would be less prone to resuspension than the actual sediments. However, including the residual concentration which remained suspended would result in finer material, lower settling velocities and higher resuspension parameters. In addition, the dynamics of solids in manholes during rainfall events were also investigated by placing a sensor above the sediment bed monitoring turbidity, total dissolved solids and water temperature. The dynamics in the manhole showed a pattern between rainfall events, flow velocities and the behavior of the measured parameters. When the intensity or duration of a rainfall event exceeded a certain threshold and there were sufficient dry hours before the event to allow solids to accumulate, a consistent pattern emerged. After the initial peak of the event, there was a subsequent decrease in total dissolved solids while turbidity increased. This observation suggests that high-intensity rainfall events can mobilize and transport solids within the system.

The limitations of relying solely on standardized test protocols were evident, emphasizing the need to consider deviations in sediment behavior and performance. For Waternet, the main message is to interpret the predictions provided by testing protocols in light of these deviations to develop more accurate stormwater management strategies. Several recommendations can be made to further understand the sediment characteristics. Conducting extensive and representative sampling campaigns that capture seasonal and temporal variations will provide a more comprehensive understanding of sediment dynamics. It is interesting to collect both sediment and water samples to assess suspended and dissolved components, estimating pollutant load and environmental impacts accurately. Refining sampling protocols by standardizing procedures and exploring alternative methods will enhance the reliability of results. Monitoring the response of solids to rainfall events and investigating the distinction between resuspension and transportation of solids through runoff will yield valuable insights for sediment behavior and stormwater management design and evaluation.

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1 Introduction

1.1. General introduction

Runoff is a major contributor to the transport of solid particles from the streets into the stormwater sewer and eventually into the receiving waterbodies. This process can result in the accumulation of sediment in the system, leading to a decrease in hydraulic capacity and overall functionality. Moreover, the solids carried by the runoff also contain pollutants that can have a significant impact on the water quality of the receiving waterbodies, soil and groundwater. If the water is to be re-used, these pollutants pose a challenge as well. The presence of pollutants in the runoff can cause surface water pollution, groundwater contamination, deterioration of the ecological water quality and other adverse effects in urban areas (Rietveld, 2021).

In recent years, urban stormwater management has gained significant importance due to the effects of climate change and urbanization. As cities expand and extreme weather events become more frequent and intense, it is crucial to prioritize the proper functioning of storm sewers. These systems play a vital role in managing and safely discharging stormwater runoff. By doing so, they help prevent flooding and safeguard the quality of surface water resources, groundwater and the ecosystems they support. Implementing effective stormwater management practices also contributes to the overall sustainability of urban areas by minimizing the entry of pollutants and sediments into waterbodies.

1.2. Problem statement

Water treatment facilities are often applied to remove pollutants from stormwater runoff before it is discharged into the environment. However, selecting the best treatment approach is complex and involves consideration of numerous variables such as local conditions, stormwater characteristics and technological constraints. Despite the critical importance of these factors, available information on these aspects is often limited. According to Vollaers et al. (2021), one of the root causes of malfunctioning treatment facilities is incomplete knowledge about the technical performance of the system. Lack of experience or available information prevents sufficient understanding of the internal processes occurring in treatment facilities (Vollaers et al., 2021).

In addition, the build-up and wash-off processes result in varying solid loading rates throughout the storm sewer, making it challenging to characterize the solids throughout the system (Rietveld et al., 2021). Projections on the removal efficiency of possible treatment facilities are often based on standardized test protocols, but previous studies have shown that these predictions often do not correspond to reality due to different circumstances (Nijman et al., 2015, 2019; Neupert et al., 2021; Little, 2022).

1.3. The objectives of this research and the role of Waternet

The increasing pressures of urbanization and climate change have highlighted the urgent need for effective stormwater management in cities worldwide, as these factors contribute to the intensification of rainfall patterns and the exacerbation of urban flooding and water pollution issues. Amsterdam, being no exception to these challenges, requires robust solutions to address stormwater runoff issues, which pose risks such as water pollution and flooding. These issues have detrimental effects on surface water quality and ecosystem health. Additionally, flooding incidents can result in substantial property damage and threaten public safety. Recognizing these risks, Waternet, representing the municipality of Amsterdam and the regional water authority Amstel, Gooi and Vecht, is committed to mitigating flood and water pollution risks through integrated stormwater management strategies.

To achieve successful stormwater management, it is imperative to select appropriate treatment methods and accurately assess the behavior of sediment within the storm sewer. Therefore, this research aims to contribute to Waternet's mission by providing a comprehensive understanding of sediment dynamics and its impact on system performance and water quality. By investigating how sediment behaves within the system, valuable insights can be gained to inform decision-making processes related to stormwater management. Through this study, we seek to equip Waternet with the knowledge necessary to make informed choices in managing stormwater runoff. By comprehending sediment movement and its interaction with the system, effective strategies can be developed to mitigate pollution risks and reduce the occurrence of flooding incidents.

1.4. Study area: Rijnbuurt Oost, Rivierenbuurt, Amsterdam

Rijnbuurt Oost is a residential neighborhood located in the Rivierenbuurt, in the southern part of Amsterdam. The Amstel River runs along the eastern edge of the neighborhood. The whole area is relatively compact, with a mix of residential and commercial buildings. Most of the buildings in Rivierenbuurt are low-rise, with a maximum height of around five stories. The streets are generally narrow and lined with trees, with occasional green spaces and playgrounds. In the study area, stormwater is collected and managed through a separate sewer system. The area faces water-related challenges, including frequent occurrence of urban flooding after extreme rainfall events. Rainproof Amsterdam (2019) identified the Rivierenbuurt as extremely urgent bottlenecks, as shown in Figure 1.1. Figure 1.2 shows the boundaries (1.2a), the water depth after a rainfall event on the streets (1.2b) and the occurance of high groundwater (1.2c) in the selected study area Rijnbuurt Oost.

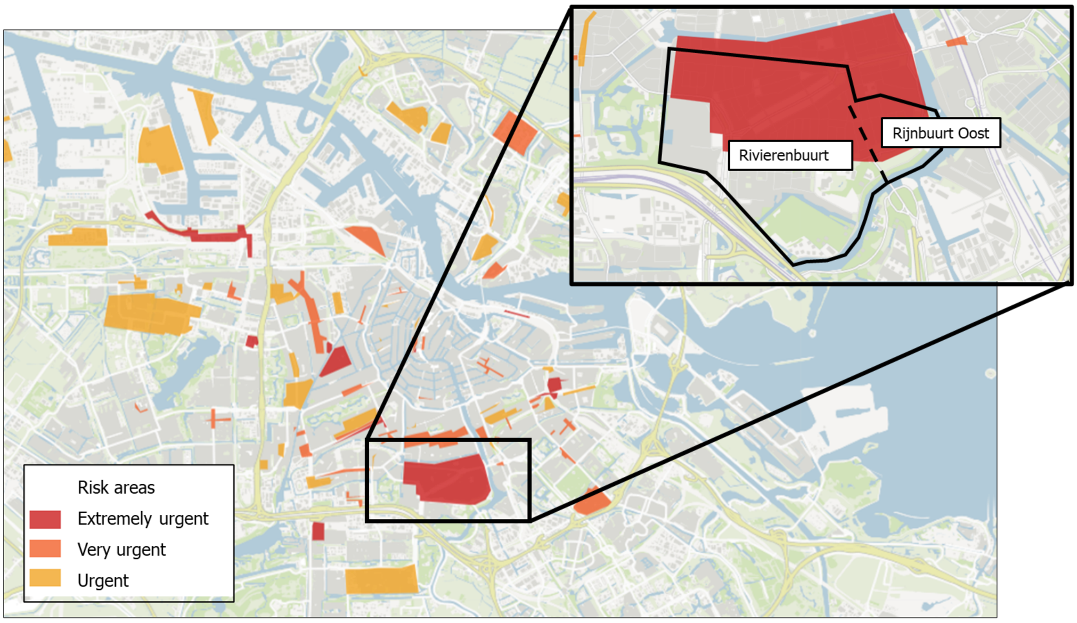
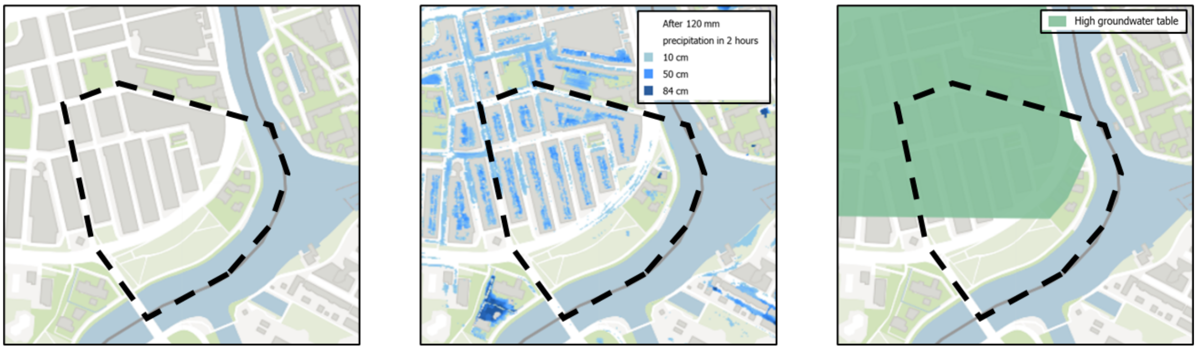


Figure 1.1: Areas in Amsterdam that are identified as bottlenecks due to water-related challenges. Adapted from the City of Amsterdam (2019)



(a) Rijnbuurt Oost marked by the dashed boundary

(b) Water depth map after 120 mm rain in 2 hours

(c) Occurrence of high groundwater in the study area

Figure 1.2: Map of the study area and water-related problems. Adapted from Rainproof Amsterdam (2019)

1.5. Policies and regulations

In the Netherlands, urban stormwater management is guided by a combination of national and local laws and standards that aim to safeguard water quality and prevent pollution. The responsibility for developing and implementing stormwater management plans and policies typically lies with the municipalities, who must align their initiatives with national legislation while considering local needs and characteristics. Unlike some countries, the Netherlands does not have specific regulations solely dedicated to stormwater discharge into surface water or groundwater. The Dutch regulatory framework for stormwater discharges is based on the principle that stormwater is presumed to be clean unless proven otherwise, as outlined in the Wet milieubeheer (Environmental Management Act). To ensure effective regulation, the national discharge regulations have been decentralized to municipalities and regional water authorities with the introduction of the Omgevingswet (Environment and Planning Act). This decentralization allows for the development of area-specific regulations that can impose stricter requirements when necessary. Municipalities incorporate the discharge regulations into their Environmental Plans, while regional water authorities include them in their Regional Water Authority Regulations.

1.6. Sedimentation devices

Water treatment facilities are used for managing surface water runoff and mitigating the environmental impacts of urbanization. These facilities are often based on the removal of solids by sedimentation. Evaluating the performance of these sedimentation devices is an essential step in choosing the most effective treatment strategy. To achieve this, standardized test protocols are used, which can be mandatory in some countries and voluntary in others. These protocols provide a systematic assessment of the devices' ability to capture pollutants and sediments under various conditions, aiding in informed decision-making.

One well-known protocol is the German Institute of Building Technology's (Deutsches Institut für Bautecknik - DIBt) National Technical Approval. It specifically addresses pollutant loads from metal roofs and highly trafficked road runoff. The DIBt protocol applies to areas in Germany with more than 300 Average Daily Traffic (ADT) and where discharge infiltrates groundwater. It assesses the annual capture rate of sediment, dissolved metals and hydrocarbons. To gain approval, devices must meet specific criteria, such as a Total Suspended Solids (TSS) capture rate of 92%, Zinc capture rate of 70%, Copper capture rate of 80% and Total petroleum hydrocarbons capture rate of 80%. In the DIBt protocol, Millisil W4 is used as a surrogate for sediment (Smoker et al., 2022).

Millisil W4 is a synthetic material with properties similar to natural sediments. It is designed to replicate the behavior of sediment under different flow conditions, allowing for a standardized and consistent assessment of stormwater treatment device performance. Compliance with these protocols provides manufacturers and stakeholders with a benchmark for comparing the performance of different devices. The adoption of these test protocols contributes to improved stormwater management and reduced environmental impact resulting from urban development (Smoker et al., 2022).

1.7. Structure of the report

The report is structured into several chapters as follows: First, the literature review (chapter 2) offers a comprehensive review of existing studies on sediment dynamics and stormwater management is presented. It examines the relevant literature to establish a solid foundation for the research. Next, the research questions that guide the study are presented in chapter 3. It defines the specific inquiries that the research aims to address and provides a framework for the analysis and discussion. The methodology chapter (chapter 4) describes the research approach, including data collection methods and analytical techniques. It provides an overview of how the study was conducted. The findings from the data analysis are presented in chapter 5. It includes the results of the measurements taken during the study period and highlights the observed patterns and trends. Chapter 6 discusses and interprets the results in the context of the research objectives. It compares the findings with previous studies, explores the implications and discusses the limitations of the research. The conclusions are summarized in chapter 7 and chapter 8 offers recommendations for future research and practical implications based on the findings. The appendices include supplementary information such as data tables, technical details and additional figures that support the main text.

2

Exploring the role of sediment in urban stormwater runoff: A literature review

This chapter presents a comprehensive literature review on urban stormwater management, with a specific focus on sediment characteristics. It explores the pathway of stormwater runoff, including surface runoff, inflow to gully pots, sand trap capture in gully pots and flow through the sewer system to the storm sewer outfall (SSO) (section 2.1). The chapter also examines various aspects such as particle size, shape and density, composition, pollutants and settling velocity (section 2.2). Additionally, the comparison to Millisil W4 and the performance of the storm sewer are discussed (section 2.3).

2.1. Pathway of stormwater runoff and sediment distribution

This section aims to provide an overview of the stormwater runoff pathway, shedding light on the key stages and factors that influence its behavior. By examining each stage of the pathway, from surface runoff to the discharge into the sewer system and ultimately the SSO, a better understanding of the dynamics and potential challenges associated with stormwater management can be gained. The distribution of sediment through the system is dependent on the transport processes, which can cause the sediment to be suspended or deposited in various areas of the sewer system. The sediment that is present in the runoff can accumulate in the gully pots, channels and treatment facilities, affecting the hydraulic capacity and sediment removal efficiency of the system.

2.1.1. Quality of stormwater

The quality of runoff water in the Netherlands can vary greatly depending on location (Rietveld, de Rijke, et al., 2020; Stichting RIONED/STOWA, 2016; Rietveld, 2021). Stichting RIONED/STOWA (2020) reported values for various pollutants found in runoff water, shown in table 2.1 and 2.2. The water samples were collected from roofs and combined roofs and roads, with the combined samples obtained from the storm sewer. These values highlight differences between different area types and roof compositions. However, it is important to note that these values do not reflect surface runoff exclusively. The quality of stormwater runoff and the solids loading to the sewer system is also largely time dependent. Variations can occur within seasons and within rainfall events. It can even vary by a factor of 100 within one rain event. This is due to the influence of atmospheric conditions, such as rainfall intensity and duration (Stichting RIONED/STOWA, 2020). Also, the initial flush of a sewer system can contain a considerable amount of pollutants and suspended solids, with the majority found in the first ten to twenty minutes (Saget et al., 1996).

Table 2.1: Average concentrations of pollutants in stormwater from different sources and the requirements. Adapted from Stichting RIONED/STOWA (2020).

		Roofs in residential areas	Roofs and roads in residential areas
Cadmium (Cd)	[μg/L]	0,29	0,18
Copper (Cu)	[μg/L]	34	21
Mercury (Hg)	[μg/L]	0,045	0,026
Lead (Pb)	[μg/L]	324	32
Nickel (Ni)	[μg/L]	3,4	4,1
Zinc (Zn)	[μg/L]	95	144
Antraceen	[μg/L]	0,0096	0,0076
Benzo(a)pyreen	[μg/L]	0,016	0,048
Minerale oil	[μg/L]	233	102
Chemical Oxygen Demand (COD)	[mg O/L]		36
P-total	[mg P/L]		0,3
N-Kjeldahl	[mg N/L]		2,1
Nitrate (NO3-N)	[mg N/L]		1,5
Total Suspended Solids (TSS)	[mg/L]	196	38
E. Coli	[#/100 ml]		2,4 10^4

Table 2.2: Median concentrations of stormwater runoff quality from different roofs types. Adapted from Stichting RIONED/STOWA (2020).

		Bitumen roofs	Roofs with Zinc gutters	Other types of roofs
Copper (Cu)	[μg/L]	19		29
Lead (Pb)	[μg/L]	210	70	17
Zinc (Zn)	[μg/L]	72	50	6,4
Antraceen	[μg/L]	0,01		0,0014
Benzo(a)pyreen	[μg/L]	0,01		0,01
Minerale oil	[μg/L]	50		50

Climate change increases the challenges of stormwater runoff quality. In Amsterdam, increasing average temperatures and precipitation patterns have been observed (KNMI, 2014). Higher temperatures contribute to more frequent heatwaves, while increased precipitation leads to more intense rainfall events. These changes have negative implications for stormwater runoff quality, including higher concentrations of pollutants and suspended solids, as well as an increased risk of urban flooding (Stichting RIONED/STOWA, 2020).

The concentration of contaminants in sediment is influenced by various factors, such as land use in the catchment area. Sources of heavy metals, including atmospheric deposition, industrial activities and automotive emissions, can contribute to elevated concentrations of these pollutants in runoff water (Little, 2022). Roof type has also been identified as a potential factor affecting the concentration of zinc and copper in stormwater runoff. High vehicle traffic areas may have higher levels of mineral oil, heavy metals and polycyclic aromatic hydrocarbons (PAHs), while areas with abundant vegetation may exhibit higher nutrient and organic matter levels. Figure 2.1 shows several pollutant concentrations from different urban sediment sources, which were obtained from a literature review conducted by Allen et al. (2014). Furthermore, weather conditions, such as heavy rainfall and temperature fluctuations, can influence the chemical properties of stormwater runoff. Seasonal variations, such as autumn leaf fall and the use of winter road salt, further contribute to the changing composition of stormwater runoff (Rietveld, 2021).

Previous research on sediment in stormwater runoff and street particles has provided insights into various sediment characteristics. The particle size distribution analysis of stormwater measurements revealed that approximately 50% of the mass consists of particles smaller than 90 μm (F. Boogaard et al., 2014). Moreover, sweeping streets has been shown to remove a significant amount of sand/sludge, with an estimated annual removal of 22,600 tons in Amsterdam (Speet, 2017). Density measurements of street particles showed varying results. According to Butler et al. (1992), the density falls within the range of 2100-2510 kg/m^2. Another study conducted by Pitt et al. (2005) based on a literature review

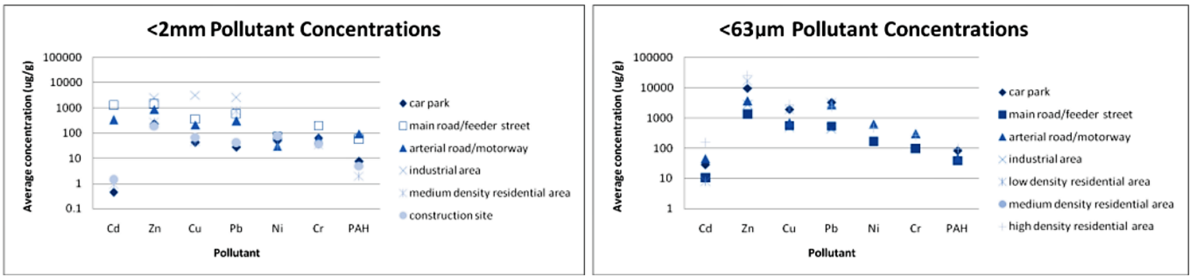


Figure 2.1: Concentrations of several pollutants from different urban sediment sources, based on a literature review of Allen et al. (2014) using data from Selbig et al. (2013); Hubbart (2012); Timperley (2005).

reported a wider range of 1500-2500 kg/m^2. The organic fraction of street particles has been found to range from 0.40 to 0.70 (Gromaire-Mertz et al., 1999). Different studies have investigated the particle size of street particles, yielding varying distributions. Most studies reported quantiles of the distribution, such as the 50th percentile (also noted as the median or the D50). Gelhardt et al. (2017) reported a D50 range of 200-550 μm, while Zafra et al. (2008) found a range of 100-360 μm. Lau & Stenstrom (2005) observed a D50 range of 200-350 μm and Bertrand-Krajewski et al. (1993) reported a range of 300-400 μm (Gelhardt et al., 2017; Zafra et al., 2008; Lau & Stenstrom, 2005; Bertrand-Krajewski et al., 1993). Regarding particle shape, previous studies have focused on road-deposited sediments and found that these particles tend to have irregular surfaces and a high proportion of elongated particles. The analysis conducted by Rommel et al. (2020) revealed similar particle shapes among the analyzed road-deposited sediments, regardless of their origin, resembling tire wear particles (Rommel et al., 2020).

2.1.2. Inflow to the gully pots

Solids entering the sewer system through gully pots differ from those found on the streets, as grading caused by runoff during transportation can alter their characteristics (Pratt & Adams, 1984; Rietveld, 2021). A monitoring campaign conducted by Rietveld et al. (2021) on solids loading to a drainage system via 52 gully pots in a residential area over two years provided valuable insights into the characteristics of these solids. Nylon filter bags with a pore size of 50 μm were used to capture the solids and the study aimed to cover a large area and all seasons. Large variations were found in the particle size distribution throughout the year. During periods when trees drop their leaves and periods of droughts, large values of D50 where found. This was explained by the reduced transport capacity of fine material to the system while leaves where still transported by wind (Rietveld et al., 2021). The time-averaged solids loading was found to be approximately 0.80 kg/day/ha. The organic fraction of the solids showed a range of 0.17 to 0.78 and the D50 showed a range of 420-24000 μm, where the smallest value was found in September and the largest in November. The organic fraction and D50 of the solids were correlated with leaf abscission, while the settling velocity of particles less than 1800 μm was strongly correlated with their organic fraction and ranged between between 0.01 and 0.06 m/s (Rietveld et al., 2021).

Other studies have also investigated the characteristics of solids loading to gully pots. Ellis & Harrop (1984) and Pratt & Adams (1984) used stack sieves in a few gully pots and found that the D50 of the solids was approximately 600-1000 μm and 680 μm, respectively. Additionally, 8 mass% of the solids in Pratt & Adams (1984) were less than 400 μm, while 10 mass% of the solids in Ellis & Harrop (1984) were less than 400 μm. Ellis & Harrop (1984) also found that the solids loading to gully pots was highest during summer and reported peak values of 1.1 kg/day/ha in their monitoring area of 533 m2 over a period of 14 days. The study also found somewhat lower solids loadings of between 0.032 and 0.67 kg/day/ha during spring. Another study by Sansalone et al. (1998) redirected the runoff from an area of 300 m2 (comparable with the surface area connected to 2–3 gully pots) to a storage tank, from which samples were taken during 13 rainfall events. The study found that the D50 values of the solids were between 350 and 800 μm and solids less than 50 μm contributed less than 8 mass% in all samples.

2.1.3. Sand trap capture in gully pots

The properties of solids entering gully pots differ from those remaining in them, as the sand trap's efficiency in removing solids depends on factors such as particle size and density (Rietveld, Clemens, & Langeveld, 2020b; Butler & Karunaratne, 1995). Rietveld, Clemens, & Langeveld (2020a) found that the rate of solids accumulating in gully pots is highest during the 'leaf abscission' phase in terms of volume. Conversely, Rietveld et al. (2021) discovered that this phase corresponds to the lowest solids loading. These findings indicate that the volume of solids retained in the gully pot does not have a direct relationship with the mass inflow. Therefore, the characteristics of the solids must be considered when converting mass inflow into the volume captured within the gully pot. Previous studies have reported different particle size distributions for the sediment found in gully pot sand traps, with D50 values ranging from 400 μm to 1500 μm (Pratt & Adams, 1984; Grottker, 1990).

Prior research has established that in 95% of gully pots, the sediment bed in the sand trap achieves equilibrium after 3-4 months, meaning an equal amount of sediment enters and leaves the gully pot. However, the remaining 5% of gully pots experience clogging (Post et al., 2016; Nijman, 2019). Typically, gully pots undergo cleaning once a year. Speet (2017) determined that around 5 kg of sediment is removed from the sand trap of each gully pot during the cleaning process, which results in approximately 526 tons per year in Amsterdam. Regular sediment removal is crucial for maintaining the effectiveness and functionality of stormwater infrastructure and treatment systems, as well as preventing clogging and potential damage to the entire system. Furthermore, research found that the sediment from the sand trap can be fully or partially flushed out when a certain threshold of rainfall intensity or volume is reached. Laboratory tests using sediment collected from gully pots in Amsterdam showed fully flushing out of the sediment at a flow rate of 0.2 l/s, which would correspond with a rainfall intensity that occurs five times a year in the Netherlands (Zandvoort & Nijman, 2019; Kregting, 2012).

2.1.4. Sewer system flow to storm sewer outflow (SSO)

Solids that are not captured by the sand trap in the gully pot flow into the sewer system. Wash-off and transport processes distribute the solids throughout the system and these processes determine the sediment characteristics. During a rainfall event, the flow velocity of the water increases as it moves through the sewer system, as shown in Figure 2.2. This increase in flow velocity leads to movement of solids and bed erosion. Bed erosion is the process by which sediment and other materials are removed from the bed of the channel or sewer system due to the force of flowing water (Murali et al., 2019).

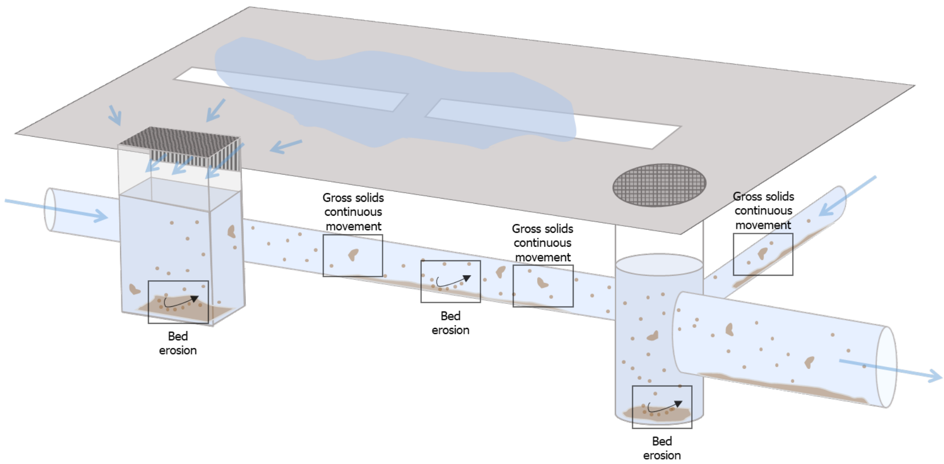


Figure 2.2: Schematic drawing of sediment transport processes in a sewer system during a rainfall event

After a rainfall event, as the flow velocity decreases. Sediment is transported through suspended sediment transport and bed load transport, as shown in Figure 2.3. Suspended solids transport refers to the movement of small, fine particles that are carried along by the flow of water. These particles are suspended in the water column and can continue to be transported long after the flow velocity has decreased. The rate of suspended solids transport is dependent on the flow velocity, the size of the particles and the concentration of particles in the water. Bed load transport refers to the movement of larger particles that are too heavy to be suspended in the water and instead move along the bed of the channel. These particles move in short jumps or rolls along the bed and can cause further erosion of the channel bed. Bed load transport is more likely to occur when the flow velocity is still high and decreases as the flow velocity decreases (Murali et al., 2019).

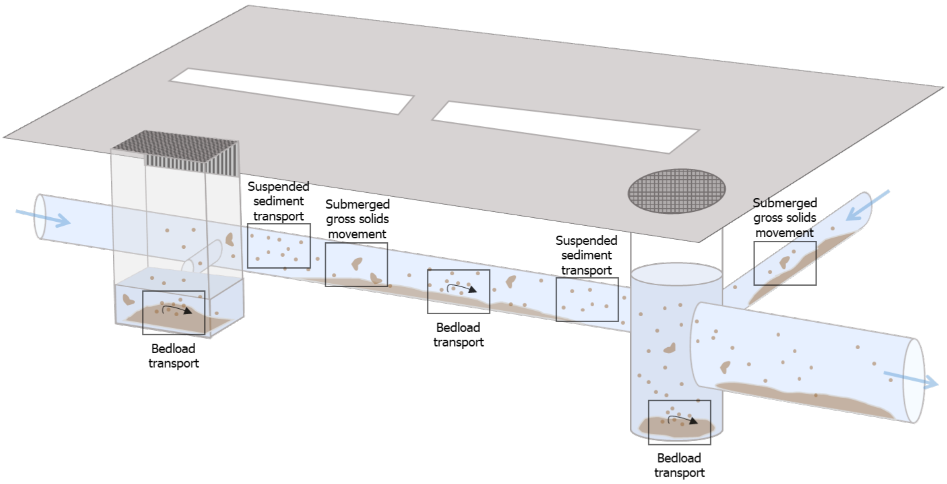


Figure 2.3: Schematic drawing of sediment transport processes in a sewer system after a rainfall event

As the flow velocity decreases further, a point is reached where the flow becomes calm and the velocity approaches zero, as shown in Figure 2.4. Sediment settling and deposition will occur. The larger and heavier particles will settle to the bottom of the channel and form a new layer of sediment, also known as the bed. However, a fraction of suspended sediment will remain suspended in the water and not settle out, even when the flow velocity is close to zero. This fraction is referred to as the residual concentration and can impact the water quality and ecology of the receiving water body. Nijman et al. (2015) found a residual concentration of approximately 8 mg/l in sedimentation pipes.

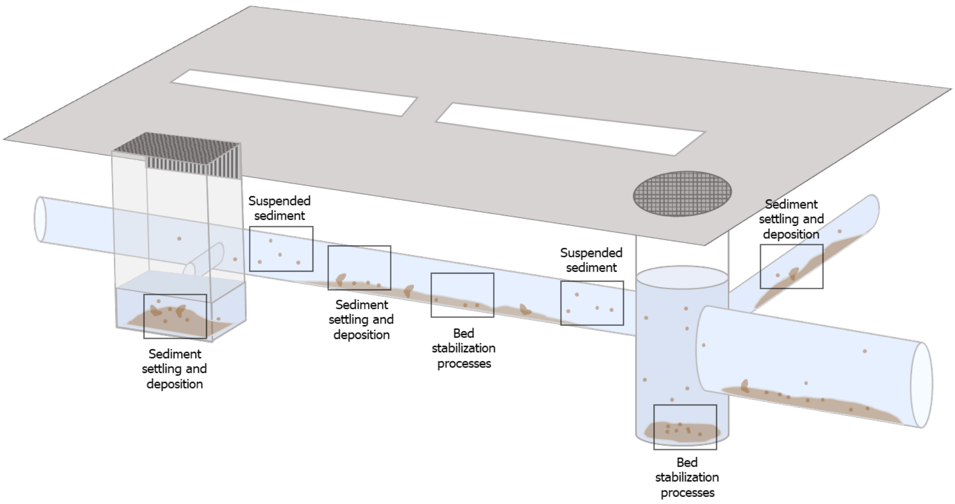


Figure 2.4: Schematic drawing of sediment transport processes in a sewer system during dry weather conditions

Studies such as Naves et al. (2020) have examined the wash-off and transport processes in drainage systems and have observed the occurrence of grading, where the particle size distribution changes. In a laboratory setup simulating initial street loads, two gully pots the SSO, different flow rates were investigated. Figure 2.5 presents the results of these experiments, revealing that the particle size distribution after a rainfall event depends not only on the initial street load but also on the characteristics of the rainfall and the sampling location. Typically, the finest particles are found at the SSO of the system, while larger particles tend to accumulate in the sand trap of the gully pot (Rietveld et al., 2021; Naves et al., 2020).

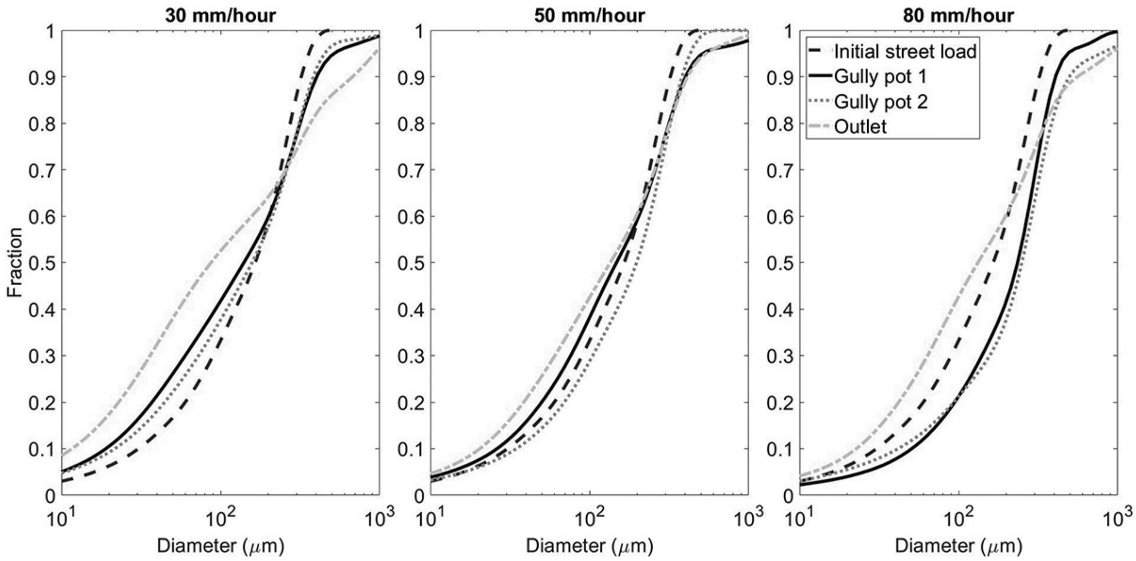


Figure 2.5: Particle size distribution after a rainfall event showing grading effects in a laboratory setup simulating initial street loads, two gully pots and the SSO (Naves et al., 2020). The finest particles are observed at the SSO.

This observation aligns with the findings of Nijman (2019), who also concluded that small contaminated particles (<50 µm) wash through to the surface water regardless of the neighborhood, system, or facilities (Nijman, 2019). Furthermore, Rietveld et al. (2021) noted that solids collected at the outfall or downstream in the drainage pipe might have undergone multiple cycles of settling and erosion within the pipe before reaching their final location. As a result, these samples represent an integral over space and time, which smoothens and masks the dynamics of wash-off processes occurring on the street. Another factor contributing to the finer particle size downstream is the breakdown of organic matter, facilitated by a longer residence time within the drainage system (Goess-Enzenberg, 2020). The density of sediments at the beginning and end of the sedimentation pipe at Ookmeerweg in Amsterdam was measured to be 1144 kg/m^2 and 1098 kg/m^2, respectively (Nijman, 2019). The organic fraction was found to be 18% and 31% at these respective locations.

2.2. Sediment characteristics

Sediment is a naturally occurring material that is found in stormwater runoff. It is composed of a variety of particles including soil, organic matter and other pollutants that are picked up and carried by the flow of water. Sediment is distributed throughout the storm sewer, with different parts of the system experiencing different sediment properties and loads as discussed in the previous section.

2.2.1. Sediment properties

Stormwater sediment can range in size from very fine clay particles to large rocks and can be categorized into different fractions based on their size distribution. Dissolved substances refer to those that are smaller than 0.45 µm, while suspended substances are larger than 0.45 µm. The total amount of suspended substances in water is of interest because pollutants tend to attach to suspended material, especially to the smallest fraction (0.45 to 63 µm) (Goess-Enzenberg, 2020; F. Boogaard et al., 2014; Nijman, 2019). The particle size distribution (PSD) is an important factor in determining the settling rate of particles, where larger particles tend to settle faster than smaller ones (Butler & Davies, 2004; Goess-Enzenberg, 2020). Furthermore, the PSD is correlated with the organic content, as discussed in the previous section. Figure 2.6 displays the correlation between particle size distribution and the organic fraction of sediment observed in a monitoring study by Rietveld et al. (2021), which shows that finer particles contain less organic material.

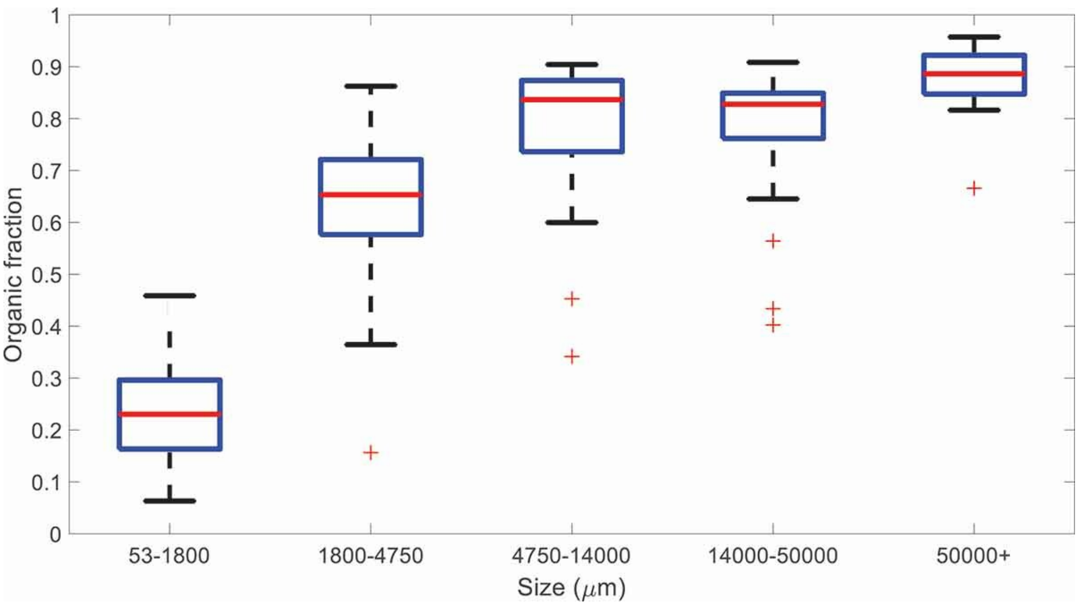


Figure 2.6: Box plots demonstrating the distribution of organic content in stormwater sediment samples across different particle size ranges (Rietveld et al., 2021).

The shape of sediment particles can range from round to angular, with silt and clay particles often exhibiting more angular shapes compared to coarser particles (Goess-Enzenberg, 2020; Le Roux, 2002). The size and shape of a particle determine the surface area of sediment, which refers to the total area of the particles exposed to the environment. This can affect interactions with substances like chemicals or pollutants and can be increased by weathering processes like erosion or mechanical weathering. However, the impact of particle shape on settling velocities remains debated. Williams (1966) compared well rounded particles with particles with sharp edges, which resulted in a reduction of the settling speed by 8-28% in case all other particle properties were not changed (Williams, 1966). However, Rommel et al. (2020) showed by conducting laboratory experiments that the impact of the particle shape on the settling velocity was negligible. It was found that the density had the largest impact (Rommel et al., 2020).

Density is another important characteristic of sediment, referring to the mass of sediment particles per unit volume. Sediment density can vary depending on the mineral and organic components present. The density of sediment particles determines their settling behavior in a fluid medium. If the density of the particles is greater than that of the surrounding fluid, they will eventually sink to the bottom when the fluid is still. On the other hand, if the density of the particles is similar to or lower than that of the fluid, they will remain suspended or they will float. The settling velocity of sediment particles can be influenced by factors such as salinity, with higher salinity leading to higher water density, leading to lower settling rates (Nijman et al., 2015). Gelhardt et al. (2021) reported a range of densities for sediment components, with mineral components ranging from 2.04 to 2.94 g/cm^3, organic components (traffic-related) ranging from 1.00 to 1.20 g/cm^3 and organic components (plant debris) ranging from 1.44 to 1.50 g/cm^3. Additionally, field measurements and theoretical calculations have shown that smaller sediment particles tend to have relatively lower densities, ranging from 1050 to 1250 kg/m^3, making them less prone to settling. By comparing the theoretical settling velocity with the measured settling velocity, de Graaf et al. (2012) found densities to be approximately 1500 kg/m^3 for particles larger than 200 µm, 1200 kg/m^3 for particles in the 100-200 µm range and 1050 kg/m^3 for particles smaller than 100 µm (de Graaf et al., 2012). These values closely align with the densities measured by Brombach et al. (1993), which were 2200 kg/m^3 for particles between 150 and 350 µm, 1230 kg/m^3 for particles in the 60-150 µm range and 1060 kg/m^3 for particles smaller than 60 µm.

The behavior of particles is also influenced by their cohesive or non-cohesive nature, which can be assessed based on several parameters. Particle size distribution provides insights into the range and distribution of particle sizes within the sediment. Fine particles, particularly those in the silt and clay size range, tend to exhibit higher cohesive properties and are more prone to aggregation. Coarser particles generally have lower cohesive tendencies. Analyzing the particle size distribution helps determine the potential for coagulation and settling behavior of sediments (Goess-Enzenberg, 2020). Non-cohesive particles, typically larger than 63 µm, interact mechanically and tend to be unevenly dispersed in the water column, forming heterogeneous clouds. The settling velocity of non-cohesive particles depends on their concentration, with higher concentrations leading to increased interaction and settling velocity. On the other hand, cohesive particles, usually smaller than 2 µm, have the ability to flocculate or aggregate due to electrochemical interactions. Fine silts and clay particles fall into this cohesive fraction and the strength and frequency of floc interactions determine their size. The formation of flocs depends on factors such as mineralogy, electrochemical nature, particle concentration, characteristics and water temperature. Additionally, the shape of flocs, such as flakes or discrete clumps, can impact their settling velocity (Goess-Enzenberg, 2020).

2.2.2. Pollutant behavior

The behavior of pollutants in stormwater is closely related to their binding to particles. Research conducted by F. Boogaard et al. (2014) investigated the distribution of pollution loads between dissolved and particle-bound forms in runoff from roofs and roads in residential areas. The study found that nutrients are less bound to particles compared to heavy metals and polycyclic aromatic hydrocarbons (PAHs) (F. Boogaard et al., 2014). The binding percentages for copper, zinc and phosphorus were approximately 65%, 75% and 55% respectively, while the binding percentages for various PAHs were higher than 70% (F. Boogaard & Lemmen, 2007; F. Boogaard et al., 2014). Similarly, Nijman et al. (2019) found that approximately 45% of the metals and 89% of the PAHs were bound to particles. Many studies emphasized that most pollutants are bound to the smaller particles (F. Boogaard et al., 2014; Nijman et al., 2019; Goess-Enzenberg, 2020). These finer particles, such as silt and clay particles with a size of less than 63 μm, possess a larger specific surface area, providing favorable conditions for pollutant adsorption (Goess-Enzenberg, 2020).

2.2.3. Settling velocity

The settling velocity of stormwater sediment is a measure of how quickly particles in the water will settle to the bottom of a container or channel due to the force of gravity. Among other factors, it is affected by the size, shape and density of the particles, as well as the viscosity of the water. One way that the settling velocity can affect the performance of a sewer system is by influencing the rate at which sediment is deposited in the system. If the settling velocity of the sediment is high, it will tend to settle out of the water more quickly, leading to a build-up of sediment in the system. This can lead to blockages and reduced flow capacity in the sewer, potentially causing flooding and other problems. Another way that the settling velocity can impact the performance of a sewer system is by affecting the efficiency of sediment removal technologies. For example, sedimentation basins and sedimentation tanks rely on the settling velocity of the sediment to separate it from the water. If the settling velocity is too low, the sediment may not settle out of the water effectively, leading to reduced efficiency of the sediment removal process.

Research by Rommel et al. (2020) investigated the influence of different factors on the settling velocity of road-deposited sediments. It was found that particle density had the most significant impact on settling velocity, while lower temperatures and higher loss on ignition (LOI) values were associated with decreased settling. The addition of deicing salt had a minimal effect on reducing the settled fraction. Generally, larger particle size, higher particle density, larger density difference between particles and fluid lower fluid viscosity contribute to higher settling velocities.

In the context of sedimentation facilities, the settling rate is an important parameter. According to Nijman et al. (2019), the sedimentation rate separates incoming material based on weight. Approximately 30% of the particles in the gully pots, 25% in the pipes and 3% in the sedimentation facilities have a settling rate of 10 m/h. It was found that 20% of the sediment settles at a rate slower than 0.5 m/h. If the sediment is not deposited on the bottom of the sedimentation facility, it will be washed away if the stormwater continues to flow (de Graaf et al., 2012).

2.3. The performance of a treatment facility and the role of Millisil W4

One of the primary mechanisms involved in the removal of pollutants in treatment facilities is sedimentation, which is a gravity-driven process that allows particles to settle out of suspension in a fluid. In treatment facilities, sedimentation is a critical mechanism for the removal of suspended solids, such as silt, sand and clay particles, as well as other pollutants that may adhere to these particles. The design of these systems aims to create conditions that promote the settling of particles, which is typically achieved by reducing flow velocities to allow particles to settle out of suspension, providing sufficient residence time for particles to settle to the bottom, creating a calm environment that minimizes turbulence and resuspension of settled particles. The dimensions and implementation of these facilities significantly influence their removal efficiency. Thus, a comprehensive understanding of stormwater quality and characteristics is essential for accurately assessing the performance of treatment facilities (F. Boogaard et al., 2014).

To evaluate the removal efficiency of treatment facilities, several protocols and standards have been developed. The DIBt (Deutsches Institut für Bautechnik) standard, widely used in Europe, provides requirements for treatment channels and filter systems using Millisil W4 as a standard reference material (Woods Ballard et al., 2015). Previous studies have contributed to the evaluation and improvement of these protocols and standards. For example, Neupert et al. (2021) aimed to enhance the representativeness of laboratory tests by developing and testing alternative test substances. Real fractionated Road Deposited Sediment (RDS) was examined as a potential alternative to improve the resemblance of laboratory results to in-situ conditions. The study highlighted that while Millisil W4 closely resembles Total Road Dust Particles (TRWP) in terms of particle size and the TSS63 parameter, it does not fully replicate the behavior of real sediment in laboratory tests (Neupert et al., 2021). The DIBt test procedure was acknowledged as a suitable basis for testing treatment facilities on the test stand. However, the evaluation was deemed insufficiently representative of in-situ conditions (Neupert et al., 2021).

Other studies, such as Houlker et al. (2022), have also assessed the performance of decentralized treatment technologies within treatment facilities. These evaluations aimed to understand the limitations and discrepancies between predicted and observed performance. The Sedipipe, a commonly used treatment technology, was examined and the study revealed differences between predicted and actual performance due to factors such as low Total Suspended Solids (TSS) inflow and the presence of finer materials (Houlker et al., 2022). These investigations provide valuable insights into the real-world behavior and challenges associated with decentralized treatment technologies within treatment facilities.

According to Selbig et al. (2016), designing treatment facilities without considering site-specific particle size and density can result in systems that are either undersized or oversized. The study compared the generalized particle size distribution commonly used in performance tests, in this case the National Urban Runoff Program (NURP) distribution, with site-specific measurements from a residential basin and a commercial parking lot. The results showed that the NURP distribution was much finer than the measured distributions. Consequently, using the NURP distribution in the design of a wet detention pond resulted in an unnecessarily large surface area to achieve an 80% reduction in total suspended solids (TSS). In contrast, using the measured median particle size distribution, two catch basins of a specific size were sufficient to achieve a 40% reduction in TSS from a commercial parking lot. However, when relying on the NURP distribution, 20 catch basins of similar size were required for the same TSS reduction. Further analysis revealed that storms with coarser particle size distributions had the greatest potential for sediment removal. These findings underscore the importance of considering site-specific particle size distributions in treatment facilities design to optimize performance and avoid unnecessary costs or inefficiencies (Selbig et al., 2016).

Various protocols for treatment facility evaluation are primarily based on total suspended solids (TSS) removal, with some also considering the removal of specific pollutants. However, relying solely on TSS removal may not be sufficient to effectively mitigate water pollution. As discussed in section 2.2.2, the binding percentages of investigated substances are around 60% to 70%. It is generally expected that the majority of this part is bound to small, difficult-to-settle particles. Based on this, achieving a sedimentation efficiency of over 50% for most pollutants is theoretically challenging. Given the low settling velocity, a sedimentation efficiency of around 25% is more likely. Such low efficiencies align with the findings of previous monitoring projects (de Graaf et al., 2012).

As mentioned, Millisil W4 has been used as a test material for stormwater treatment systems due to its unique physical and chemical properties, which make it a useful surrogate for natural sediment in laboratory studies (Quarzwerke GmbH, n.d.; Rommel et al., 2020; Neupert et al., 2021). The consistent composition and relatively stable properties make it easier to control variables and interpret results when using Millisil W4 in laboratory studies. In comparison, sediment from the stormwater sewer is made up of a wide range of materials that can vary depending on the catchment and weather conditions.

In general, Millisil W4 may have different physical properties compared to sediment from the stormwater sewer due to its composition and origin. Figure 2.7 shows the particle size distribution of Millisil W4 and stormwater runoff in different countries (F. C. Boogaard et al., 2015). It can be seen that the distributions are quite similar, but deviate in the smaller fractions. However, previous research indicated that the smaller particles carry most of the pollutants (Nijman et al., 2019; F. C. Boogaard et al., 2015). In addition, sediment found further downstream tends to be finer and would show a different particle size distribution. Rommel et al. (2020) showed a difference in particle size distribution between Millisil W4 and road-deposited sediments, specifically in the smaller fractions (Rommel et al., 2020).

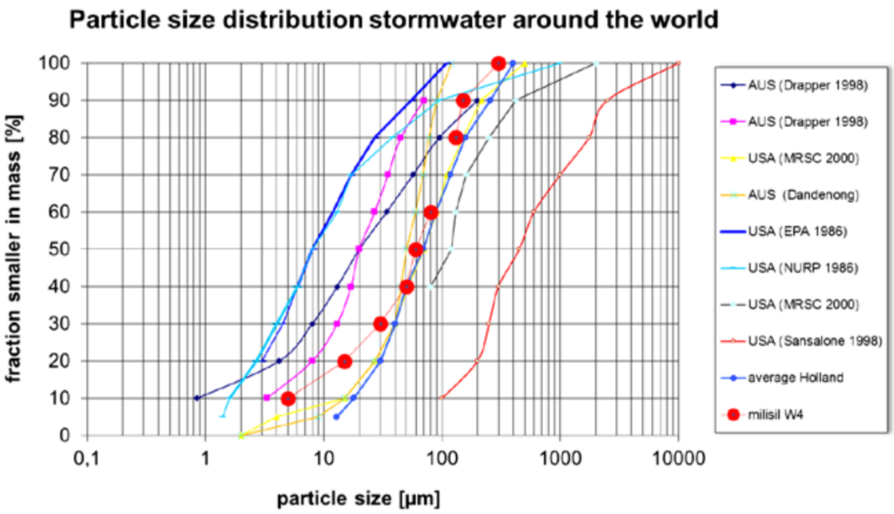


Figure 2.7: Cumulative particle size distribution of urban stormwater and Millisil W4 (F. C. Boogaard et al., 2015). It can be seen that the average distribution of the Netherlands shows similarities to Millisil W4, but deviates in the smaller fractions.

Furthermore, the densities found by Nijman et al. (2019) of 1098 and 1250 kg/m^3 are much lower than the density of 2650 kg/m^3 of Millisil W4. Sediment from the stormwater sewer may have a wider range of its properties depending on the materials it is made up of. In addition, the shape and surface area of Millisil W4 and sediment from the stormwater sewer may also be different due to the differences in their origins and formation processes. Millisil W4 has less irregular-shapes particles, while sediment contains a wide range of different shapes and sizes (Rommel et al., 2020). Furthermore, Millsil W4 does not contain nutrient and organic matter content of Millisil W4 is generally low due to the lack of these substances in the particles, is not biodegradable and does not degrade in the environment (Quarzwerke GmbH, n.d.). Stormwater sediment on the other hand is a mixture of inorganic and organic materials that is produced by the runoff of precipitation. Stormwater sediment is biodegradable and will degrade over time in the environment. Additionally, the re-mobilization of Millisil W4 was examined in gully pots (Kregting, 2012; Zandvoort & Nijman, 2019). Leaching occurred only at flow rates higher than 0.7 l/s, typically around 2 l/s, which are intensities not commonly observed in the Dutch situation. As mentioned in section 2.1.3, sediment from Amsterdam leached out at the lowest tested flow rate of 0.2 l/s which shows that the sediment behavior in Amsterdam differed from Millisil W4 (Kregting, 2012; Zandvoort & Nijman, 2019).

In summary, various protocols and standards have been developed to evaluate the removal efficiency of treatment facilities. However, improvements are continually being made to enhance the representativeness of laboratory tests and address discrepancies between predicted and observed performance. The evaluation of decentralized treatment technologies contributes to our understanding of their real-world behavior and helps refine their design and implementation in treatment facilities.

3

Knowledge gaps and research questions

3.1. Knowledge gaps

Previous studies on stormwater runoff have primarily focused on water quality aspects, particularly the solids present in the gully pot and the overall solids loading to the system. However, less research has been conducted on other parts of the system and the few studies that have been done mostly involve taking water samples rather than sediment samples from the bottom. This sampling approach presents an incomplete picture of the dynamics of wash-off processes on the street since the solids collected downstream may have been settled and eroded multiple times in the drainage pipe before arrival. Furthermore, there is no clear understanding of the transport processes of solids within the system. These knowledge gaps highlight the need for further investigation to improve the accuracy of stormwater models and management practices.

3.2. Research questions

To address the aforementioned knowledge gaps and improve stormwater management practices in Amsterdam, the following research questions will be explored:

1. **How do the characteristics of sediment vary throughout different locations within the storm sewer and how do they compare to those of Millisil W4?**
   This question aims to examine the sediment behavior in the storm sewer by collecting field data on the physical and chemical properties of sediment at different locations. The collected data will provide insight into the variation of sediment characteristics in different parts of the system, which can help to understand the behavior of sediment in the Amsterdam storm sewer and the differences to Millisil W4.

2. **What are the dynamics of solids in manholes during rainfall events and how do they correlate with precipitation patterns and intensity?**
   The intention is to investigate how the presence and behavior of solids in manholes change in response to rainfall events and how these changes relate to the characteristics of the rainfall itself. By studying the dynamics of solids in manholes and their correlation with precipitation patterns and intensity, insights can be gained into how rainfall events affect the transport, deposition and resuspension of solids in the storm sewer.

3. **To what extent do the sediment characteristics impact the performance of the storm sewer and how do the projections based on Millisil W4 correspond to the actual performance of the Amsterdam storm sewer?**
   The intention of this question is to investigate the potential impact of sediment characteristics on the performance of the storm sewer. The performance of the sewer system will be tackled in terms of removal efficiency, which refers to the ability of the system to remove sediment and pollutants from the water. This is used to evaluate the accuracy of projections made based on Millisil W4 for the Amsterdam storm sewer.

4 Methods

In the field of stormwater management, characterization of stormwater sediment is a crucial step in understanding the sources, impacts and management strategies of sediment in the storm sewer. In order to do this, samples of sediment are collected from various parts of the storm sewer and analyzed to determine the properties of different types of sediment (section 4.2). In addition, the dynamics in a stormwater manhole is investigated during rainfall events, to gain understanding of the sediment movement at varying intensities (section 4.3). At first, the study area and the surrounding area are described (section 4.1).

4.1. Site description and surrounding factors

The characteristics of stormwater runoff and sediment in the sewer system are strongly influenced by the surrounding factors of the research area. Each location, city and neighborhood has unique characteristics that impact the composition of stormwater runoff and sediment. Therefore, it is essential to provide a detailed site description to understand the characteristics of the runoff and sediment in the research area.

4.1.1. Runoff surface

Rijnbuurt Oost is a residential neighborhood located in the southeast of Amsterdam (Figure 4.1). The area covers approximately 19 hectares and has a total of 1,635 households. The surface cover types in the study area consist of a mix of urban and natural land uses. The northern part of the area is characterized by residential buildings, including both low-rise and high-rise apartment buildings. Most houses in the area were built between 1925-1950 and mainly have roofs made of bitumen, which is a common roofing material that can contribute to the accumulation of pollutants in the stormwater runoff. The southern part of the area consists of the Martin Luther Kingpark, which is an important recreational space for the residents of the neighborhood. The park includes green spaces, walking paths and sports fields. The area includes a regional road with an annual average daily traffic of around 16,000 vehicles, which runs through the middle of the study area, separating the residential neighborhood from the park. The study area is bounded by the Amstel River to the east.

4.1.2. The layout of the storm sewer

The sewer system in the study area is a separate sewer system, which means that the stormwater and wastewater are conveyed in separate pipes. The stormwater runoff collected by the sewer system is conveyed to the Amstel River. The layout of the sewer system, including the flow rates during a precipitation event with a return period of 0.25 years, is displayed in Figure 4.2. The flow rates were extracted from Infoworks, which is a hydraulic modeling software used to simulate the performance of sewer systems. The conduits in the sewer system are primarily made of concrete, while some are made of PVC or vitrified clay pipes. The materials used in the construction of the sewer system are displayed in Figure A.2 in Appendix A.

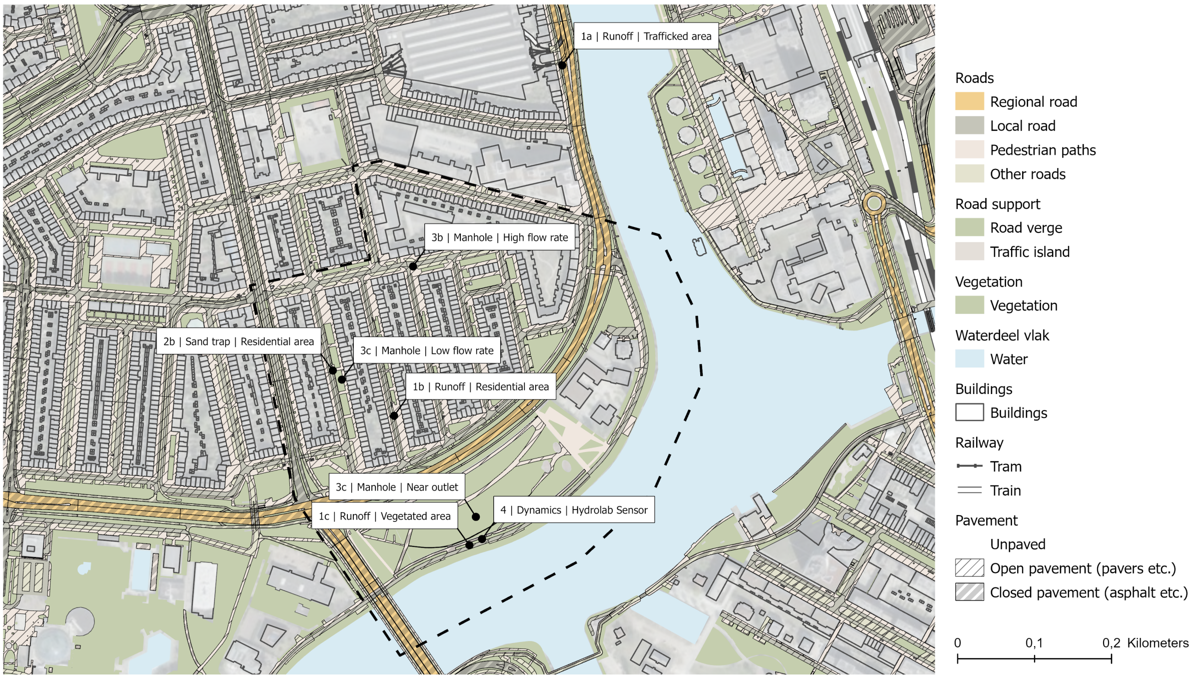


Figure 4.1: Overview of surface cover types, the sewer system and the sampling locations in the study area Rijnbuurt Oost.

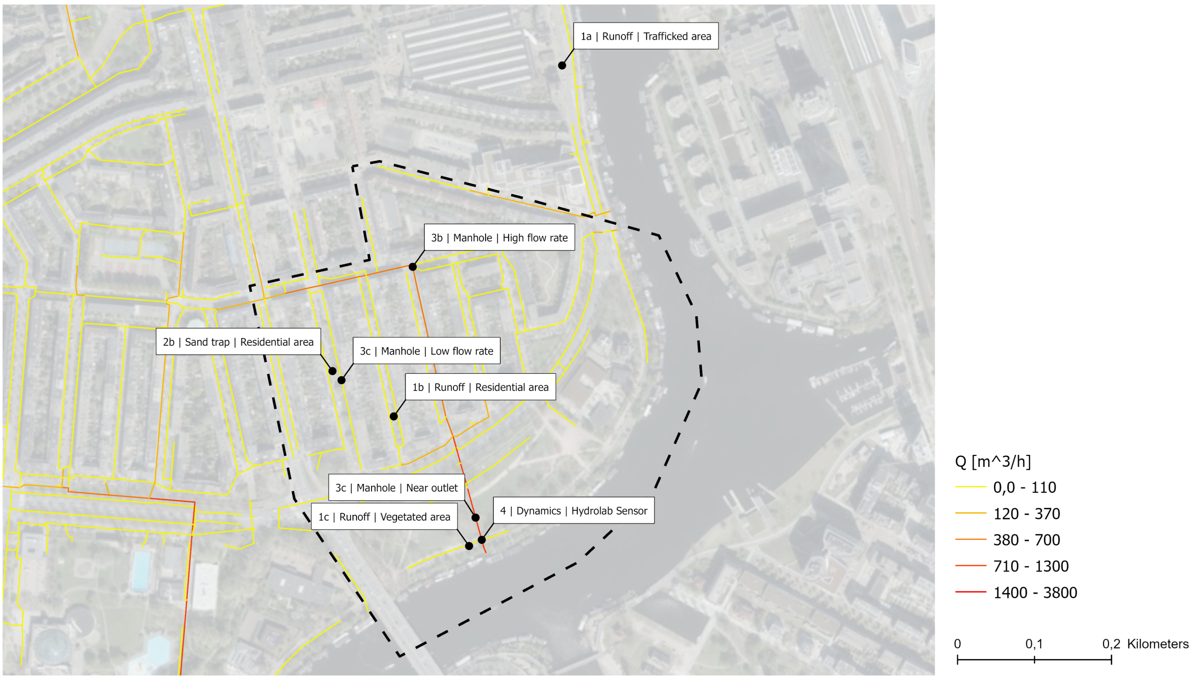


Figure 4.2: Flow rates during a precipitation event with a return period of 0.25 years

4.1.3. Weather conditions

Amsterdam's climate is characterized as temperate oceanic, with mild temperatures and consistent rainfall throughout the year. Nevertheless, due to climate change, extreme weather events have become more frequent and intense, leading to increased stormwater runoff and sediment transport. During the study period, precipitation data is obtained from the Royal Dutch Meteorological Institute's (KNMI) meteorological radar data set. This data set provides rain volume measurements on a grid with a spatial resolution of 1 km^2 and a temporal resolution of 5 minutes. Given the relatively small monitoring area, rainfall is assumed to be spatially homogeneous within the area. The air temperature data is collected from a weather station situated at Schiphol, which is approximately 10 km away. This data, obtained at a temporal resolution of 5 minutes, is utilized as an approximation of the average daily temperature in the surrounding area. Although there may be some deviation, it is deemed sufficiently accurate for indicative purposes only.

4.2. Sediment characterisation

In this study, sediment at different parts of the storm sewer is characterized by analyzing its physical and chemical properties and assessing behavior characteristics. An overview of the sampling locations is shown in the schematic drawing in Figure 4.3. The investigation involves collecting and analyzing solids from various locations, including the runoff to the gully pot, the settled solids in the sand trap of the gully pot and the bottom of the manhole.

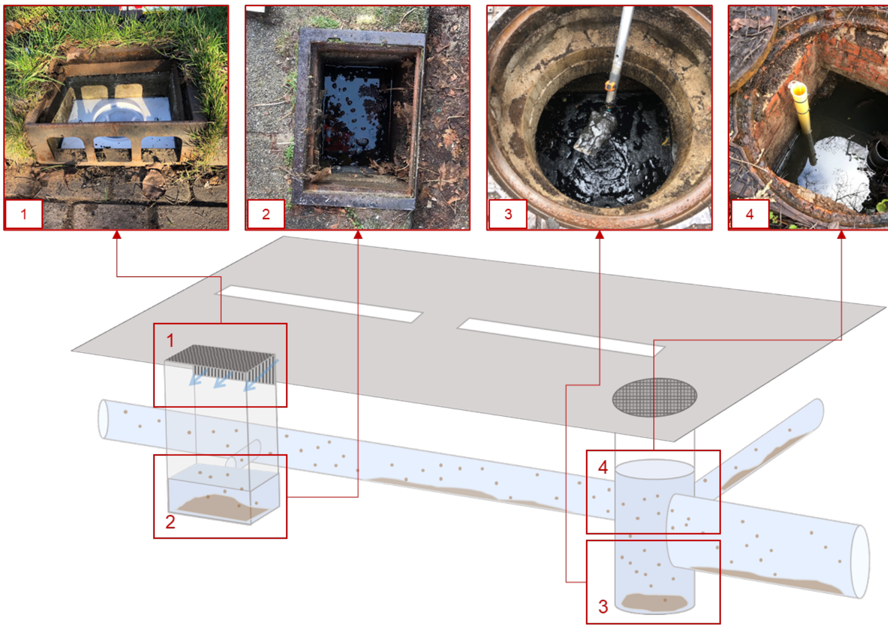


Figure 4.3: Schematic drawing of a sewer system and the sampling points. 1. Runoff samples are taken at the inlet of the gully pot. 2. Sediment bed samples are taken from the sand trap of the gully pot and 3. the bottom of the manhole. 4. The Hydrolab sensor is placed in a manhole.

4.2.1. Sample collection

To capture the solids that are transported by the runoff and enter the sewer system, samples are taken from the inflow of the gully pots (1) by placing a polypropylene filter bag with a pore size of 25 μm in three different gully pots and emptying these after a sufficient amount of sediment is collected. The same method was used by Rietveld et al. (2021), but with a pore size of 50 μm. In order to capture more fine particles, a smaller pore size was chosen. These filter bags are attached to a plate with a hole and securely placed in the gully pots. This setup ensures that no sediment particles could bypass the filters. Figure 4.4 shows an example of a filter bag secured in a gully pot in a vegetated area. After a designated period, the filters are checked for captured solids. These samples are referred to as runoff samples.

Figure 4.4: Filter bag secured in a gully pot in the vegetated area

Furthermore, samples are taken from the sediment bed in the sand traps of the gully pots (2) and stormwater manholes (3) using a hand tool. Figure 4.5a illustrates the scoop used for this purpose. The samples are collected as depicted in Figure 4.5b, with safety measures in place, such as the orange traffic cones. After collection, the mixed samples are initially stored in buckets, as shown in Figure 4.5c. Subsequently, these mixed samples are transferred to glass jars for further analysis, as seen in Figure 4.5d. Single samples are also collected in glass jars. All samples are stored in a refrigerator and collected by the laboratory of Waterproef on the same day or the following day for analysis. This is done during dry weather conditions, with little or no precipitation in the 5 days prior to the sampling so that the solids are able to settle.

(a) Scoop used for sediment collection

(b) Collecting a sediment sample

(c) Mixed samples stored in buckets

(d) Samples in glass jars

Figure 4.5: Photographs illustrating the sediment sampling methods

4.2.2. Sample locations

The gully pots for the runoff samples and the sediment bed samples are selected based on different surrounding factors to capture the variability in sediment characteristics in different areas of the study region, as shown in Figure 4.1. The sample points or the runoff samples are shown in Figures 4.6a, 4.6b and 4.6c. The gully pot location in the trafficked area is characterized by the presence of bitumen roofs and roof tiles nearby. Additionally, tram rails run adjacent to the sampling point. The area experiences a relatively high Average Daily Traffic (ADT) of approximately 16,000 vehicles. In the residential area, the gully pot is situated among predominantly bitumen roofs, with parked cars lining the road. The presence of trees along the road contributes to the overall environmental context. The gully pot in the vegetated area is located along a quiet road, surrounded by bushes. The proximity to a nearby park further enhances the vegetated nature of the surroundings.

(a) Gully pot location in the trafficked area (b) Gully pot location in the residential area (c) Gully pot location in the vegetated area

Figure 4.6: Gully pot locations for the runoff samples

The manholes are selected based on differences in the flow rate through the nodes. One particular manhole is strategically chosen near the storm sewer outfall (SSO) of the system, representing a more downstream location. This choice aims to investigate the type of solids that would potentially leave the system. However, obtaining samples from the SSO manhole proved to be challenging due to accessibility constraints. The gully pots and manholes are also selected based on accessibility and the presence of a sediment bed. It is ensured that the selected sampling locations have a sufficient amount of sediment that can be analyzed in the laboratory. The accessibility of the sampling locations is also considered, as it is important to collect samples safely and efficiently. The location of the sand trap sample in the residential area is presented in Figure 4.7a and the manhole locations are shown in Figure 4.7b. These samples are referred to as single sediment bed samples.

In order to be able to compare the types of sediments found in the study area Rijnbuurt Oost to a larger area, Rivierenbuurt, and to assess the representativeness of the area, mixed samples are taken both areas. In both areas, samples are taken from the sediment bed from multiple sample points and mixed to one sample. These samples are referred to as the mixed sediment bed samples. The sample locations are shown in Figure 4.8

Table 4.1 gives an overview of the sample locations and the sample dates.

Table 4.1: Sediment sample points

	Description	Surrounding factors	Sample date
1a	Runoff gully pot	Trafficked, bitumen roofs, tram rails	8-2-2023 - 14-3-2023 and 14-3-2023 - 12-4-2023
1b	Runoff gully pot	Residential, bitumen roofs, parked cars, trees	8-2-2023 - 14-3-2023 and 14-3-2023 - 12-4-2023
1c	Runoff gully pot	Vegetated, quiet road, trees and bushes	8-2-2023 - 14-3-2023 and 14-3-2023 - 12-4-2023
2a	Sand trap	Residential, bitumen roofs, parked cars, trees	14-12-2022 (mixed), 15-2-2023 and 1-3-2023
3a	Manhole	Low flow rate	14-12-2022 (mixed), 15-2-2023 and 1-3-2023
3b	Manhole	High flow rate	14-12-2022 (mixed), 15-2-2023 and 1-3-2023
3c	Manhole	Near storm sewer outflow (SSO)	14-12-2022 (mixed), 15-2-2023 and 1-3-2023

(a) Location of the sand trap of the gully pot in the residential area, alongside of the street with parked cars and trees

(b) Manhole locations and flow rates during a standard design event (Bui02)

Figure 4.7: Sediment sample locations

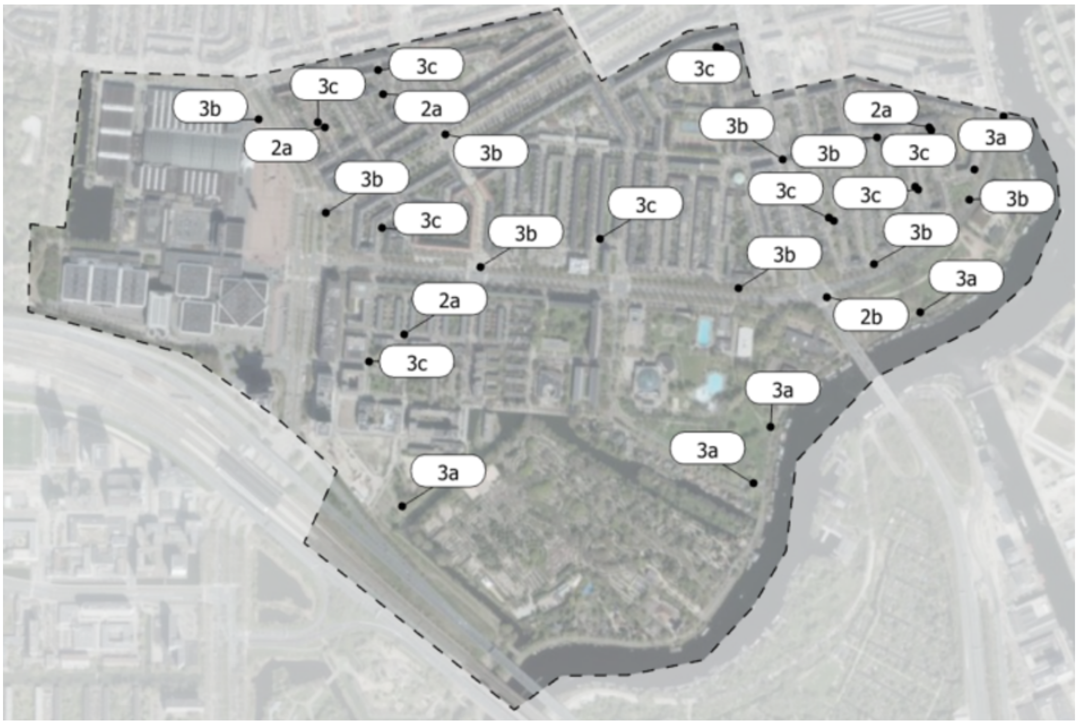


Figure 4.8: Sample points in Rijnbuurt Oost and Rivierenbuurt

4.2.3. Sample analysis

The collected sediment samples undergo various laboratory analyses to characterize their properties and composition. These analyses are conducted at different laboratories, including Omegam and Waterproef, as well as the TU Delft laboratory for particle shape analysis. Table 4.2 summarizes the methods used for each property, together with the uncertainties.

Omegam laboratory performs the analysis of particle size distribution (PSD). This involves sieving the samples using a certified 2 mm sieve to separate particles larger than 2 mm, followed by pretreatment with hydrogen peroxide and hydrochloric acid to remove organic matter, carbonates and binding components. The samples are then wet-sieved through a 63 µm sieve and the dried residue is further sieved using certified sieves to obtain fractions of different sizes. Sedigraph fractions are considered for finer particle sizes. The expanded uncertainty is 10-15% for fractions smaller than 63 μm and 5-10% for fractions greater than or equal to 63 μm, according to NEN 7779. The intralaboratory standard deviation is less than 4% for sieving fractions and less than 7.5% for sedigraph fractions.

Waterproef laboratory conducts analyses on particle density, organic content and the concentrations of zinc, copper, phosphorus, heavy metals, PAHs and mineral oils. Particle density is determined by dividing the dry mass of the sample by its volume. The organic content is assessed by measuring the difference in mass before and after heating the samples in an oven at 600°C. The concentrations of total phosphorus, copper, zinc and mineral oils are determined using specific methods and following relevant standards.

The particle shape analysis is performed at the TU Delft laboratory using a digital microscope. Prior to analysis, the samples are dried and sieved. Measurements are taken to determine parameters such as maximum and minimum average diameters of particles, average area, perimeter and circle equivalent (indicated in Figure B.2b in Appendix B). From these measurements, the sphericity (S) and aspect ratio (ψA) of the particles are calculated using equation 4.1 and 4.2, respectively.

$$S = \frac{P_{EQPC}}{P_{real}} = \frac{2\sqrt{\pi A}}{P_{real}} \tag{4.1}$$

In this equation, P_{EQPC} represents the perimeter of the equivalent circle, P_{real} is the actual perimeter of the particle and A is the projection area of the particle. The resulting value of S ranges between 0 and 1. A smaller S value indicates a more irregular shape of the particle, as irregular shapes tend to have increased perimeters.

$$\psi_A = \frac{x_{Feret,min}}{x_{Feret,max}} \tag{4.2}$$

Here, $x_{Feret,min}$ and $x_{Feret,max}$ represent the minimum and maximum Feret diameters, respectively. The aspect ratio (ψA) provides insight into the elongation of the particle. It falls within the range of 0 to 1, where higher values indicate a more elongated shape of the particle.

Table 4.2: Analysis Methods and uncertainties for particle size distribution, density, organic fraction, pollutant concentrations and shape properties.

Property	Method	Laboratory	Uncertainty
PSD	Pretreatment and sieving	Omegam	5-15%
Density	Dry mass divided by the volume	Waterproef	5%
Organic fraction	Change in mass after heating	Waterproef	5%
Total - P	Acid digestion (H2SO4) and photometric analysis	Waterproef	24%
Mineral oil	According to 3210-6, NEN 6972, NEN 6975 and NEN 6978	Waterproef	13%
Sum of PAHs	Own method by Waterproef	Waterproef	13%
Cu	According to NEN 6966	Waterproef	15%
Zn	According to NEN 6966	Waterproef	12%
Shape	2D analysis using digital microscope	Waterlab TU Delft	Unk.

4.2.4. Settling velocity and resupension parameters

The settling velocity of particles in the sediment samples is determined using the Stokes' equation, which provides an estimation of the particle's velocity when settling through a fluid medium. The Stokes' law, as shown in Equation 4.3, assumes that the particle is spherical and settling through a fluid at rest with constant viscosity. It also assumes that the Reynolds number, a dimensionless parameter indicating the relative importance of inertial and viscous forces, is much less than 1, indicating that viscous forces dominate.

$$V = \frac{g \cdot d^2 \cdot (p_s - p_f)}{18 \cdot \mu} \tag{4.3}$$

where:

V is the settling velocity of the particle [m/s], g is the acceleration due to gravity (9.81 m/s^2), d is the diameter of the particle [m], p_s is the density of the particle [kg/m^3], p_f is the density of the fluid in which the particle is suspended (1000 kg/m^3) and μ is the viscosity of the fluid (0.001304 m^2/s at 10°C).

To assess the resuspension behavior of the sediment, the Shields parameter is used. The Shields parameter, also known as the Shields criterion or Shields number, is a dimensionless number that determines the initiation of sediment motion in a flowing fluid. It is calculated using Equation 4.4, where the same conditions are applied to all samples for comparison.

$$\theta = \frac{\tau}{(\rho_s - \rho) \cdot g \cdot d} \tag{4.4}$$

Here, θ represents the Shields parameter, τ is the shear stress, ρ_s is the density of the sediment, ρ is the density of the fluid, g is the acceleration due to gravity and d is the diameter of the sediment particle. The value of θ depends on the properties of both the sediment and the fluid. As the parameter is used for comparison, a constant value for the shear stress at the sediment surface of 0.001304 Pa is used. The Shields parameter can be calculated and used to predict the initiation of motion of sediment particles in the fluid flow. If the Shields parameter is less than a critical value, θ_{crit}, then the sediment particles will remain in place. If the Shields parameter is greater than θ_{crit}, then sediment particles will begin to move and the sediment transport rate will increase. The value of θ_{crit} is dependent on the size and properties of the sediment particles and the fluid in which they are suspended and can be determined experimentally.

4.2.5. Correlation between the properties

In order to evaluate the impact of different parameters on the performance of the sewer system, correlation factors were calculated using the Python pandas library. Correlation factors provide insights into the relationships between variables and help us understand how they influence each other.

First, the correlations between the physical properties of the sediment and the concentrations of pollutants are analyzed. These correlations provide valuable information about the distribution and transport of pollutants within the sewer system. By studying the relationships between physical properties and pollutant concentrations, we can gain insights into the areas where pollutants tend to accumulate or get transported. Furthermore, the correlations between the physical properties of sediment and key factors such as settling velocity and resuspension factor are investigated. These correlations shed light on the relationship between the physical properties and the behavior of sediment particles in terms of settling and resuspension.

The correlation coefficients range from -1 to 1, where a value of 1 indicates a perfect positive correlation, -1 indicates a perfect negative correlation and 0 indicates no correlation. Positive correlations imply that as one variable increases, the other tends to increase as well, while negative correlations indicate an inverse relationship.

4.3. Solids dynamics in a manhole

The turbulence is investigated by placing a multiparameter sonde, the Hydrolab HL4, in a stormwater manhole during a period of two months. The sonde is calibrated by the supplier, set up according to the manufacturer's instructions and secured in place within the manhole. As the goal of the study is to investigate the turbulence of the water due to suspended sediment, the sonde is placed at a depth where sediment is likely to be present. The sonde is placed as close to the sediment bed as possible while still allowing for an accurate measurement. The sensor is connected to a power source and ensured that it is functioning properly. After a week, the battery is replaced and the data is retrieved. During the initial week of monitoring, data is collected at a temporal resolution of 5 minutes. For the remaining duration of the monitoring period, data is collected at a slightly lower temporal resolution of 6 minutes to conserve battery life. Photographs of the sensor setup and data retrieval process can be seen in Figure B.3 in Appendix B.

Table 4.3 summarizes specifics of the parameters monitored by the multiparametersonde, including the method and the accuracy. The device monitors the turbidity and the conductivity, which are commonly used indicators for water quality. Turbidity is a measure of the clarity of a water sample and measures the presence of suspended solids in water. Conductivity is a measure of the water's ability to conduct electricity and is related to the concentration of ions in the water. High conductivity levels can indicate the presence of salts and other dissolved minerals.

The collected measurements are plotted over time, along with precipitation data. These plots provide a visual representation of parameter changes during different intensities of rainfall events. Additionally, time series analysis was conducted to explore patterns and trends in the data.

Table 4.3: Hydrolab HL4 measurements specifics, adapted from (OTT HydroMet GmbH, n.d.)

Sensor	Range	Accuracy	Resolution	Method	Comments
Temperature	–5 to 50 °C	±0.1 °C	0.01 °C	SM 2550	
Conductivity	0 to 100 mS/cm	±0.5% of reading ±0.001 mS/cm	0.001 mS/cm	SM 2520-B	Open cell design with graphite electrodes
Dissolved Oxygen	0 to 60 mg/L	±0.1 mg/L for 0–8 mg/L, ±0.2 mg/L for more than 8 mg/L and ±10% reading for more than 20 mg/L	0.01 mg/L	ASTM D888 (Method C)	Optical Sensor, HACH LDO® Luminescent
Turbidity	0 to 3000 NTU	0 to 100 NTU: ±1%, 100 to 400 NTU: ±3% and 400 to 3000 NTU: ±5%	0 to 400 NTU: 0.1 and 400 to 3000 NTU: 1.0	ISO 7027	Self-Cleaning Wiper and central cleaning brush
Salinity	0-70 psu	±0.2 psu	0.01 psu		Calculated from Conductivity and Temperature
Specific Conductance	0 to 100 mS/cm	±0.5% of reading + 0.001 mS/cm	0.001 mS/cm		Calculated from Conductivity and Temperature
TDS (Total Dissolved Solids)	0 to 64 g/l	N/A	0.01 g/l		Calculated from Conductivity, Temperature and defined constant

5 Results

The purpose of this chapter is to present the results of the research conducted on the sediment characteristics in the study area. The chapter is divided into several sections to present the findings comprehensively. First, the conditions during the research period (section 5.1) and the conduct of the samples (section 5.2) are described. The conditions are essential to take into account when interpreting the results. Next, the characteristics of the collected sediment samples are presented (section 5.3) and compared to each other and to Millisil W4 (section 5.5). The correlations between the parameters and the settling velocity are presented (section 5.7). Finally, the solids dynamics in the manhole are evaluated by presenting the measurements of the multiparameter sonde in the manhole (section 5.8).

5.1. Conditions during sampling

The research period took place during winter from December 2022 to April 2023. This period was characterized by relatively mild weather conditions, with a normal amount of precipitation and frequent sunshine. Figure 5.1 provides an overview of the study period, including the precipitation, temperature, leaf phases and sampling days. The samples were taken during dry weather conditions, with little or no precipitation in the days leading up to the sampling days. It should be noted that the study period was during the "no leaves" phase and the beginning of the "leaf growth" phase.

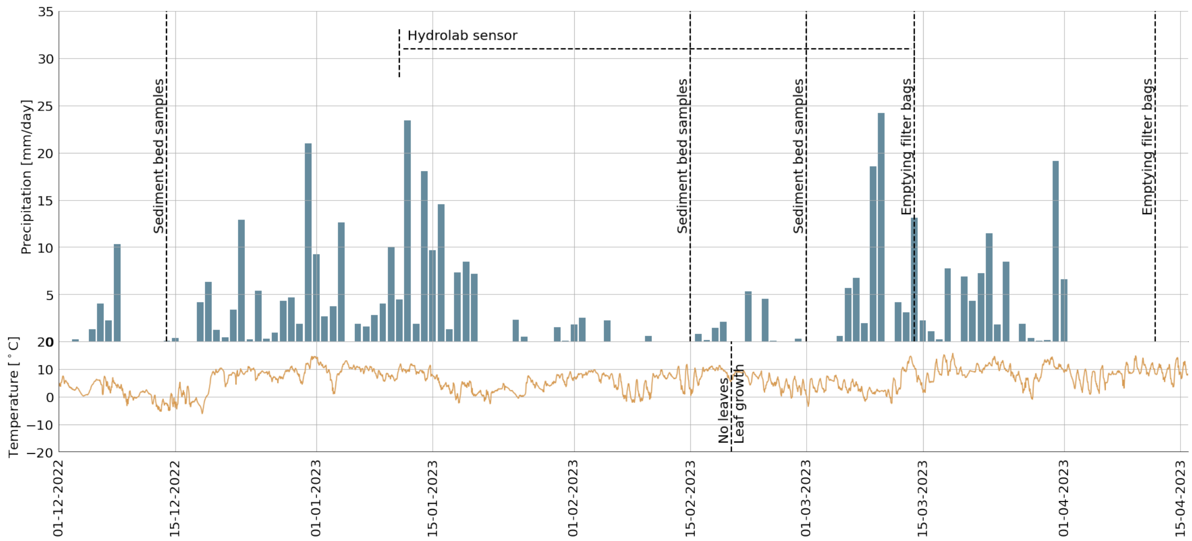


Figure 5.1: An overview of the whole study period, including the precipitation and the temperature over time (extracted from KNMI data).

5.2. Sample conduct and visual observations

The collection of samples varied based on the availability and quantity of sediment. Some filter bags did not collect enough solids for all analyses, resulting in choices having to be made. Notably, the filter bag used in the vegetated area gully pot became clogged, leading to water remaining on the street even after removing the clogged filter. Additionally, certain samples could not be collected due to the absence of sediment, such as the sediment from the sand trap gully pot in the trafficked area. Along the trafficked road in the area, there was a long gutter with limited gully pots available for sampling. For a comprehensive overview of the collected samples, including those taken and those not taken, as well as the analyses performed, it is referred to table 5.1.

Table 5.1: Overview of the collected samples and the conducted laboratory analysis

		Study area	Method	Laboratory analysis D, ρ and OC	 Chemical comp.	 Shape
1. Runoff						
High trafficked road						
14-3-2023	Yes	Rijnbuurt Oost	Filter bag	x	x	
12-4-2023	Yes	Rijnbuurt Oost	Filter bag	x		
Residential area						
14-3-2023	Yes	Rijnbuurt Oost	Filter bag		x	
12-4-2023	Yes	Rijnbuurt Oost	Filter bag	x		
Vegetated area						
14-3-2023	Yes	Rijnbuurt Oost	Filter bag		x	
12-4-2023	No	Rijnbuurt Oost	Filter bag			
2. Sand trap						
High trafficked road						
14-12-2022	No	Rivierenbuurt	Mixed scoops			
14-12-2022	Yes	Rijnbuurt Oost	Mixed scoops	x	x	
15-2-2023	No	Rijnbuurt Oost	Single scoop			
1-3-2023	No	Rijnbuurt Oost	Single scoop			
Residential area						
14-12-2022	Yes	Rivierenbuurt	Mixed scoops	x		
14-12-2022	Yes	Rijnbuurt Oost	Mixed scoops	x	x	
15-2-2023	Yes	Rijnbuurt Oost	Single scoop	x		x
1-3-2023	Yes	Rijnbuurt Oost	Single scoop	x		
3. Manhole						
Low flow rate						
14-12-2022	Yes	Rivierenbuurt	Mixed scoops	x		
14-12-2022	Yes	Rijnbuurt Oost	Mixed scoops	x	x	
15-2-2023	Yes	Rijnbuurt Oost	Single scoop	x		x
1-3-2023	Yes	Rijnbuurt Oost	Single scoop	x		
High flow rate						
14-12-2022	Yes	Rivierenbuurt	Mixed scoops	x		
14-12-2022	Yes	Rijnbuurt Oost	Mixed scoops	x	x	
15-2-2023	Yes	Rijnbuurt Oost	Single scoop	x		x
1-3-2023	Yes	Rijnbuurt Oost	Single scoop	x		
Storm sewer outfall (SSO)						
14-12-2022	Yes	Rivierenbuurt	Mixed scoops	x		
14-12-2022	Yes	Rijnbuurt Oost	Mixed scoops	x	x	
15-2-2023	Yes	Rijnbuurt Oost	Single scoop	x		x
1-3-2023	Yes	Rijnbuurt Oost	Single scoop	x		
Total samples				20	8	4

Solids that are transported by runoff into the gully pots were captured using filter bags with a pore size of 25 μm. The filter bags were emptied after 5 weeks the first time and 4 weeks the second time, as not enough solids were capture sooner. After checking the first time (after 3 weeks) not enough solids were captured and the filter bags were not clogged. After 5 weeks, the filter bags in the gully pots in the residential and the vegetated area were clogged, which caused water on the streets. Visual observations of the samples showed that the solids transported by runoff from the trafficked area were finer, darker and smoother compared to the samples from the residential and vegetated areas. The samples from the residential and vegetated areas contained more diverse particles, including large particles and debris. In addition to analyzing the solids transported by runoff stormwater, samples were also taken from the sediment bed in the sand traps using scoops. Visually, it was noticed that the samples contained many different materials, including a lot of debris and trash. Similarly, samples of the sediment bed in the manholes were also collected using scoops. During the sample collection, it was noticed that there was a significant difference in the amount of sediment present in different manholes. Some manholes contained a substantial amount of sediment, while others had very little or none at all. It was also observed that the sediment in the manholes further downstream was finer, darker and had a more gel-like texture. In some of these manhole, bubbles appeared while lowering the scoop in the water.

5.3. Sediment characteristics

In the following sections, the laboratory results of the sediment characteristics are presented.

5.3.1. Density

In this section of the results chapter, the laboratory results of the parameters are presented in the Figures 5.2 to 5.7. Figure 5.2 shows the density analysis of the samples. When examining the solids loading in the gully pots, it was observed that the density of samples from the trafficked area was higher than the density of the sample from the residential area. In the sediment bed of the sand traps, higher density values were observed on the first sampling day when mixed samples were taken. However, the single samples collected on the second and third sampling days showed lower densities. Similar patterns were observed for the densities of the sediment bed in the manholes. The mixed samples collected on the first sampling day had higher densities, whereas the single samples exhibited lower densities for manholes with higher flow rates and those located near the storm sewer outfall (SSO). The sediment bed in the manhole with a low flow rate displayed a higher density, indicating the presence of more compacted materials.

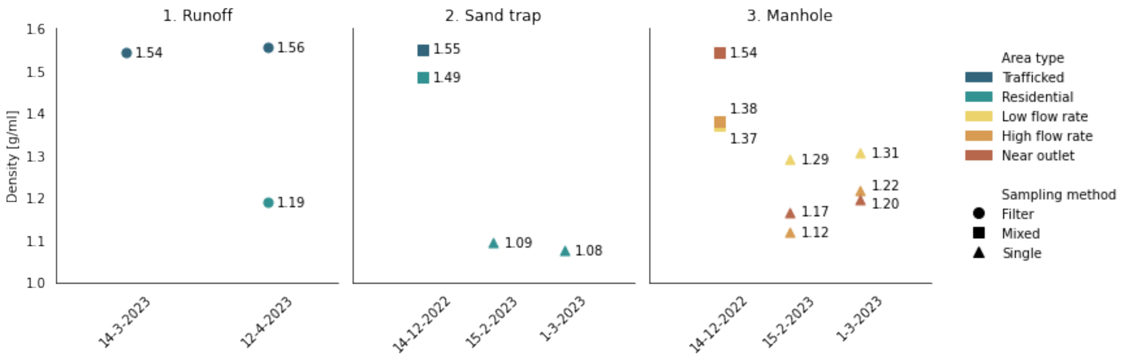


Figure 5.2: Scatter plots of the density (ρ) analysis of all samples, divided per sampling location and per sampling day. The colors indicate different area types and the markers indicate different sampling methods.

5.3.2. Organic content

Looking at Figure 5.3, the organic content of the runoff sample from the residential was significantly higher (54.6%) compared to that of the sample from the trafficked area (3% and 5.5%). The organic content of the sand trap samples showed relatively low values, except for the sample taken on the second sampling day, which had a higher organic content compared to the other samples. Analyzing the organic content of the manhole samples reveals differences between the mixed samples and single samples. The first sampling day (mixed samples) exhibited the lowest values near the SSO, while the single samples from the same manhole taken on the last two days displayed the highest values near the SSO.

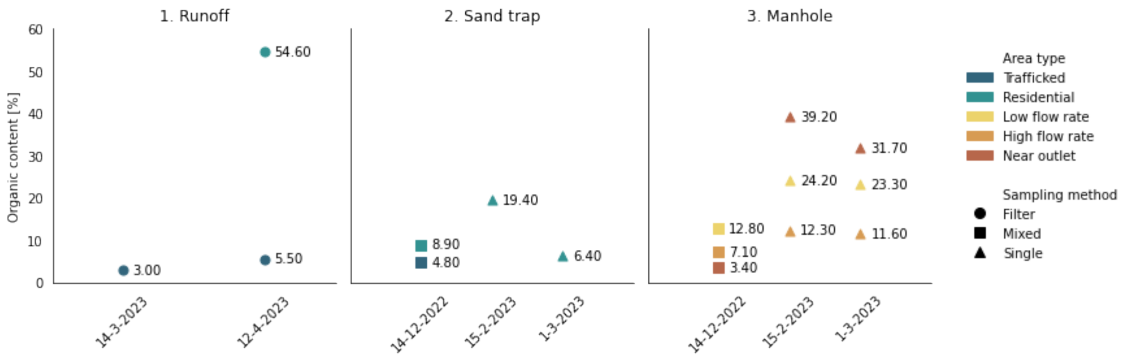
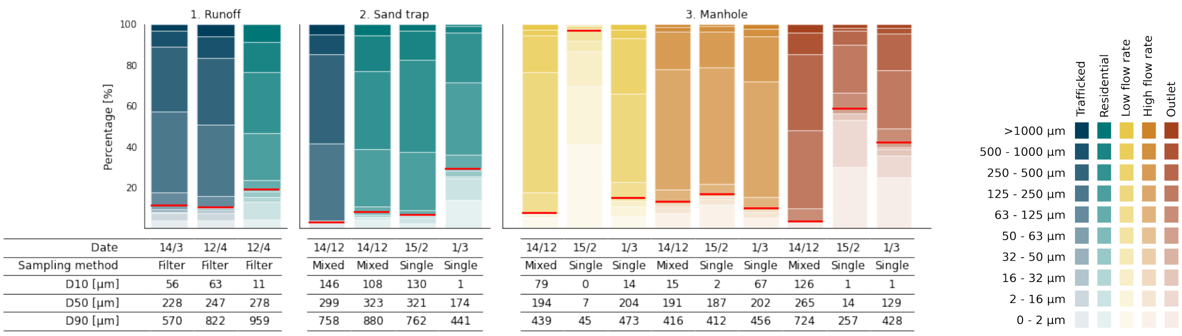


Figure 5.3: Scatter plots of the organic fraction (OF) analysis of all samples, divided per sampling location and per sampling day. The colors indicate different area types and the markers indicate different sampling methods.

5.3.3. Particle size

Figure 5.4 displays the particle size distribution (PSD) of all samples. The stacked bars represent 100% of the sample. Each shade represents the fraction of the particles in a sample within a size range. The darker the bars, the more large particles were found in the samples. The red lines highlights the fraction smaller than 63 μm. In the table, the 10th, 50th and 90th percentiles are given. The runoff samples from the trafficked area had a low fraction of small particles, with only 10-11% below 63 μm. In contrast, the residential sample had a higher fraction of small particles, with 18.8% below 63 μm. The residential area exhibited a higher proportion of fine material but also a larger amount of coarse material. Visually, the residential samples appeared more diverse, containing debris and leaves, while the trafficked area samples appeared more homogeneous. The sand trap samples generally had a low proportion of small particles, except for the sample from the last day. In the manhole samples taken on the first occasion, the manhole near the SSO had coarser material compared to the other manholes. On the second occasion, a significant amount of fine material was found in the manhole with a low flow rate and near the SSO. Finally, on the third occasion, the finest material was observed near the SSO of the manhole.

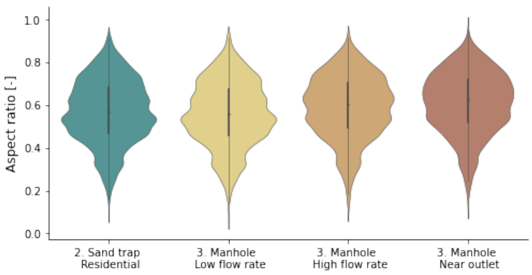


Date	14/3	12/4	12/4	14/12	14/12	15/2	1/3	14/12	15/2	1/3	14/12	15/2	1/3	14/12	15/2	1/3
Sampling method	Filter	Filter	Filter	Mixed	Mixed	Single	Single	Mixed	Single	Single	Mixed	Single	Single	Mixed	Single	Single
D10 [µm]	56	63	11	146	108	130	1	79	0	14	15	2	67	126	1	1
D50 [µm]	228	247	278	299	323	321	174	194	7	204	191	187	202	265	14	129
D90 [µm]	570	822	959	758	880	762	441	439	45	473	416	412	456	724	257	428

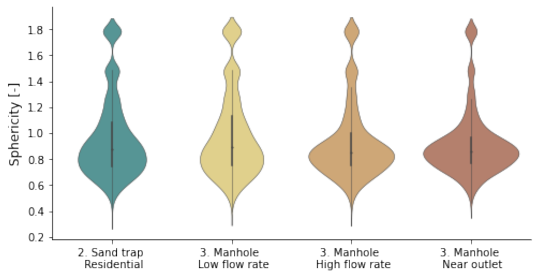
Figure 5.4: The PSD analysis of all samples. The stacked bars represent 100% of the sample. Each shade represents the fraction of the particles in a sample within a size range. The red lines indicate the fraction of particles smaller than 63 μm (TSS63) and the 10th, 50th (median) and 90th percentiles are presented in the table.

5.3.4. Particle shape

The particle shape analysis provides insights into the geometric characteristics of the particles in the sediment samples. Figure 5.5 displays the violin plots showcasing the distribution of shape parameters, including the aspect ratio and the sphericity, for four samples. These samples were collected on the second sampling day (15-2-2023) and include one sample from the sand trap and three from different manholes (low flow rate, high flow rate and near the SSO). A violin plot shows the distribution of data, allowing us to see the shape, spread and concentration of values within different groups or categories. The width of the curve at a particular point indicates the density or frequency of values at that point, while the height represents the range of values. In this case, the x-axis represents the amount of particles that have a certain aspect ratio and sphericity. Across all samples, the violin plots reveal a relatively similar distribution of shape parameters. However, there is a wide range within each sample, indicating significant variability in particle shapes. Notably, all samples exhibit an average sphericity greater than 0.9.



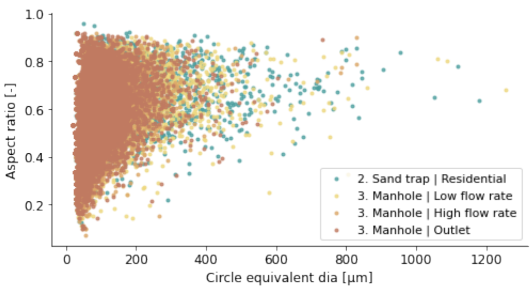
(a) The aspect ratio (ψA), which provides insight into the elongation of the particle. Higher values indicate a more elongated shape of the particle.



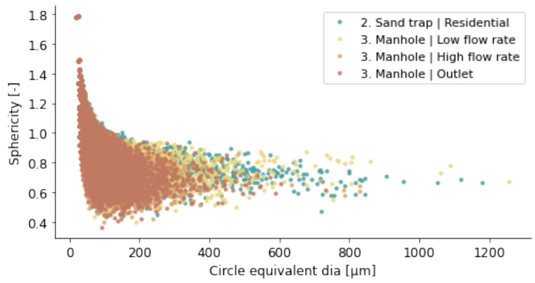
(b) The sphericity (S) parameter, which assesses the roundness of a particle. A smaller S value indicates a more irregular shape of the particle.

Figure 5.5: Distribution of the shape parameters of sediment bed samples collected on 15-2-2023 from the sand trap and three manholes. Violin plots illustrate the range and distribution of shape characteristics within each sample.

Figure 5.6 presents scatter plots illustrating the relationship between shape parameters (aspect ratio and sphericity) and the circle equivalent diameter of particles. These plots allow us to visualize the variation in particle shape across different particle sizes. In Figure 5.6a, the aspect ratio is plotted against the circle equivalent diameter. It can be observed that as the particle size increases, the aspect ratio tends to be more uniform, indicating a more regular particle shape and less elongated shapes. Smaller particle sizes exhibit greater deviations in aspect ratio, suggesting more irregular shapes. Similarly, Figure 5.6b shows the relationship between sphericity and the circle equivalent diameter. Sphericity values greater than 1 are observed for smaller particle sizes, which is not physically possible. All samples show similar patterns.



(a) The circle equivalent diameter against the aspect ratio (ψA)

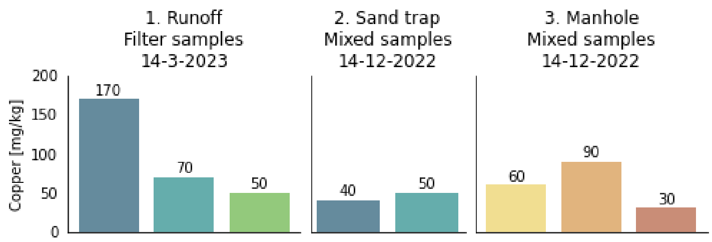


(b) The circle equivalent diameter against the sphericity (S)

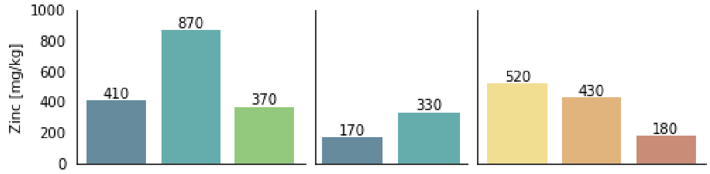
Figure 5.6: Scatter plot illustrating the relationship between the shape parameters and the circle equivalent diameter of particles collected from the sand trap and three manholes on 15-2-2023.

5.3.5. Pollutants

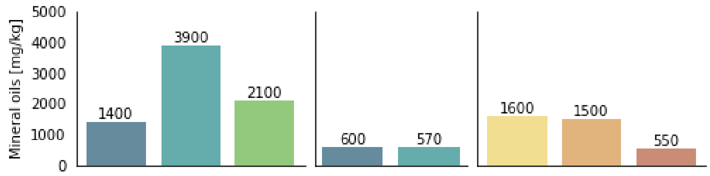
The chemical analysis of the samples shed light on the presence of various pollutants within the system. The lab results for phosphorus (P), copper (Cu), zinc (Zn), mineral oils and PAHs are presented in Figures 5.7. These figures visually depict the concentrations of these pollutants in the different samples analyzed. These samples include the runoff samples collected using the filter bags on 14-3-2023 and the sediment bed samples collected using the mixed samples on 14-12-2022. Examining the runoff samples, it was observed that the sample collected from the trafficked area had relatively low concentrations of all measured pollutants, except for copper. The concentration of copper in this sample was notably higher, measuring 228.11 mg/kg. In contrast, the runoff sample from the residential area exhibited elevated concentrations of mineral oils and PAHs. Furthermore, variations in phosphorus concentrations were observed among the different land use areas. The vegetated area had the highest phosphorus concentration, followed by the residential area and the trafficked area. Moving on to the sediment samples from the sand traps, the analysis of mixed samples taken on the first sampling day revealed that the gully pot in the trafficked area had lower concentrations of zinc, copper and PAHs compared to the gully pot in the residential area. However, a slightly higher concentration of mineral oils was observed in the gully pot of the trafficked area. Notably, the concentrations of phosphorus in the sand trap samples were below the detection limit of the laboratory analysis. Similarly, in the manhole samples, the concentrations of phosphorus were below the laboratory's detection limit of 5 g/kg. The concentrations of pollutants in the manholes were generally lowest near the SSO. This suggests that pollutants attached to particles tend to settle upstream in the system. However, it also indicates that some of these pollutants have reached close to the SSO, potentially posing a risk of being discharged from the system along with the fraction that does not attach to particles.



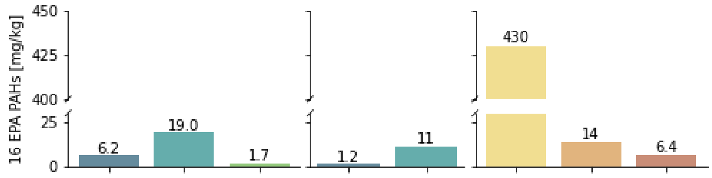
(a) Copper (Cu)



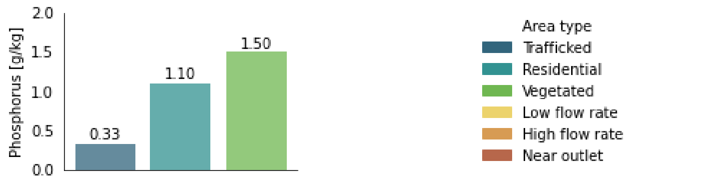
(b) Zinc (Zn)



(c) Mineral oils



(d) 16 EPA PAHs



(e) Phosphorus

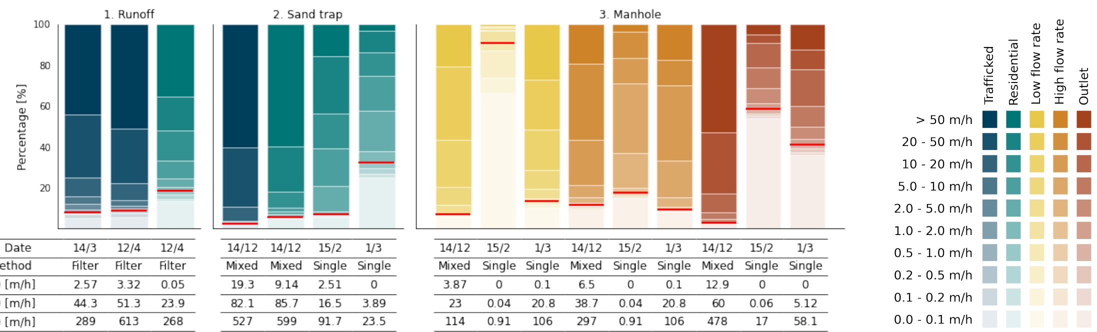
Figure 5.7: Chemical analysis of all samples. The bar plots show the concentration of key pollutants, divided per location. The runoff samples are collected using filter bags on 14-3-2023 and the sediment bed samples are collected using mixed samples on 14-12-2023.

5.4. Calculated behavior parameters

In order to gain a deeper understanding of sediment dynamics within the storm sewer system, two calculated parameters based on particle size and density were analyzed. These parameters provide insights into particle settling and resuspension, shedding light on the differences of the behavior of sediment particles under constant conditions.

5.4.1. Particle settling

Figure 5.8 illustrates the settling velocity distributions, which were calculated using the Stokes' law equation. Similar to the PSD, the bars represent 100% of the sample and each shade represents a settling velocity range. The darker the bar, the more particles that settle faster were found in the sample. The red lines indicate the fraction of the particles that settle slower than 1 m/h. The table presents the V10, V50 and V90 values (representing the 10th percentile, median and 90th percentile) of the settling velocity distributions. For the runoff samples, a higher settling velocity is observed in the trafficked area compared to the residential area. This can be attributed to the higher density of particles in the trafficked area. Regarding the sand trap samples, the mixed samples from the first sampling day exhibit particularly high settling velocities, consistent with the high densities observed in these samples. In contrast, the settling velocities of the single samples from the second and third sampling days are lower. In the manhole samples, the mixed samples show elevated settling velocities, especially in the manholes near the SSO. Conversely, the single samples from the second and third sampling days, particularly in the manhole near the SSO, exhibit very low settling velocities.

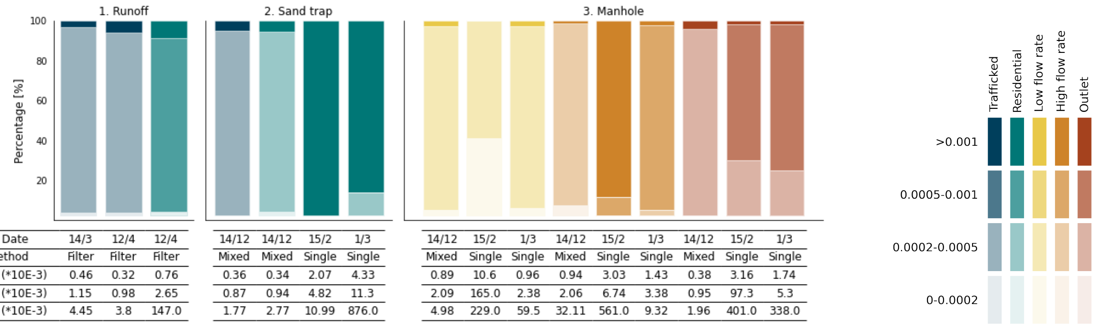


Date	14/3	12/4	12/4	14/12	14/12	15/2	1/3	14/12	15/2	1/3	14/12	15/2	1/3	14/12	15/2	1/3
Sampling method	Filter	Filter	Filter	Mixed	Mixed	Single	Single	Mixed	Single	Single	Mixed	Single	Single	Mixed	Single	Single
V10 [m/h]	2.57	3.32	0.05	19.3	9.14	2.51	0	3.87	0	0.1	6.5	0	0.1	12.9	0	0
V50 [m/h]	44.3	51.3	23.9	82.1	85.7	16.5	3.89	23	0.04	20.8	38.7	0.04	20.8	60	0.06	5.12
V90 [m/h]	289	613	268	527	599	91.7	23.5	114	0.91	106	297	0.91	106	478	17	58.1

Figure 5.8: The settling velocity distribution analysis of all samples, calculated using the Stokes' equation. The stacked bars represent 100% of the sample. Each shade represents the fraction of the particles in a sample within a settling velocity range. The red lines indicate the fraction of the particles that settle slower than 1 m/h. The table gives the 10th percentile, the median and the 90th percentile of the distribution.

5.4.2. Resuspension

The Shields parameters presented in Figure 5.9 provide insights into the critical shear stress required to initiate sediment motion for different sediment samples. The Shields parameter is a dimensionless parameter that takes into account the particle size and the density. It serves as an indicator of the likelihood of sediment resuspension. A lower Shields parameter value indicates that the sediment particle is more resistant to movement, while a higher value indicates that the particle is more easily transported by the fluid flow. From the table, it can be seen that the sediment samples from the sand trap have the lowest Shields parameter values, indicating that they are more resistant to movement than the other samples. Conversely, the sediment samples from the downstream manhole have the highest Shields parameter values, indicating that they are more easily transported by the fluid flow.



Date	14/3	12/4	12/4	14/12	14/12	15/2	1/3	14/12	15/2	1/3	14/12	15/2	1/3	14/12	15/2	1/3
Sampling method	Filter	Filter	Filter	Mixed	Mixed	Single	Single	Mixed	Single	Single	Mixed	Single	Single	Mixed	Single	Single
T10 (*10E-3)	0.46	0.32	0.76	0.36	0.34	2.07	4.33	0.89	10.6	0.96	0.94	3.03	1.43	0.38	3.16	1.74
T50 (*10E-3)	1.15	0.98	2.65	0.87	0.94	4.82	11.3	2.09	165.0	2.38	2.06	6.74	3.38	0.95	97.3	5.3
T90 (*10E-3)	4.45	3.8	147.0	1.77	2.77	10.99	876.0	4.98	229.0	59.5	32.11	561.0	9.32	1.96	401.0	338.0

Figure 5.9: The Shields parameter distribution analysis of all samples. The stacked bars represent 100% of the sample. Each shade represents the fraction of the particles in a sample within a Shields parameter range. The table gives the 10th percentile, the median and the 90th percentile of the distribution.

5.5. Deviations throughout the system and Millisil W4

The distributions of the parameters for all samples collected using single scoops and filter bags, grouped per location, are shown in Figures 5.10, 5.11 and 5.12. The yellow line represents the value of the parameter for Millisil W4. In Figure 5.10, the density, organic fraction and fraction of small particles (TSS63) are displayed. The density exhibits the widest range in the runoff samples, while the other locations show similar densities, with the sand trap having the least compacted sediment. The organic fraction also displays the widest range in the runoff samples. The organic content of the sediment increases as it moves through the system, with the highest organic content found in the sample from the manhole near the SSO. Millisil W4, in contrast, does not contain organic material. Furthermore, the runoff and sand trap samples have a lower fraction of small particles (>63 µm) compared to Millisil W4. The manhole samples exhibit a wide range, with the manhole near the SSO showing a similar amount of small particles as Millisil W4.

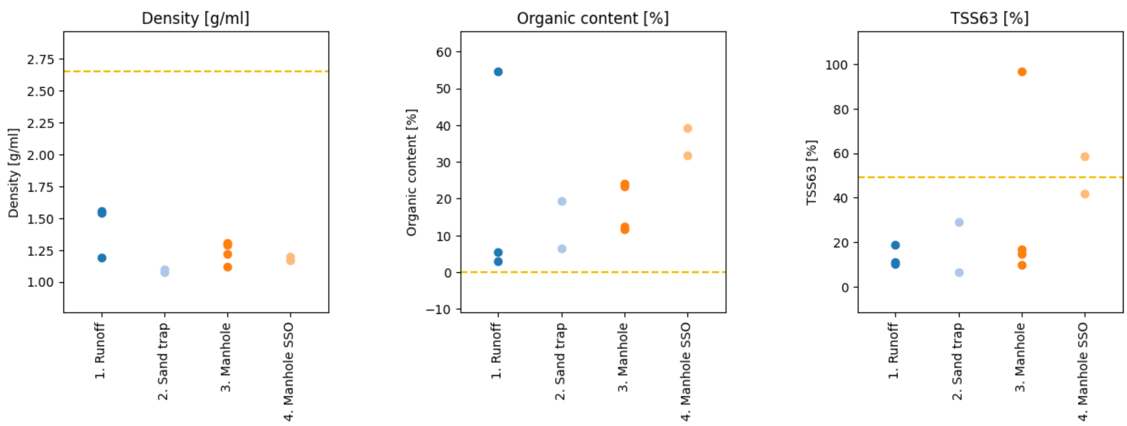


Figure 5.10: Scatter plots showing the distribution of density, organic content and fraction of small particles among the runoff, sand trap and manhole samples. The dashed lines represent the corresponding values of Millisil W4.

Figure 5.11 illustrates the PSD. The analysis focuses on the D10, D50 and D90 values, which represent the particle sizes below which 10%, 50% and 90% of the particles fall, respectively. One notable observation is the wide range of D10 values across all locations, particularly in the sand traps. This indicates that the sediment in the sand traps consists of a diverse range of particle sizes, ranging from fine particles to coarser ones. On the other hand, the D50 values for all sample types, except the downstream manhole, exceed 100 µm. This suggests that the sediment in the system is predominantly composed of sand-sized particles. Comparing the sediment in the sand traps to the sediment in the manhole samples, it is evident that the sand trap sediment appears relatively coarser. Furthermore, the PSDs indicate a trend of finer sediments being present further downstream in the system.

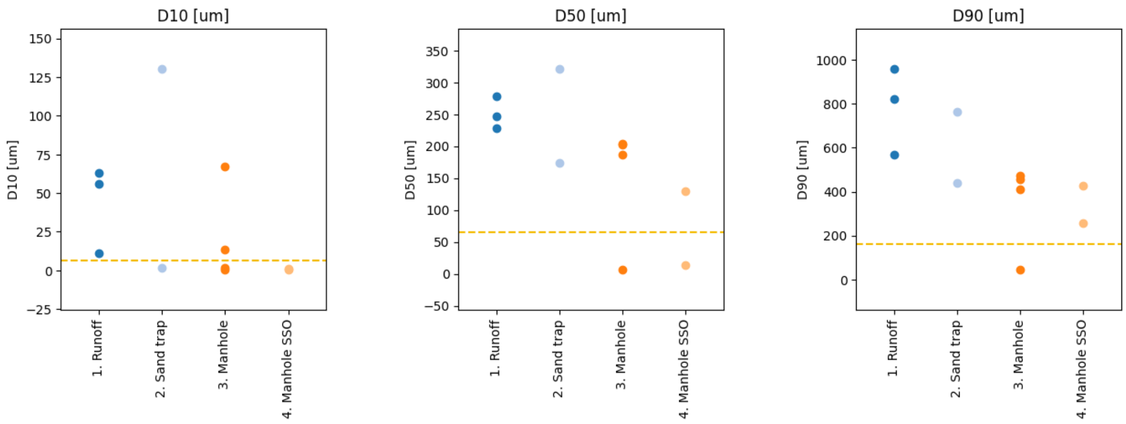


Figure 5.11: Scatter plots illustrating the distribution of particle size (D10, D50 and D90) for the runoff, sand trap and manhole samples. The dashed lines represent the corresponding values of Millisil W4.

Figure 5.12 presents the distribution of settling velocities among the different locations within the stormwater system, as well as a comparison with Millisil W4. The settling velocities are represented by V10, V50 and V90, which indicate the fractions (10%, 50% and 90%) of particles that settle slower than the respective velocity values. The V10 values show a clear decrease in settling velocity as it moves further downstream in the system. This indicates that at the start of the system, where the runoff enters the gully pots, the sediment particles settle rapidly. However, as it approaches the SSO near the end of the system, the sediment particles settle at a much slower rate. Examining the V50 and V90 values, it is observed that the differences in settling velocities between the sand trap samples and the manhole samples become smaller. This suggests that the settling velocities of sediment particles in these two locations tend to converge, showing similar median and 90th percentile settling velocities. Furthermore, the settling velocities of the sediment samples from both the sand traps and manholes exhibit similarities to those of Millisil W4. The V50 and V90 values for the runoff samples are considerably higher compared to the sediment samples.

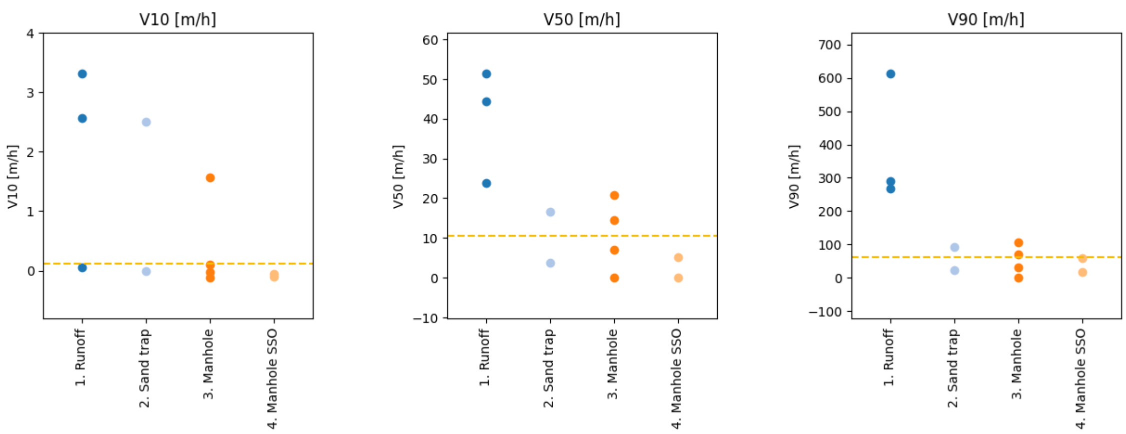


Figure 5.12: Scatter plots displaying the distribution of settling velocities (V10, V50 and V90) for the runoff, sand trap and manhole samples. The dashed lines represent the corresponding values of Millisil W4.

Figure 5.13 presents the distribution of Shields parameters (T10, T50 and T90) among the runoff, sand trap and manhole samples, with dashed lines representing the corresponding values of Millisil W4. The Shields parameters indicate the fraction of particles that would remain settled under specific flow conditions. The higher the Shields parameter, the more likely the particles are to resuspend. Analyzing the results, it can be seen that the runoff samples exhibit the lowest values for T10, T50 and T90, suggesting that these solids would resuspend less quickly compared to the other samples under the same flow conditions. In contrast, the sediment samples collected from the sand traps and manholes show comparable Shields parameters, indicating a relatively higher resuspension potential compared to the runoff samples. However, there is a slight increase in the Shields parameters for the manhole near the SSO, particularly for T50 and T90. This implies that sediments closer to the SSO may be less resistant to resuspension. Comparing the results to the values of Millisil W4, it is observed that the Shields parameters in the sediment samples from the stormwater system are similar to or higher than those of Millisil W4. This suggests that the sediment particles in the stormwater system, particularly in the sand traps and manholes, have a comparable or greater potential for resuspension under specific flow conditions compared to the standardized test material.

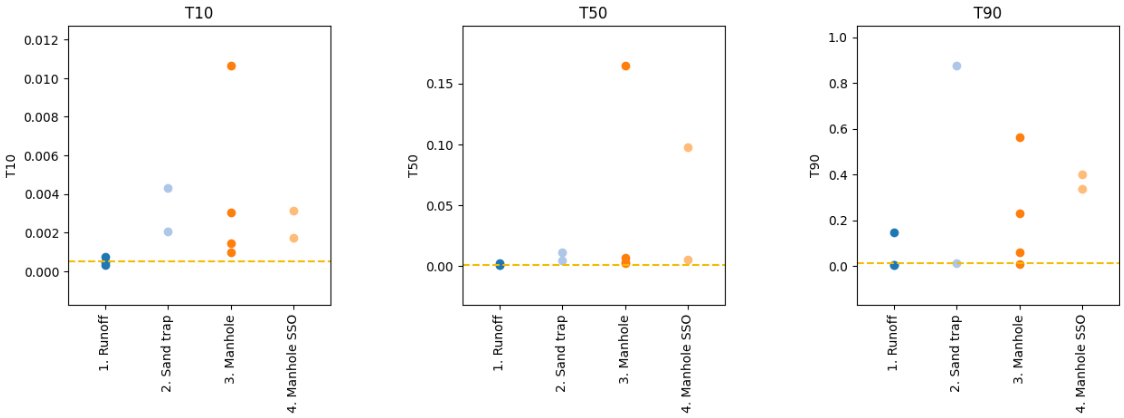


Figure 5.13: Scatter plots displaying the distribution of Shields parameters (T10, T50 and T90) for the runoff, sand trap and manhole samples. The dashed lines represent the corresponding values of Millisil W4.

Figure 5.14 presents the average concentrations of pollutants found in the samples. It is important to note that not all samples were taken on the same day and the runoff samples were collected using the filter bag method rather than scooping from the sediment bed. For most pollutants, the highest concentrations were found in the runoff samples, followed by the manholes within the system, the sand trap and finally, the manhole near the SSO. The phosphorus concentration was only reported for the runoff samples, as the other locations were below the detection limit. Additionally, one manhole sample exhibited exceptionally high concentrations of polycyclic aromatic hydrocarbons (PAHs).

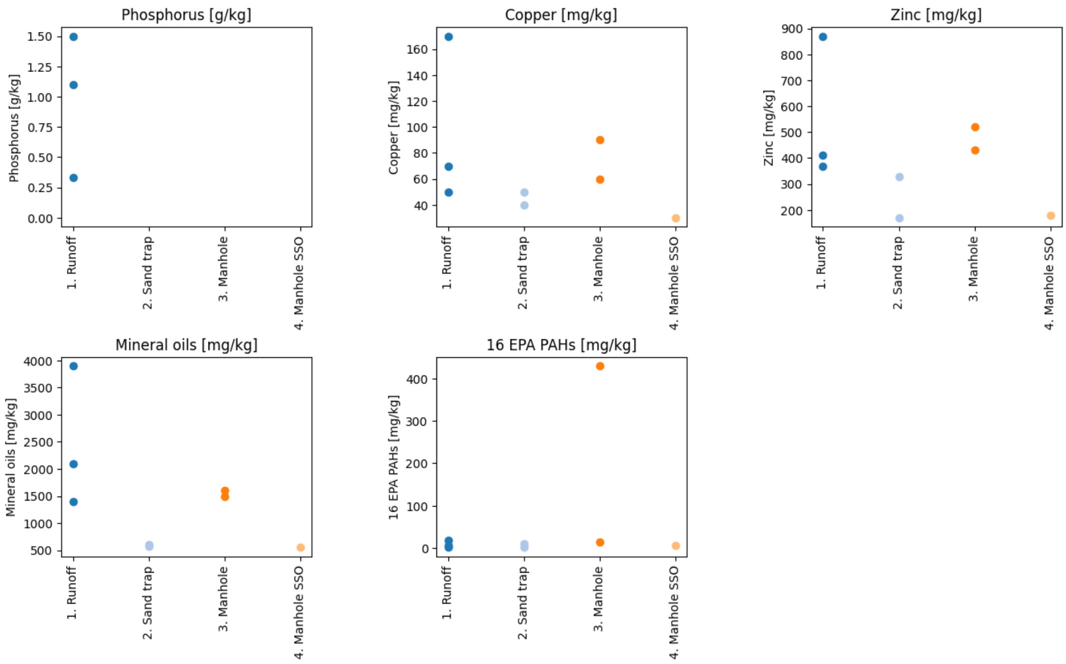


Figure 5.14: Scatter plots displaying the distribution of the concentrations of the pollutants for the runoff, sand trap and manhole samples

5.6. Comparison to the larger area Rivierenbuurt

Mixed samples were collected on the first sampling day in the study area Rijnbuurt Oost and the larger area Rivierenbuurt and analyzed for various physical characteristics, including density, organic content and PSD. The results, presented in Figure 5.15, allow for an assessment of the similarities and differences between the two study areas. Average values are used per location (the sand traps, manholes and the manholes near the SSO). The average of the whole area is indicated by the dashed lines.

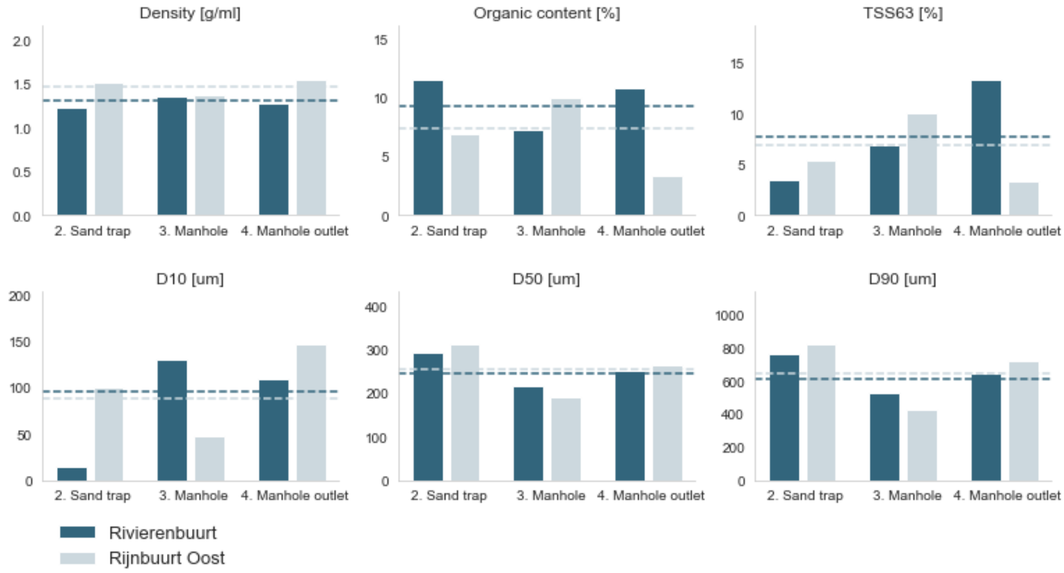
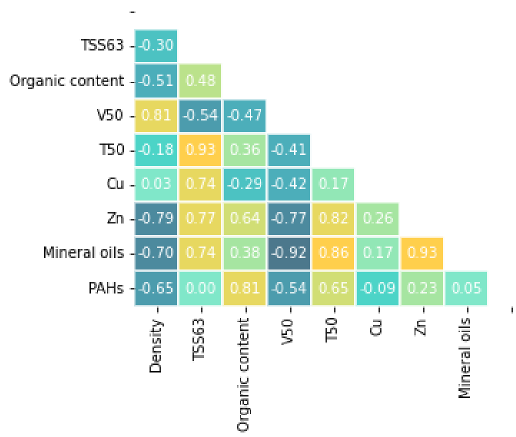


Figure 5.15: The density, organic content, the fraction small particles (TSS63) and particle size distribution (presented as D10, D50 and D90) of the mixed samples taken the first sampling day in Rijnbuurt Oost and the larger area Rivierenbuurt. The results are showed as the average per type of sampling location (with the manholes near the SSO considered seperate).

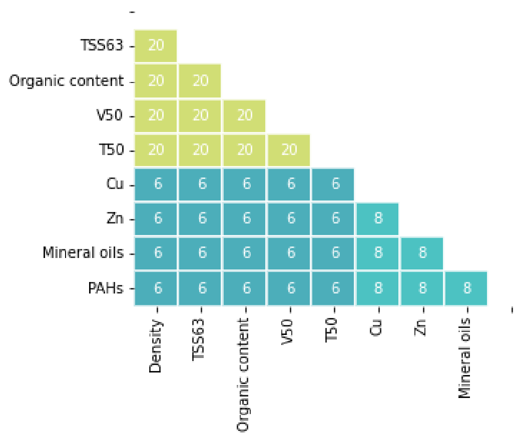
5.7. Correlation between the parameters

To explore the relationships between the parameters discussed in this chapter, a correlation matrix was constructed. Figure 5.16a presents the calculated correlation factors, ranging from -1 to 1, indicating negative and positive correlations, respectively. The matrix provides an overview of the associations between the parameters and Figure 5.16b indicates the number of samples used for the correlation analysis.

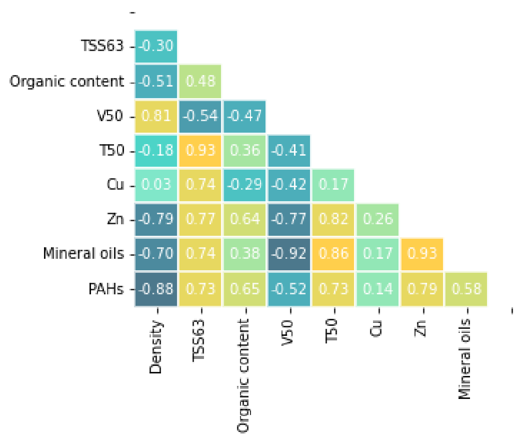
Analyzing the correlation matrix reveals several correlations. The fraction of small particles (TSS63) demonstrates a relatively high positive correlation with the concentrations of copper, zinc and mineral oils. This suggests that samples with a higher proportion of small particles also tend to have elevated levels of these pollutants. However, the correlation between TSS63 and PAHs was not observed, likely due to a single sample exhibiting an exceptionally high PAH concentration. To assess the correlation without this outlier, a revised correlation matrix was created (Figure 5.16c). Notably, this revised matrix shows an increased correlation factor between the concentration of PAHs and TSS63. Moreover, the median of the settling velocity distribution shows a positive correlation with density and a negative correlation with the fraction of small particles (TSS63). These correlations align with expectations, as the settling velocity calculation is based on particle size and density. Additionally, density and V50 (median settling velocity) display a negative correlation with the concentrations of zinc, mineral oils and PAHs. Conversely, there is a relatively high positive correlation factor among the concentrations of zinc, mineral oils and PAHs.



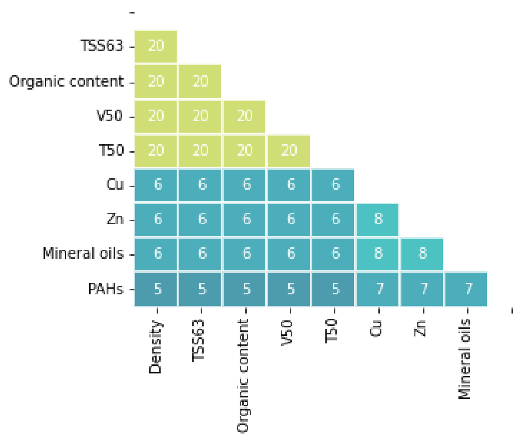
(a) Calculated correlation factors for the analyzed parameters, ranging from -1 to 1, indicating negative and positive correlations.



(b) Number of samples used for the calculation of the correlation factor between the parameters.



(c) Revised correlation factors for the analyzed parameters excluding the outlier.



(d) Number of samples used for the calculation of the correlation factor between the parameters (excluding the outlier).

Figure 5.16: Correlation matrix and number of samples

5.8. Solids dynamics in manholes

To investigate the dynamics in a manhole, a multiparameter sonde was used to measure turbidity, conductivity and water temperature. The measurements were taken during the study period and plotted over time in Figure 5.17, along with the hourly precipitation data and the flow velocity which was modeled based on the precipitation data. Upon initial examination, it was observed that the parameters exhibited a response following precipitation events. During dry days, the turbidity levels remained relatively stable, with values ranging between 0 and 10 NTU.

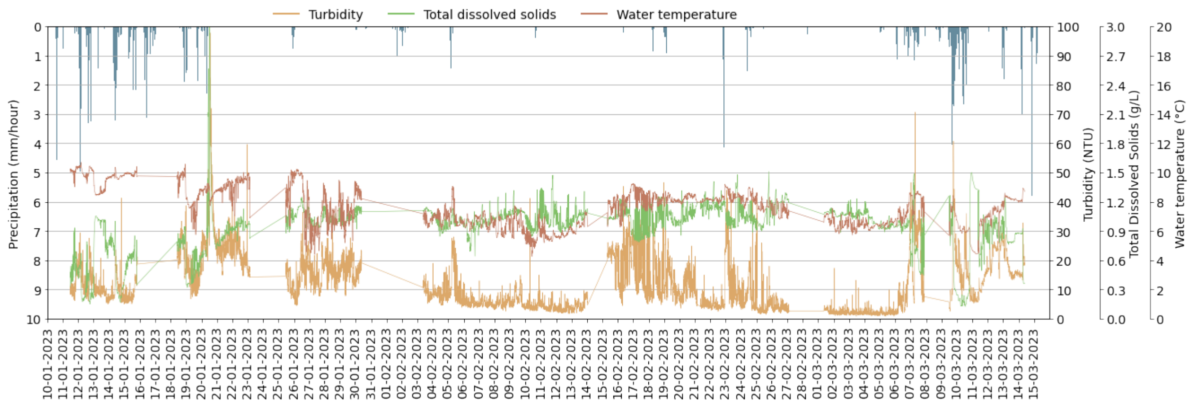


Figure 5.17: Hydrolab sensor measurements during the study period, including turbidity, conductivity and water temperature, plotted over time along with hourly precipitation data.

To assess the behavior of the parameters during rainfall events, the precipitation events occurring within the study period were identified and summarized in Table 5.2. The study period had a limited number of heavy rainfall events, with only a few instances where the total amount of rainfall exceeded 10 mm. These events were characterized by a longer duration. Similarly, there were only a few cases where the maximum intensity of rainfall surpassed 10 mm/h. The parameters' behavior was evaluated for each event. These figures are displayed in Appendix D, together with the observations. Two events are elaborated on in this section. Figures 5.18 and 5.19 depict the parameter response during two rainfall events with relatively higher precipitation amounts and maximum intensities.

Table 5.2: Identified rainfall events during the measurement period of the Hydrolab sensor, including the sum of the precipitation of the event, the duration, the average intensity, the maximum intensity and the amount of dry hour prior to the event.

	Start	End	Sum [mm]	Duration [h]	I [mm/h]	I_{max} [mm/h]	ADT [hours]
1	2023-01-11 18:00	2023-01-11 19:15	2.72	1.58	1.72	5.46	16.3
2	2023-01-12 00:10	2023-01-12 05:35	10.4	5.75	1.82	9.37	2.0
3	2023-01-12 14:55	2023-01-12 18:05	7.18	3.5	2.05	7.94	0.83
4	2023-01-12 20:10	2023-01-12 20:55	3.25	1.08	3.00	12.6	0.5
5	2023-01-14 05:55	2023-01-14 16:15	17.3	10.7	1.62	6.11	8.33
6	2023-01-15 07:35	2023-01-15 09:10	2.33	1.92	1.21	9.73	11.9
7	2023-01-15 16:55	2023-01-15 19:10	3.96	2.58	1.53	6.28	0.83
8	2023-01-18 21:10	2023-01-18 22:55	4.69	2.08	2.25	5.27	0.58
9	2023-01-20 08:15	2023-01-20 10:10	5.62	2.25	2.50	5.47	2.25
10	2023-02-22 20:25	2023-02-22 21:50	5.21	1.75	2.98	8.12	87.3
11	2023-03-09 15:25	2023-03-10 00:50	17.6	9.75	1.80	11.0	1.17
12	2023-03-10 01:35	2023-03-10 03:50	2.69	2.58	1.04	7.42	0.75
13	2023-03-10 04:20	2023-03-10 04:50	1.46	0.83	1.76	4.82	0.5
14	2023-03-10 06:50	2023-03-10 12:20	13.5	5.83	2.31	8.38	2.0
15	2023-03-12 22:25	2023-03-12 23:30	3.57	1.42	2.52	6.82	18.0
16	2023-03-13 00:00	2023-03-13 01:40	2.54	2.0	1.27	5.71	0.5
17	2023-03-14 04:15	2023-03-14 06:50	6.01	2.92	2.06	8.39	21.3

Rainfall event 5

During rainfall event 5, which had a long duration of 10.7 hours, a clear response was observed in the measured parameters. After the peak intensity of 6.11 mm/h, turbidity increased, indicating a higher presence of suspended solids in the water. Simultaneously, the total dissolved solids (TDS) exhibited a decrease, suggesting the dilution of water. The water temperature also showed a gradual increase. This response suggests that the high-intensity and long-duration rainfall event mobilized and transported solids within the manhole, leading to increased turbidity and a decrease in dissolved solids. The delayed response observed in this event indicates that it takes time for the solids to be transported and deposited within the system, resulting in changes in the measured parameters.

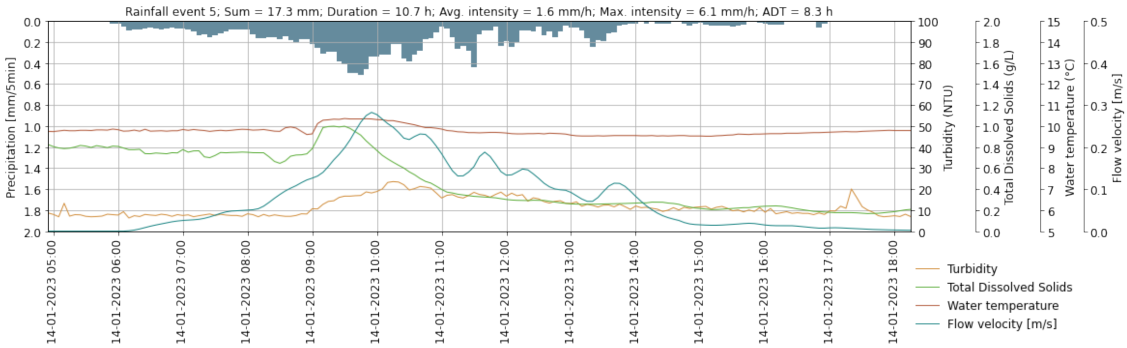


Figure 5.18: The turbidity, total dissolved solids, water temperature and precipitation per five minutes during rainfall event 5.

Rainfall event 11

Rainfall event 11, characterized by its relatively heavy intensity and a duration of 9.75 hours, displayed a clear response in all measured parameters. Approximately an hour after the initial peak intensity of 11.0 mm/h, turbidity increased from 10 NTU to 60 NTU in an hour, while the flow velocity already peaked right after the precipitation peak. The total dissolved solids (TDS) exhibited a similar response, with a slight increase followed by a substantial decrease, indicating the dilution of the water. The water temperature also decreased slowly during the event.

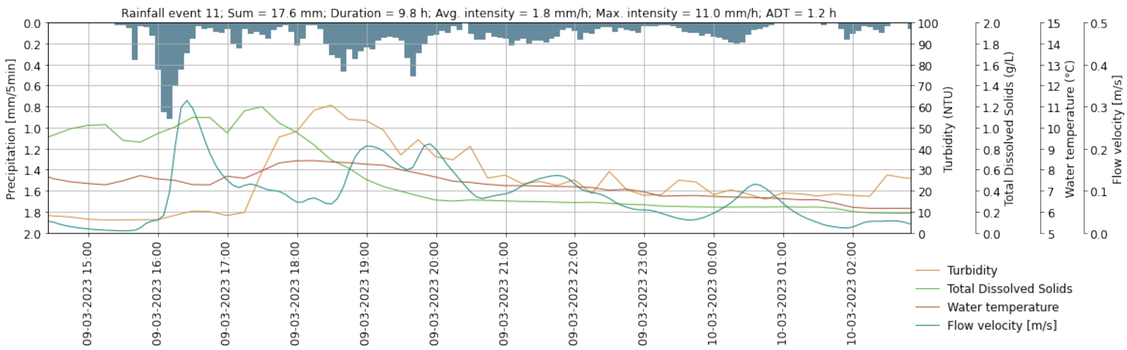


Figure 5.19: The turbidity, total dissolved solids, water temperature and precipitation per five minutes during rainfall event 11.

Observed pattern

Based on the analysis of the rainfall events, a consistent pattern was observed in many of the events with a relatively higher rainfall duration or intensity. The parameters showed a delayed response, with changes occurring after the peak intensity of the rainfall event. This delayed response suggests that it takes time for the solids to be transported and deposited within the system, leading to changes in the measured parameters. Furthermore, it was noticed that several events displayed a common pattern. After the initial peak of the event (when the intensity exceeded a certain threshold), the total dissolved solids decreased while turbidity increased. Over time, both parameters tended to return to their "stable" values. However, it is important to note that not all events exhibited this pattern. Some events showed a limited or no response in the parameters. The rainfall events are shown in Appendix D, together with the observations. Table 5.3 provides a summary of the rainfall events, a short description based on the parameter responses and an indication of whether the consistent pattern (as observed in many graphs) was seen in each event.

Table 5.3: Summary of the rainfall events, their descriptions based on the parameter responses and an indication of whether the consistent pattern was seen in each event.

	Description	**Pattern**
1	Not very heavy rain. Turbidity shows no response. TDS shows variations. Temperature varies slightly.	No
2	Relatively heavy event. TDS initially increases, then decreases. Turbidity shows minimal response.	No
3	Same day as event 2. TDS shows slight decrease. Turbidity shows slight increase during flow peak.	Yes
4	High maximum intensity, but no significant response in parameters.	No
5	Long duration event with clear responses in TDS and turbidity.	Yes
6	No response observed, likely due to low precipitation reaching the sewer system.	No
7	Responses seen approximately 1 hour after the peak. TDS decreases, turbidity increases.	Yes
8	Variations in all parameters, short dry period before event. Turbidity increases, TDS decrease.	Yes
9	Similar to event 8, but larger response in conductivity observed.	No
10	Long dry period before event, relatively high intensity. Only slight (and late) changes of parameters.	No
11	Relatively heavy rainfall event. Clear responses observed in TDS, turbidity and water temperature.	Yes
12	Minimal response in parameters, possibly due to short dry period or insufficient precipitation.	No
13	Similar to event 12, limited response observed.	No
14	Turbidity increases after the highest peak, no significant response in TDS and water temperature.	No
15	Variations in all parameters, but not significant. Event considered light.	No
16	Little response observed, minor variations in TDS.	No
17	Clear responses observed in TDS, turbidity and water temperature.	Yes

6 Discussion

The discussion chapter interprets the results obtained from the study. It provides a comprehensive analysis and interpretation of the results (section 6.1) and addresses uncertainties and limitations of the study. The chapter explores the representativeness of the study area Rijnbuurt Oost, evaluates the sampling methods employed (section 6.2) and discusses the overall limitations of the study (section 6.3).

6.1. Interpretation of the results

In this section, an interpretation of the results obtained from the sediment analysis is provided. Each parameter, including particle size distribution (PSD), particle shape, density, organic fraction and the chemical composition, is discussed. The potential correlations are explored between these parameters as well as their implications for the settling and resuspension of sediment. By examining the relationships between these factors, a better understanding can be gained of how they influence the behavior of sediment in stormwater systems.

6.1.1. Particle density

The density of the sediment samples varied among the different areas and sampling occasions. It was expected that coarser sediments and sediments with higher organic fractions would exhibit lower densities (de Graaf et al., 2012; Gelhardt et al., 2021; Rietveld et al., 2021). This trend was observed within the runoff samples, where samples from the trafficked area displayed higher densities compared to samples from the residential area. The differences in density could be attributed to the different composition and sources of sediment in each area. The residential area, characterized by more natural and organic materials, may have lower densities due to the presence of organic matter.

However, when examining the overview of densities among the locations in Figure 5.10, the density values did not follow the same trend as the organic fractions and PSDs. While it expects the density to decrease further down the system based on the organic fractions and PSDs, the sand trap samples exhibited the lowest densities. The sediment bed in the manhole with a low flow rate showed a higher density, indicating the presence of more compacted materials. This can be attributed to the longer residence time for sediments in manholes with low flow rates, allowing for increased compaction over time. The observed variations in density among the samples highlight the influence of flow conditions and sediment accumulation patterns within the system. It is worth noting that the density values found in the manholes were slightly higher than the densities of sediments at the beginning and end of the sedimentation pipe in Amsterdam, which were measured to be 1144 kg/m^3 and 1098 kg/m^3 respectively, as reported by Nijman et al. (2015). This difference in density could be attributed to variations in sampling methods and locations within the sewer system.

6.1.2. Organic fraction

The organic content of the sediment samples showed significant differences between the areas and sampling occasions. The runoff samples from the residential area exhibited significantly higher organic content compared to samples from the trafficked area. This finding aligns with the study conducted by Rietveld et al. (2021), which reported organic fractions ranging from 17% to 78% in runoff samples from a residential area. In contrast, the samples from the trafficked area had lower organic content. The variations in organic fraction can be attributed to the different land uses and sediment sources in each area. The presence of natural and organic materials, such as vegetation and soil, in the residential area likely contributed to the higher organic fraction in the samples. On the other hand, the trafficked area, characterized by compacted materials and limited organic matter, resulted in lower organic content. It is worth noting that the samples were collected around the start of the leaf growth phase, which could also impact the organic fraction.

Examining the sand trap samples, most of them displayed relatively low organic content, except for the sample taken on the second sampling day, which had a slightly higher organic content compared to the other samples. The variation in organic content between the second and third sampling days, despite being collected from the same gully pot, could be attributed to variations in preceding rainfall events, which may have influenced the amount of organic material washed into the system.

Analyzing the organic content of the sediment bed in the manholes, differences were observed between the mixed samples taken on the first sampling day and the single samples collected on the last two days. The mixed samples displayed the lowest organic content near the storm sewer outfall (SSO), while the single samples exhibited the highest organic content near the SSO. This observation suggests that a greater amount of organic material is transported downstream compared to inorganic material. It may also indicate that more organic material becomes attached to particles, leading to increased accumulation of settled organic material. Additionally, variations in organic content could be influenced by biological breakdown processes and the residence time of sediments in the manholes. the organic fractions found by Nijman et al. (2015) in Amsterdam, both before and after the sedimentation pipe, were reported to be 18% and 31% respectively. These values are consistent with the organic fractions observed in this study, with values above 30% at the SSO and ranging from 12% to 25% further upstream.

6.1.3. Particle size

The observed differences in PSD among the runoff samples were notable. Samples collected from the trafficked area exhibited a lower fraction of small particles (<63 µm) compared to samples from the residential areas. In contrast, the samples from the residential area displayed a higher fraction of small particles but also exhibited a larger amount of coarse material. The differences in PSD could be attributed to the different sources and characteristics of sediment in each area. The residential area with more natural and organic materials may have contributed to the presence of a higher fraction of small particles and coarse material. Visually, the samples from the residential area appeared more diverse as well. The D50 values obtained in this study were slightly lower than those reported by Rietveld et al. (2021), who documented a range of 420-24000 µm. This difference could be attributed to the use of a filter bag with a smaller pore size in the sampling method. The PSD of the sand trap samples also revealed slightly lower D50 values compared to those reported by Pratt & Adams (1984) and Grottker (1990), ranging from 400 to 1500 µm. Additionally, upon visual examination of the microscope photos, it seemed apparent that the sand trap sample contained a higher abundance of sand particles compared to the manhole samples. This visual observation further supports the notion that the sand trap captures a larger proportion of coarser sediment particles.

On the first sampling day, the mixed samples from the manholes near the system's SSO displayed coarser material compared to the other manholes. which is not consistent with previous findings in the literature. Studies, such as Naves et al. (2020) and Nijman (2019), have investigated the wash-off and transport processes in drainage systems and consistently reported that finer particles tend to be found at the SSO of the system. They explain that PSD after rainfall events depends on factors such as initial street load, rainfall characteristics and sampling location. The finest particles, typically smaller than 50 µm, are more likely to wash through to the surface water, regardless of the neighborhood or the specific facilities in place (Nijman, 2019). Larger particles are more likely to settle earlier in the system. Solids collected at the outfall or downstream in the drainage pipe may have undergone multiple settling and erosion cycles during transport, which can smooth out the dynamics of wash-off processes on the street (Rietveld et al., 2021). Additionally, the breakdown process of organic matter over a longer residence time can contribute to the finer particle size observed downstream (Goess-Enzenberg, 2020). Given these established patterns in the literature, the coarser material observed near the SSO on the first sampling day in the mixed samples may be an exception or a result of potential errors introduced during sampling. On the subsequent sampling days, the single samples collected from the same location near the system's SSO showed a shift towards finer material which aligns with the literature.

The unexpected observation of coarser material near the SSO on the first sampling day in the mixed samples raises questions regarding the accuracy and representativeness of the results. It is important to consider potential factors that could have contributed to this deviation from the expected pattern observed in the literature. One possibility is the presence of an outlier or a localized source of coarser sediment in the mixed sample, which could have skewed the overall PSD. Another factor to consider is the sampling method itself, which may have introduced variability and influenced the distribution of sediment particles within the manholes. Variations in sampling techniques, such as the position and depth at which samples were collected, could have influenced the PSD observed in the mixed samples on the first sampling day. Further investigation and refinement of the sampling protocols could help minimize these potential sources of error and improve the reliability of the results.

6.1.4. Particle shape

The analysis of particle shape parameters revealed similarities among the different samples. All samples exhibited similar distributions with high standard deviation values, indicating a wide dispersion in sphericity and aspect ratio values within each sample. This finding suggests that particles within each sample possess a diverse range of shapes.

A previous study conducted by Rommel et al. (2020) also reported similar findings in street dust samples collected from various locations. This research investigated the particle shape of road-deposited sediments and indicated that these particles often have irregular surfaces and a high proportion of elongated particles (Rommel et al., 2020). The size and shape of the samples analyzed by Rommel et al. (2020) were comparable to tire wear particles and regardless of their origin, all road-deposited sediments exhibited similar particle shapes.

It is worth noting that some sphericity parameter values were found to be above 1, which is not physically possible and suggests the presence of errors in the measurements. Therefore, it is important to acknowledge the uncertainties associated with the measurement method and microscope analysis, as they can contribute to variations in the observed particle shape characteristics.

6.1.5. Pollutant behavior

Analyzing the results, it is evident that the highest concentrations of pollutants, such as zinc, copper mineral oils, were found in the runoff samples. This can be attributed to the direct contact of the runoff with various pollution sources, including vehicles, road surfaces and other anthropogenic activities. In the runoff sample from the trafficked area, a high concentration of copper was observed. This could be attributed to the proximity of the sampling point to tram rails. Additionally, the high concentration of zinc in the residential area can be linked to the presence of bitumen roofs, as reported by Stichting RIONED/STOWA (2020). This study also demonstrated that areas with bitumen roofs displayed higher concentrations of mineral oils, which aligns with the findings of the current study. Surprisingly, the trafficked area exhibited lower values of mineral oils and PAHs than expected. Conversely, the residential area showed higher values, which could be attributed to parked cars or other residential pollution sources. Regarding phosphorus concentration, the vegetated area exhibited the highest concentration, followed by the residential area and then the trafficked area, which aligns with expectations considering the varying levels of vegetation cover.

The sand trap samples consistently displayed lower pollutant values across all parameters. The manholes, on the other hand, exhibited slightly higher values, with the manhole near the SSO displaying the lowest concentrations. This pattern is especially notable for zinc, copper mineral oils. However, it is important to note that the PAH concentration in the manhole with a low flow rate showed an exceptionally high value, which deviated from the expected pattern due to this outlier.

The behavior of pollutants in stormwater is influenced by their binding to particles. Previous studies, such as the research conducted by F. Boogaard et al. (2014), have highlighted the distribution of pollution loads between dissolved and particle-bound forms in runoff. It has been observed that nutrients are less bound to particles compared to heavy metals and polycyclic aromatic hydrocarbons (PAHs). The binding percentages for copper, zinc phosphorus ranged from approximately 55% to 75%, while the binding percentages for various PAHs exceeded 70% (F. Boogaard & Lemmen, 2007; F. Boogaard et al., 2014). Moreover, it is consistently observed that the majority of pollutants tend to be bound to smaller particles. Finer particles, such as silt and clay particles with a size smaller than 63 µm, possess a larger specific surface area, making them more favorable for pollutant adsorption (F. Boogaard et al., 2014; Goess-Enzenberg, 2020; Nijman, 2019).

Based on these findings, it can be observed that the higher concentrations of pollutants shown in the runoff samples collected directly from the streets can be attributed to the initial flush of particles carrying pollutants into the system during rainfall events. As the sediment progresses through the system, there is more time for pollutants to attach to particles and settle. The sand trap, predominantly containing sand particles, exhibits lower pollutant concentrations due to the shorter residence time and limited opportunity for pollutant attachment and settling. Furthermore, the concentrations of pollutants near the SSO of the system are lower compared to upstream locations, as attached pollutants have already settled earlier in the system. It is important to note that the limited number of samples and the presence of outlier values emphasize the need for cautious interpretation of the data.

6.1.6. Settling velocity and resuspension

The evaluation of settling velocity and resuspension provides insights into the dynamics of sediment transport within the stormwater system. The settling velocity analysis indicates that larger particles tend to settle more rapidly than smaller ones, contributing to sediment deposition in the system. However, it is important to note that the analysis was based on the average density of the samples and did not consider the density within specific particle size ranges. The settling velocity analysis relied on the simplified Stokes' equation. While this equation provides a useful approximation, it is important to recognize that it may overestimate the settling velocities in this context. Therefore, the calculated settling velocities should be interpreted as relative values for comparison rather than absolute values.

The settling rates were observed to be highest in the runoff samples. In comparison, Rietveld et al. (2021) reported settling velocities ranging from 36 to 216 m/h, with a v50 value of 140 m/h for runoff samples collected from a residential area during their monitoring period. Their settling velocities were determined using a settling column, while the values in the current study were calculated using a simplified equation. Also, the samples collected in this study contained more fine material. As a result, the settling velocities in this study were slightly lower than those reported by Rietveld et al. (2021).

The sand trap samples exhibited lower settling velocities compared to the runoff samples. The settling velocities of the sand traps and manholes were comparable for v50 and v90. Notably, the settling velocities near the SSO were the lowest. This pattern aligns with the findings of Nijman (2019), who reported that 30% of particles in the sand traps, 25% in the conduits only 3% in the sedimentation facilities had settling rates exceeding 10 m/h. This suggests a decrease in settling rates further downstream in the system.

Another observation is the presence of a fraction with very low settling rates in all samples, indicating that a portion of sediment particles will not settle and will remain in suspension. This finding aligns with the observations made by Nijman et al. (2015), who noted the presence of a residual concentration that remains suspended in the system.

The evaluation of settling velocity also raises the issue of resuspension. During high flow conditions, there is a potential for suspended solids to be reintroduced into the water column, posing challenges for effective sediment control and the prevention of re-contamination in stormwater systems. Similar to the settling velocity, the Shields parameter analysis employed a simplified approach to compare the samples. The analysis presented here offers a simplified comparison between the samples without considering all the complexities involved.

A reversed pattern is observed in comparison to the settling velocity analysis, which was expected considering the similar equations. This suggests that sediment located at the end of the system would be more prone to resuspension compared to sediment found near the start. Furthermore, the boxplots shown in Figure 5.13 indicate that the Shields parameters for the sediment samples are higher than that of Millisil W4. This implies that the sediment in the system would have a higher likelihood of resuspending at a given flow rate compared to Millisil W4. These findings align with the results reported by Kregting (2012); Zandvoort & Nijman (2019), who observed that sediment from Amsterdam fully leached out of a gully pot at a significantly lower flow rate (0.2 l/s) than the flow rate at which Millisil W4 leached out (2 l/s). These observations underscore the importance of considering resuspension dynamics in sediment management strategies. Effective measures and controls must be implemented to minimize resuspension events and prevent the reintroduction of sediment into the water column.

The analysis of settling velocity and resuspension provides insights into the transport of sediment within the stormwater system. However, it is important to consider the limitations of the simplified settling velocity calculations and the inherent complexities of sediment dynamics in real-world systems.

6.1.7. Comparison to the larger area Rivierenbuurt

The comparison between the study area Rijnbuurt Oost and the larger area Rivierenbuurt provides insights into the representativeness of the study area. One notable difference observed is the higher densities of the samples taken in Rijnbuurt Oost compared to those taken in the Rivierenbuurt. This variation in density could be attributed to differences in land use, sources of sediment, or the accumulation patterns within the respective areas. Additionally, the organic content of the samples was relatively low for both study areas, ranging between 3% and 12%. However, the samples taken in the Rivierenbuurt showed higher organic contents in the sand traps and near the SSO, while the samples from Rijnbuurt Oost exhibited higher values in the manholes.

The fraction of small particles (TSS63) of the samples in the Rivierenbuurt showed an increase downstream of the system, with the lowest value in the gully pot, higher in the manholes and the highest near the SSO. For Rijnbuurt Oost, the same pattern was observed, except for the sample near the SSO, which had a very low fraction of small particles. As discussed in the previous section, this was different than expected. The D10 values showed a wide range for all samples, which may be attributed to the sampling method. However, the D50 and D90 values for the two study areas were comparable and the same pattern through the sampling locations was observed.

It is important to consider certain factors that may influence the accuracy of the findings. The mixed sampling method, although providing an overall picture of sediment characteristics, may introduce some discrepancies due to the presence of outliers or variations within the mixed samples. Additionally, the larger number of sampling points used for the Rivierenbuurt compared to Rijnbuurt Oost may contribute to differences. Despite some differences in physical characteristics, the ranges of the parameters are relatively similar between the two areas.

6.1.8. Solids dynamics

The dynamics of solids within the manholes during rainfall events reveal certain patterns. However, it is important to consider that the findings are based on the specific events observed during the study period, which limits the generalizability of the results. The relatively low turbidity values observed can be attributed to the absence of heavy rainfall events during the study period. Nevertheless, a pattern emerges when the rainfall intensity or duration exceeded a certain threshold. An increase in turbidity and a decrease in total dissolved solids can be observed.

An increase in turbidity and a decrease in total dissolved solids were observed during events with higher rainfall intensity or longer durations. These patterns suggest a dynamic response of solids within the manholes to rainfall events. However, not all events exhibited the same responses. Some events showed limited or no changes in the parameters, which could be attributed to factors such as lower flow velocities that were insufficient to transport solids through the sewer or the sediment bed remaining undisturbed. It is assumed that the accumulation of at least 2-3 mm of precipitation is typically required to generate runoff and transport solids to the gully pots. Moreover, the timing of the events and the characteristics of the sewer system can influence the observed patterns. Additionally, errors in the precipitation data or prior flushing of solids by previous events may have affected the parameter responses in some cases.

The placement of the sensor just above the sediment bed and close to the side of the manhole ensured better security and stability, especially during high flow rates. However, it is important to consider that different results may have been obtained if the sensor was placed in the middle of the manhole or at a different height. To gain a comprehensive understanding of solids dynamics in manholes during rainfall events, further investigation is required, taking into account influencing factors such as sediment bed conditions and the specific characteristics of the sewer system. These factors play a role in determining the observed patterns and can contribute to a more accurate assessment of solids behavior within the stormwater system. This could also help in determining whether the responses are cause by resuspension of the sediment bed or the transport of solids by the runoff.

6.1.9. The impact on the performance of a stormwater treatment facility

The analysis of sediment characteristics and dynamics within the stormwater system provides insights into the impact on the performance of stormwater treatment facilities. The correlations observed between different parameters highlight their interrelationships and potential influencing factors. Notably, the correlations between pollutant concentrations and sediment characteristics suggest their association with particle properties. For example, the higher concentrations of the pollutants in sediment samples are linked to the fraction of small particles. However, it is important to note that these correlations are based on a limited number of samples, which may introduce some uncertainty in the results. Additionally, the samples were collected from various locations within the system, adding to the variability. Despite these limitations, correlations between certain parameters can still be observed, suggesting potential relationships and dependencies between sediment characteristics and pollutant concentrations. The results of the pollutant concentrations and the correlations offer information on where pollutants may accumulate within the system. It was observed that the sand trap mainly contained sand particles, with lower pollutant concentrations. This indicates that cleaning of the sand traps primarily removes total suspended solids (TSS) but may have limited efficiency in removing specific pollutants.

Furthermore, differences between the sediment and Millisil W4 were observed in various parameters. The PSD of the sediment samples is more similar to Millisil W4 at the SSO, based on the sediment bed. However, it is important to consider that suspended small particles, which are not included in the sediment bed analysis, would likely result in a finer sediment size at the end of the system compared to Millisil W4. Another difference is the presence of organic material in the sediment, which is absent in Millisil W4. The presence of organic material is negatively correlated with density, indicating that sediment with organic material would have a lower density compared to Millisil W4. Indeed, the density of Millisil W4 is consistently higher than the densities of sediment found at all locations within the system. The settling velocities in the system appear similar to Millisil W4 based on the sediment bed analysis. However, it is important to consider that if the residual concentration of suspended sediment were included, the settling velocities would be lower. Consequently, the settling velocities of the sediment from the stormwater sewer would be lower than that of Millisil W4, potentially leading to a lower removal efficiency of sedimentation devices. Moreover, the resuspension analysis indicated that Millisil W4 resuspends at a higher flow rate compared to sediment from the stormwater sewer. If the residual concentration were also considered, the Shields parameter for sediment would be even higher, indicating a higher likelihood of resuspension. The insights gained from the measurements of turbidity and total dissolved solids further contribute to understanding the transport of solids within the system. During rainfall events with intensities exceeding a certain threshold, observable changes, such as a decrease in total dissolved solids and an increase in turbidity, indicate the transport or resuspension of solids.

Overall, these observations underscore the significant influence of sediment characteristics on the performance of stormwater treatment facilities. Understanding the behavior and properties of sediment within the stormwater system is essential for designing and optimizing stormwater treatment facilities to effectively mitigate the impact of pollutants and ensure sustainable water management.

6.2. Sampling methods

Three different sampling methods were employed in this study: filter bags, mixed samples (scoops taken from different sampling points and combined) and single samples (individual scoops). Evaluating these methods is needed for understanding the strengths and limitations of each approach and interpreting the results accurately. Additionally, the findings from this evaluation will inform future research in the field.

Filter bags were utilized in this study with a smaller pore size of 25 μm compared to the 50 μm used in previous research. The smaller pore size was chosen to capture smaller particles of interest. However, during the initial checks, it was found that the filter bags were not yet fully saturated. In the subsequent checks, the filters in the residential and vegetated area were clogged which caused water to remain on the streets. Consequently, it is difficult to determine which solids were captured in the filter bags and which remained on the streets. Moreover, even after a five-week period, an insufficient amount of solids was collected to conduct all laboratory analyses, necessitating choices regarding which analyses could be performed. Therefore, the results of the runoff samples in the residential and vegetated area obtained from the filter bags should be viewed as indicative rather than accurate.

The scooping method, which involved taking mixed samples from multiple sampling points on the first sampling day, provides an average representation of the parameters. However, this method may be influenced by the presence of extreme outliers, potentially caused by contamination or other factors. On the other hand, the single sampling method involved taking individual scoops. The violin plots in Figure 6.1 depict the parameter distributions for the mixed and single samples collected from the sand traps and manholes. The plots are categorized based on the sampling methods and locations. The x-axis represents the different locations (sand traps and manholes), while the y-axis represents the values of the analyzed parameters. The width of the violin indicates the density of the data points, while the height of the violin represents the range of the data distribution.

A comparison of the parameter distributions between the mixed and single samples reveals that the densities of the mixed samples are generally higher and exhibit a larger range compared to the single samples. Conversely, the organic fractions of the mixed samples exhibit lower values and a smaller range compared to the single samples. This indicates that the mixed sampling method may not capture the full range of organic fractions present in the samples. Regarding PSDs, the mixed samples generally display smaller ranges for all parameters, except for the D10 of the manhole samples. Notably, the mixed samples contain a higher proportion of larger particles compared to the single samples.

It should be noted that during the scooping method, fine material can flow off the scoop, resulting in a lower amount of fine particles in the collected samples. Additionally, the samples were taken specifically from the sediment bed, which does not fully represent the particle distribution throughout the entire water column as a residual concentration will remain suspended.

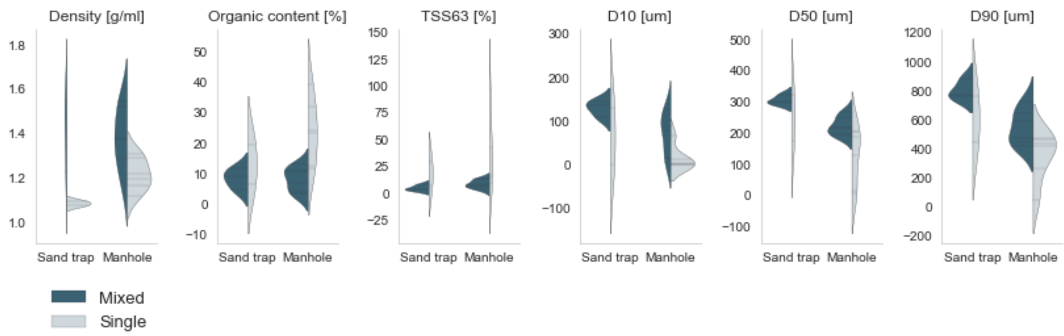


Figure 6.1: The distributions of the densities, organic fractions, the fractions of small particles (TSS63) and particle size distributions (presented as D10, D50 and D90) of the samples per sampling method (e.g. mixed and single samples). The results are shown per type of sampling location (sand trap or manhole).

6.3. Limitation of the study

This study is subject to several limitations that should be considered when interpreting the results and drawing conclusions. Firstly, the study period covered only a relatively short period of time and not all seasons were included. The dynamics of solids in the stormwater system can vary throughout the year due to seasonal variations in weather patterns, land use and other factors. Therefore, the findings of this study may not fully capture the complete range of variations that can occur over a longer time frame. Furthermore, it is important to note that the turbidity measurements were conducted during a period with relatively small rainfall events. Consequently, the observed changes in turbidity may not be as pronounced as they would be during larger and more intense rainfall events. The limited range of precipitation events during the turbidity measurements may restrict the ability to observe and analyze the full dynamics of solids in response to different rainfall conditions.

Moreover, the precipitation data used in this study were obtained from the KNMI radar data and were assumed to be homogeneous over an area of 1 km^2. However, it is important to acknowledge that precipitation patterns can vary within a relatively small geographic area. Therefore, the specific location and amount of rainfall can have a substantial impact on the dynamics of solids in the stormwater system and the results may be influenced by local variations in precipitation distribution.

In addition, due to time, resource and budget constraints, the number of samples collected during the study was limited. As a result, choices had to be made regarding the selection of key parameters for analysis. While efforts were made to include relevant parameters, it is important to acknowledge that there may be other parameters that could provide valuable insights into the dynamics of solids in the stormwater system.

Another limitation relates to the practical challenges encountered during sampling. In practice, obtaining sediment samples from the sewer system can be more complex than anticipated. The sediment bed may not always be easily accessible and in some cases, it may not even be present at the bottom of the manholes. The bottom of the manholes may not always be flat, which makes conducting the sampling in the same manner sometimes difficult. These variations in the sediment bed conditions can introduce uncertainties and potential biases in the collected samples. Furthermore, it should be noted that the stormwater system contains various materials besides sediment, such as rocks and debris. These materials can influence the composition and characteristics of the samples. Additionally, the presence of illicit connections between the stormwater and wastewater sewer systems can introduce additional complexities. If wastewater flows are interconnected with the stormwater system, it can affect the composition of the samples, potentially leading to mixed or contaminated results.

7

Conclusion

The study aimed to investigate the sediment characteristics and dynamics within the storm sewer in Amsterdam. The research questions focused on the variation of sediment characteristics throughout different locations within the system, the dynamics of solids in manholes during rainfall events and the impact of sediment characteristics on the performance of the storm sewer compared to the commonly used test material, Millisil W4. Based on the findings, several conclusions can be drawn.

1. Sediment characteristics:

   The analysis of sediment samples from different locations within the storm sewer revealed several insights. The particle size distribution (PSD) showed that finer material tends to accumulate near the storm sewer outfall (SSO), while larger particles settle upstream. The PSD of the sediment bed near the SSO resembled that of Millisil W4. Including the residual concentration that remained suspended would result in finer material.

   The organic content of the sediment samples increased along the system, with the highest concentrations near the SSO. The organic content showed large ranges in runoff samples, which could be attributed to different land uses and sediment sources. Runoff samples exhibited higher concentrations of pollutants compared to sand trap and manhole samples. Variations in pollutant concentrations among areas were observed, attributed to different pollution sources. Sand trap samples consistently displayed lower pollutant concentrations, suggesting that sand particles predominantly make up the sediment in the traps which contain a low amount of attached pollutants. The lower concentrations near the SSO indicate that settling occurs within the system, with pollutants attaching to sediment particles. However, it also indicates that part of the pollutants reach the manhole near the SSO and will probably also reach the receiving water body, in addition to the pollutants that are not attached to particles.

   The settling velocity of the sediment particles was observed to be lower at the end of the system compared to the starting point. This observation aligns more closely with the settling velocity of the reference material, Millisil W4, suggesting a convergence in settling behavior as sediment progresses through the system. It is important to note that the settling velocity calculations were based on a simplified equation, considering only particle size and the average density. This simplified approach allowed for relative comparisons between samples but should be interpreted cautiously. In addition, including the residual concentration would result in a lower settling velocity than Millisil W4. The presence of a fraction with very low settling rates indicated suspended sediment remaining in the water column. The Shields parameter analysis indicated a higher likelihood of sediment resuspension near the system SSO compared to upstream locations and to Millisil W4.

   It is important to note the uncertainties associated with the sediment characteristics analysis. The study was based on a relatively low number of samples collected over a few months, which limits the representation of all seasons and temporal variations. The laboratory tests and sampling methods also introduce inherent uncertainties, as obtaining a representative and accurate sample can be challenging. Additionally, the spatial variation within the system and the influence of countless factors on sediment characteristics further contribute to the overall uncertainties of the study.

2. Dynamics of sediment transport in manholes:

   By utilizing sensors placed above the sediment bed in manholes, the dynamics of solids during rainfall events were monitored. The parameters of turbidity, total dissolved solids and water temperature showed a correlation with precipitation patterns and intensity, indicating the response of solids to rainfall events and increasing flow velocities. When rainfall occurred and flow velocities increased, the monitored parameters exhibited noticeable changes. The turbidity showed an increase while the total dissolved solids showed a decrease, indicating the mobilization and transport of solids within the system. This suggests that rainfall events play a role in the resuspension and movement of sediment within the storm sewer.

   However, it is important to note that not all rainfall events displayed the same pattern. Some events did not exhibit significant changes in the monitored parameters due to factors such as low event intensity or the absence of sufficient dry hours preceding the event. In such cases, the solids may have already been flushed away or the event intensity may not have been strong enough to induce sediment movement.

3. The impact on treatment facilities and comparison to Millisil W4:

   The correlations observed between pollutant concentrations and sediment characteristics suggest their association with particle properties. The higher concentrations of pollutants in sediment samples are linked to the fraction of small particles. The sand trap mainly contains sand particles with lower pollutant concentrations, indicating that cleaning the sand traps primarily removes total suspended solids (TSS) but may have limited efficiency in removing specific pollutants. Information on the performance projections solely based on TSS removal is not sufficient.

   The settling velocities in the system appear similar to Millisil W4 based on the sediment bed analysis. However, considering the residual concentration of suspended sediment would lower the settling velocities. This suggests that the settling velocities of sediment from the stormwater sewer near the SSO would be lower than that of Millisil W4, potentially leading to a lower removal efficiency of sedimentation devices. The resuspension analysis indicates that Millisil W4 resuspends at a higher flow rate compared to sediment from the stormwater sewer. Taking into account the residual concentration would further increase the likelihood of resuspension, as indicated by the higher Shields parameter for sediment. This would mean that the sediment from the sewer would resuspend faster than Millisil W4, which affects the efficiency of a treatment facility.

The characterization of sediment throughout the system provides insights into the dynamics of sediment transport, settling velocity and resuspension, which are key factors influencing the efficiency and effectiveness of treatment facilities. The comparison between sediment characteristics from the storm sewer and Millisil W4 highlighted notable differences. Sediment from the storm sewer exhibited a wider PSD, higher organic content and a more diverse composition including debris and organic matter. These variations emphasize the importance of considering the specific properties and composition of the sediment when designing and evaluating stormwater treatment systems.

8 Recommendations

To advance our understanding of sediment characteristics within the storm sewer, several recommendations for further research can be made.

- Firstly, it is crucial to collect, share and utilize information about the storm sewer across the country to improve our knowledge and understanding. Creating an up-to-date database would provide decision-makers with valuable information and prevent duplication of research efforts and data loss. Rioned currently provides such a database, so it is important to improve and maintain its accuracy. Standardizing sampling methods for each type of sample collection would enhance comparability. Additionally, implementing a specific template for documentation would improve clarity and reduce the time spent searching for research protocols.
- Secondly, it is crucial to conduct a more extensive and representative sampling campaign to capture seasonal and temporal variations. This will involve collecting sediment samples from a wider range of locations and over a longer duration to account for fluctuations in sediment properties throughout the year. By incorporating different seasons and weather patterns, a more comprehensive picture of sediment dynamics can be obtained. Additionally, to obtain a more complete picture of the solids characteristics, it is recommended to collect water samples in addition to settled solids. This approach will enable the assessment of both suspended and dissolved components within the storm sewer. It will also provide a more accurate estimation of pollutant load and potential environmental impacts. Samples from the outflow to the connected water body and the water body itself should also be taken to determine the actual substances flowing out of the system.
- To enhance the reliability of results, refining sampling protocols is recommended. Standardizing procedures for sample collection, including factors such as sampling location, depth and position, will minimize variations in sampling techniques and enhance the accuracy of collected sediment samples. Considering the runoff samples to the gully pots, alternative sampling methods should be explored or filter bags with larger pore sizes should be used to avoid filter clogging while ensuring an adequate amount of sediment collection. The scooping method employed for sampling the sediment bed, which is fast, cost-effective and easy, is an acceptable approach for obtaining indications of materials in the sewer. However, the choice between using single or mixed samples is complex. While multiple single samples provide a more precise representation, it can be costly in case many locations have to be sampled. Mixed samples, on the other hand, offer an average but may be influenced by outliers. If mixed samples are used, it is advisable to take a large number of samples to ensure a robust average. Additionally, proper documentation of sampling procedures will enable better comparability with future studies and improve the overall understanding of sediment characteristics in the storm sewer.

- By monitoring the response of solids to rainfall events, it becomes possible to gain insights into the transport, deposition and resuspension of sediment within the storm sewer. This information can aid in the design and evaluation of stormwater management practices and infrastructure. Further research in this area could focus on expanding the data set by monitoring a larger number of rainfall events and examining the relationships between precipitation characteristics, flow velocities and sediment dynamics in more detail. To gain a better understanding of the distinction between resuspension of solids and the transportation of solids through runoff, several investigation ideas can be explored. One approach is to set up a system where clean water is pumped through a sensor-equipped manhole, allowing for the monitoring of sediment bed variations and the observation of any resuspension events during the flow of clean water. Another idea is to continuously monitor sediment bed variations in a manhole using a sensor, providing valuable insights into sediment behavior under different flow conditions and enhancing our understanding of resuspension processes. Additionally, monitoring the runoff passing through a manhole during rainfall events and measuring characteristics such as sediment concentration and flow rate can enable a comprehensive analysis of sediment transportation dynamics.
- To further investigate the actual behavior of these sediments it would be interesting to use a test set up of a system to assess the removal efficiency of a system based on the actual sediment and Millisil W4. By establishing correlations between these 'easy' parameters and the observed differences, they can serve as indicators for future research and the evaluation of alternatives in specific cases. Considering the numerous factors that influence sediment behavior, such investigations can provide valuable information for improving sediment control measures and enhancing water quality management practices.

Specifically for Waternet, collecting sediment and water samples, analyzing particle size distributions, density and pollutants and conducting system-level tests will provide valuable insights. By addressing these recommendations, future research can contribute to the understanding of sediment characteristics within the storm sewer. While the existing protocols provide reliable indications of system performance and are reproducible, it is essential to interpret these predictions within the context of specific cases. By doing so, we can develop tailored strategies that optimize sediment control measures and water quality management practices, ensuring the sustainability and efficiency of our approaches. These efforts can contribute to the development of sustainable and efficient approaches for sediment control and water quality management.

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Appendix A

Study area

The study area is depicted in the maps shown below, providing extra information of the geographical layout and features of the system. Figure A.1 illustrates the heights of the conduits within the system, providing insights into the vertical arrangement of the infrastructure. The conduit materials used in the stormwater network are presented in Figure A.2. The ground level is visualized in Figure A.3, providing an understanding of the topography and elevation of the study area. This information helps assess the natural terrain and its influence on the stormwater system.

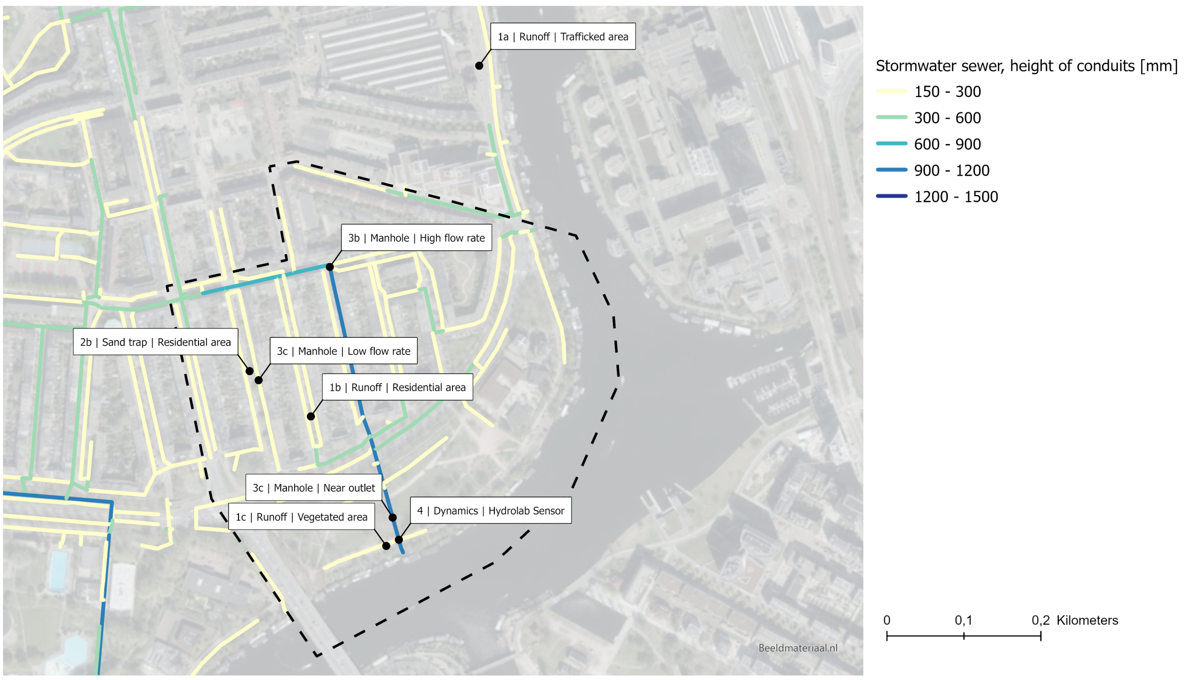


Figure A.1: Layout of the stormwater system showing conduit heights

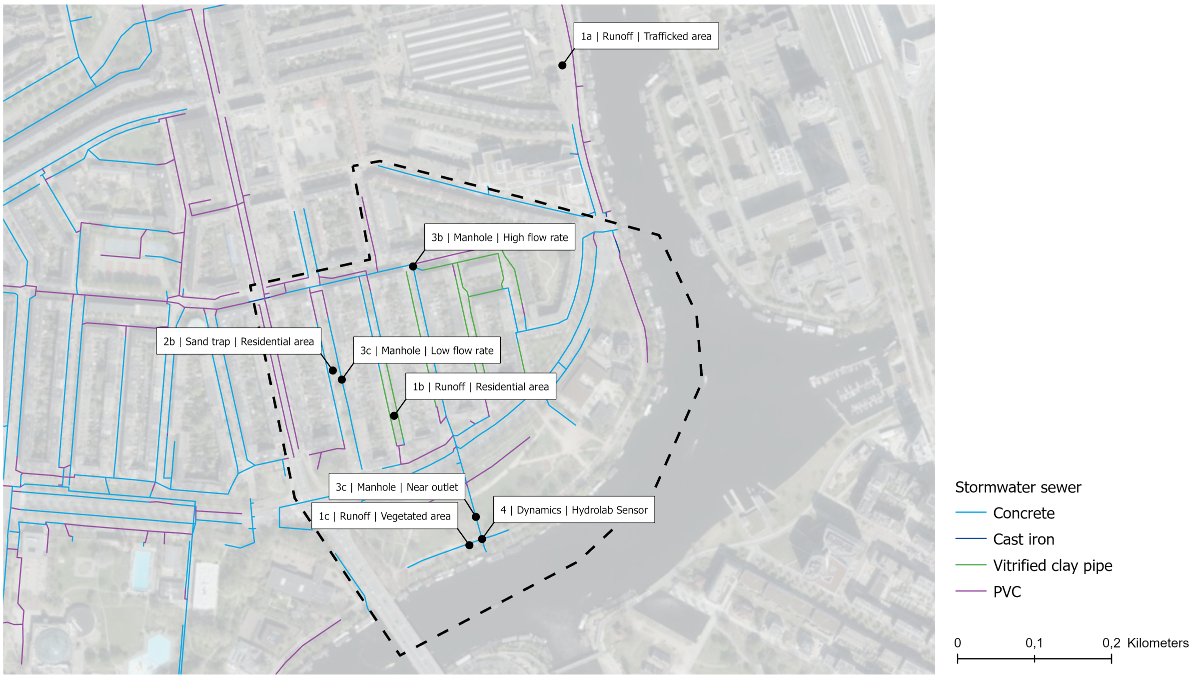


Figure A.2: Conduit materials used in the stormwater system

Figure A.3: Ground level and topography of the study area

Appendix B

Methods

This appendix provides additional information of the methods used in the study. It includes photographs illustrating the procedures employed to collect the data.

B.1. Runoff samples

To collect runoff samples, filter bags made of polypropylene with a pore size of 25 μm were utilized. These filter bags were attached to a plate with a hole and securely placed in the gully pots. This setup ensured that no sediment particles could bypass the filters. After a designated period, the filters were checked for captured solids. Figure B.1a depicts the first check after three weeks of deployment. Figure B.1b and B.1c shows the clogged filters after five weeks in the vegetated and residential area.

(a) First check of the filters after three weeks of deployment

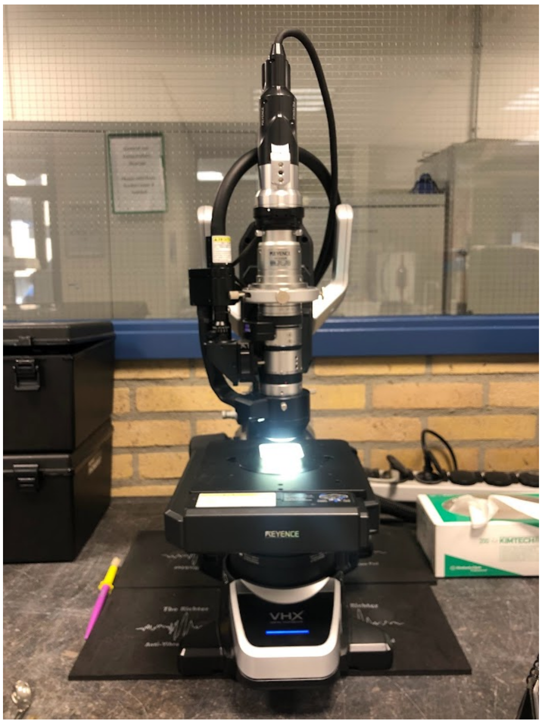
(b) Clogged filter bag in the vegetated area

(c) Clogged filter bag in the residential area

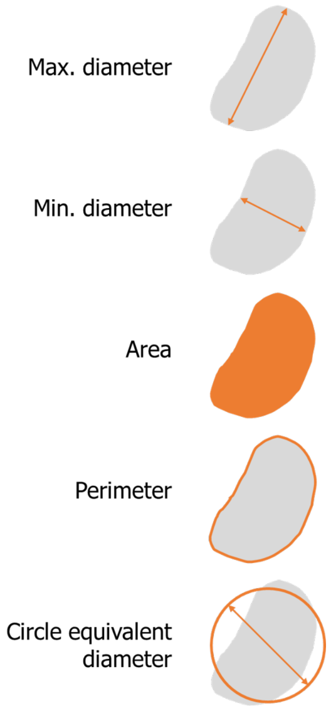
Figure B.1: Photographs illustrating the runoff sampling method

B.2. Particle shape analysis

Particle shape analysis was conducted using a microscope, as shown in Figure B.2a. The microscope measured various particle shape parameters, including maximum diameter, minimum diameter, area, perimeter and circle equivalent, as depicted in Figure B.2b.



(a) Microscope used for particle shape analysis



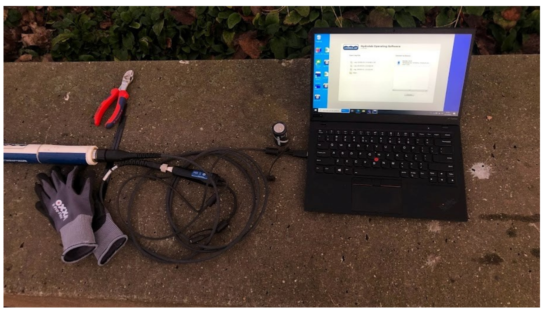
(b) Measurements of particle shape parameters

Figure B.2: Sediment sample locations

B.3. Hydrolab sensor

A Hydrolab sensor was used to monitor various parameters within the manholes. To facilitate its placement and easy retrieval, the sensor was secured in a PVC pipe, as shown in Figure B.3a. This setup allowed for convenient placement in the manhole as well as easy removal on a weekly basis to read the data and replace the battery, as depicted in Figure B.3b.

(a) Sensor secured in PVC pipe



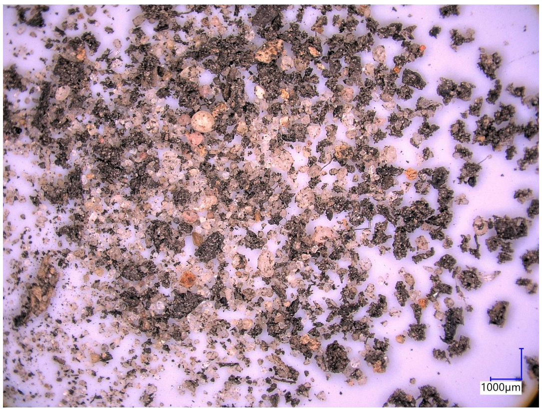
(b) Reading the data from the Hydrolab sensor

Figure B.3: Hydrolab sensor setup and data retrieval

Appendix C

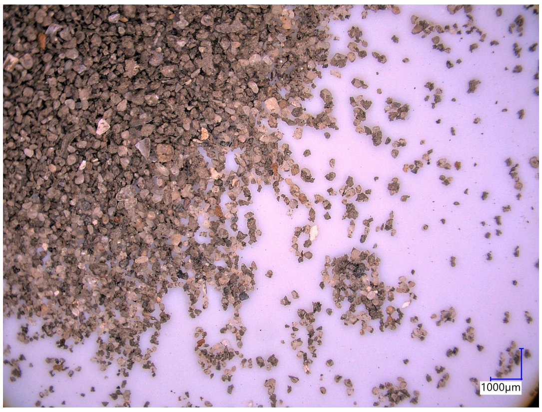
Laboratory results

This appendix presents additional figures and reports that provide further insights into the laboratory results of the sediment analysis. In Figure C.1, microscope photos of the sediment samples are presented. These photos offer a visual representation of the particle shape and texture. Figure C.2 displays the particle size distribution (PSD) results in a format commonly used in the literature. The PSD curves show the distribution of particle sizes in the sediment samples, highlighting the relative proportions of different size fractions. Additionally, the reports of Waterproef, the laboratory responsible for conducting the sediment analysis, are included in this appendix.

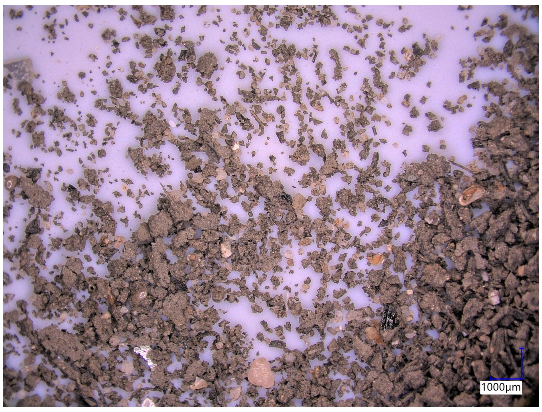


(a) Microscope photograph of the sample collected from the sand trap on 15-2-2023

(b) Microscope photograph of the sample collected from the manhole with a low flow rate on 15-2-2023



(c) Microscope photograph of the sample collected from the manhole with a high flow rate on 15-2-2023



(d) Microscope photograph of the sample collected from the manhole near the outlet on 15-2-2023

Figure C.1: Microscope photographs of the sand trap and manhole samples

Analyserapport

Waternet, TOP
MTW
T.a.v. de heer E. Bontjes
Postbus 94370
1090 GJ AMSTERDAM

Datum:	Rapportnummer:	Uw Kenmerk:
17-01-2023	439476	714355
Project:	**Monstername door:**	**Uw projectcode:**
dooea005/005, Kwaliteit hemelwater en slib	Opdrachtgever	

Geachte heer Bontjes,

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.

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

De resultaten op dit rapport zijn geautoriseerd door de directeur van Stichting Waterproef J .S.C. Bruin.

Kopie aan:
MTW , t.a.v. mevrouw A. Hoornick

Volgnummer	**Puntcode**	**Monsteromschrijving***
690370	oh080007	Overig Hemelwaterput uitlaat
690371	oh080007	Overig Hemelwaterput hoog
690372	oh080007	Overig Hemelwaterput laag
690373	oh080007	Overig Kolkdruk

Volgnummer	**690370**	**690371**	**690372**	**690373**
Monstercode klant*	UIT-1	HD-1	LD-1	DS-1
Monstertype*	Overige	Overige	Overige	Overige
Bemonsteringstype*	steekmonster	steekmonster	steekmonster	steekmonster
Monsternemer*	E. Bontjes	E. Bontjes	E. Bontjes	E. Bontjes
Monstername datum*	16-12-2022	16-12-2022	16-12-2022	16-12-2022
Monstername tijd*	15:00	15:00	15:00	15:00
Acceptatiedatum	19-12-2022	19-12-2022	19-12-2022	19-12-2022

Fysisch- Chemische analyses	690370		690371		690372		690373		**Eenheid**
Carbonaat, volumetrisch	3	a	4	a	2	a	2	a	g/kg dg
Totaal-fosfor in vaste matrix	< 5		< 5		< 5		< 5		g/kg P dg
Dichtheid van vaste matrix	1,5421		1,3795		1,3695		1,5502		g/ml
Indamprest van vaste matrix	49,6		32,7		28,5		47,3		%
Gloeirest van de indamprest	94		88		85		94		% van dg
Organisch stof gehalte	3,4	a	7,1	a	12,8	a	4,8	a	%dg
Voorbehandeling SCG kromme									
Afval	nb	a	nb	a	nb	a	nb	a	%
Grind	14,5	a	< 0,1	a	< 0,1	a	< 0,1	a	%
Grond	81,9	a	91,2	a	88,7	a	85,4	a	%
Puin	nb	a	nb	a	nb	a	nb	a	%
Korrelgrootte voor SCG									
Korrelgrootte <2 um, sedigraaf	< 2,5	a	7,2	a	5,1	a	< 2,5	a	% md
Korrelgrootte <16 um, sedigraaf	2,5	a	10,2	a	5,7	a	< 2,5	a	% md
Korrelgrootte <32 um	2,6	a	11,0	a	6,5	a	< 2,5	a	% md
Korrelgrootte <50 um	2,9	a	11,8	a	7,0	a	< 2,5	a	% md
Korrelgrootte <63 um	3,3	a	12,7	a	7,4	a	< 3	a	% md
Korrelgrootte <125 um	9,8	a	18,9	a	17,5	a	3,8	a	% md
Korrelgrootte <250 um	47,8	a	77,9	a	76,6	a	41,5	a	% md
Korrelgrootte <500 um	85,2	a	96,1	a	94,3	a	85,0	a	% md
Korrelgrootte <1000 um	95,9	a	98,4	a	97,0	a	94,7	a	% md

Metaal analyses	690370	690371	690372	690373	**Eenheid**
Koper in vaste matrix na destructie	30	90	60	40	mg/kg dg
Zink in vaste matrix na destructie	180	430	520	170	mg/kg dg

Organische analyses	690370	690371	690372	690373	**Eenheid**
Minerale olie in vaste matrix	550	1500	1600	600	mg/kg dg

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Rapportnummer:

439476

Pagina

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Volgnummer	**690370**	**690371**	**690372**	**690373**	
PAK EPA in vaste matrix					
Acenafteen	0,10	0,21	17	< 0,01	mg/kg dg
Acenaftyleen	0,08	0,06	0,42	< 0,02	mg/kg dg
Anthraceen	0,15	0,28	22	0,02	mg/kg dg
Benzo(a)antraceen	0,48	1,0	25	0,10	mg/kg dg
Benzo(a)pyreen	0,48	1,1	18	0,10	mg/kg dg
Benzo(b)fluorantheen	0,81	1,9	25	0,17	mg/kg dg
Benzo(g,h,i)peryleen	0,42	0,91	9,8	0,13	mg/kg dg
Benzo(k)fluorantheen	0,20	0,51	11	0,05	mg/kg dg
Chryseen	0,48	1,0	21	0,11	mg/kg dg
Dibenzo(a,h)antraceen	0,22	0,52	11	0,07	mg/kg dg
Fenanthreen	0,50	1,3	92	0,04	mg/kg dg
Fluoreen	0,07	0,14	16	< 0,01	mg/kg dg
Fluorantheen	1,0	2,6	75	0,17	mg/kg dg
Indeno(1,2,3-c,d)pyreen	0,33	0,71	14	0,08	mg/kg dg
Naftaleen	0,06	0,06	3,8	0,02	mg/kg dg
Pyreen	0,97	2,1	64	0,16	mg/kg dg
Som 16 PAK EPA	6,4	14	430	1,2	mg/kg dg

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Volgnummer	Puntcode	Monsteromschrijving*
690374	oh080007	Overig Kolk rustig

Volgnummer	**690374**
Monstercode klant*	RS-1
Monstertype*	Overige
Bemonsteringstype*	steekmonster
Monsternemer*	E. Bontjes
Monstername datum*	16-12-2022
Monstername tijd*	15:00
Acceptatiedatum	19-12-2022

Fysisch- Chemische analyses			Eenheid
Carbonaat, volumetrisch	< 1	a	g/kg dg
Totaal-fosfor in vaste matrix	< 5		g/kg P dg
Dichtheid van vaste matrix	1,4851		g/ml
Indamprest van vaste matrix	47,8		%
Gloeirest van de indamprest	90		% van dg
Organisch stof gehalte	8,9	a	%dg
Voorbehandeling SCG kromme			
Afval	nb	a	%
Grind	< 0,1	a	%
Grond	87,2	a	%
Puin	nb	a	%
Korrelgrootte voor SCG			
Korrelgrootte <2 um, sedigraaf	4,0	a	% md
Korrelgrootte <16 um, sedigraaf	5,2	a	% md
Korrelgrootte <32 um	5,4	a	% md
Korrelgrootte <50 um	6,6	a	% md
Korrelgrootte <63 um	7,8	a	% md
Korrelgrootte <125 um	10,8	a	% md
Korrelgrootte <250 um	38,8	a	% md
Korrelgrootte <500 um	77,0	a	% md
Korrelgrootte <1000 um	94,1	a	% md

Metaal analyses		Eenheid
Koper in vaste matrix na destructie	50	mg/kg dg
Zink in vaste matrix na destructie	330	mg/kg dg

Organische analyses		Eenheid
Minerale olie in vaste matrix	570	mg/kg dg
PAK EPA in vaste matrix		
Acenafteen	0,09	mg/kg dg
Acenaftyleen	0,06	mg/kg dg
Anthraceen	0,24	mg/kg dg
Benzo(a)antraceen	0,80	mg/kg dg

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Volgnummer	690374	
Benzo(a)pyreen	0,72	mg/kg dg
Benzo(b)fluorantheen	1,1	mg/kg dg
Benzo(g,h,i)peryleen	0,51	mg/kg dg
Benzo(k)fluorantheen	0,31	mg/kg dg
Chryseen	0,80	mg/kg dg
Dibenzo(a,h)antraceen	0,31	mg/kg dg
Fenanthreen	1,5	mg/kg dg
Fluoreen	0,11	mg/kg dg
Fluorantheen	2,3	mg/kg dg
Indeno(1,2,3-c,d)pyreen	0,50	mg/kg dg
Naftaleen	0,11	mg/kg dg
Pyreen	1,6	mg/kg dg
Som 16 PAK EPA	11	mg/kg dg

Opmerkingen

a Analyse uitgevoerd door OMEGAM

Methodeverwijzingen

Fysisch- Chemische analyses in overige

Carbonaat, volumetrisch
Totaal-fosfor in vaste matrix
Dichtheid van vaste matrix
Indamprest van vaste matrix
Gloeirest van de indamprest
Organisch stof gehalte
Voorbehandeling SCG kromme
    Alle componenten
Korrelgrootte voor SCG
    Alle componenten

Metaal analyses in overige

Koper in vaste matrix na destructie
Zink in vaste matrix na destructie

Organische analyses in overige

Minerale olie in vaste matrix
PAK EPA in vaste matrix
    Alle componenten

Analyserapport

Waternet, TOP
MTW
T.a.v. de heer E. Bontjes
Postbus 94370
1090 GJ AMSTERDAM

Datum:	**Rapportnummer:**	**Uw Kenmerk:**
17-01-2023	439477	714355
Project:	**Monstername door:**	**Uw projectcode:**
dooea005/005, Kwaliteit hemelwater en slib	Opdrachtgever	

Geachte heer Bontjes,

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.

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

De resultaten op dit rapport zijn geautoriseerd door de directeur van Stichting Waterproef
J.S.C. Bruin.

Kopie aan:
MTW , t.a.v. mevrouw A. Hoornick

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

Volgnummer	**Puntcode**	**Monsteromschrijving***
690375	oh080007	Overig Hemelwaterput uitlaat
690376	oh080007	Overig Hemelwaterput hoog
690377	oh080007	Overig Hemelwaterput laag
690378	oh080007	Overig Kolk rustig

Volgnummer	**690375**	**690376**	**690377**	**690378**
Monstercode klant*	UIT-2	HD-2	LD-2	RS-2
Monstertype*	Overige	Overige	Overige	Overige
Bemonsteringstype*	steekmonster	steekmonster	steekmonster	steekmonster
Monsternemer*	E. Bontjes	E. Bontjes	E. Bontjes	E. Bontjes
Monstername datum*	16-12-2022	16-12-2022	16-12-2022	16-12-2022
Monstername tijd*	15:00	15:00	15:00	15:00
Acceptatiedatum	19-12-2022	19-12-2022	19-12-2022	19-12-2022

Fysisch- Chemische analyses	690375		690376		690377		690378		**Eenheid**
Carbonaat, volumetrisch	6	*a*	4	*a*	2	*a*	< 1	*a*	g/kg dg
Dichtheid van vaste matrix	1,2811		1,518		1,1774		1,2256		g/ml
Indamprest van vaste matrix	32,9		51,2		23,1		38,1		%
Gloeirest van de indamprest	86		94		74		85		% van dg
Organisch stof gehalte	10,8	*b*	3,9	*b*	10,7	*b*	11,5	*b*	%dg
Voorbehandeling SCG kromme									
Afval	nb	*a*	nb	*a*	nb	*a*	nb	*a*	%
Grind	< 0,1	*a*	5,8	*a*	< 0,1	*a*	< 0,1	*a*	%
Grond	62,3	*a*	93,3	*a*	66,6	*a*	90,9	*a*	%
Puin	nb	*a*	nb	*a*	nb	*a*	nb	*a*	%
Korrelgrootte voor SCG									
Korrelgrootte <2 um, sedigraaf	6,1	*a*	2,8	*a*	2,6	*a*	< 2,5	*a*	% md
Korrelgrootte <16 um, sedigraaf	10,6	*a*	6,1	*a*	4,3	*a*	< 2,5	*a*	% md
Korrelgrootte <32 um	11,6	*a*	6,8	*a*	5,2	*a*	3,1	*a*	% md
Korrelgrootte <50 um	12,3	*a*	7,1	*a*	5,8	*a*	3,4	*a*	% md
Korrelgrootte <63 um	13,3	*a*	7,9	*a*	5,9	*a*	3,5	*a*	% md
Korrelgrootte <125 um	16,6	*a*	13,5	*a*	10,9	*a*	7,2	*a*	% md
Korrelgrootte <250 um	49,8	*a*	63,7	*a*	64,6	*a*	42,7	*a*	% md
Korrelgrootte <500 um	86,8	*a*	88,6	*a*	93,8	*a*	83,5	*a*	% md
Korrelgrootte <1000 um	97,9	*a*	96,6	*a*	98,7	*a*	95,8	*a*	% md

Opmerkingen

a Analyse uitgevoerd door OMEGAM
b Analyse uitgevoerd door OMEGAM

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Methodeverwijzingen

Fysisch- Chemische analyses in overige

Carbonaat, volumetrisch
Dichtheid van vaste matrix
Indamprest van vaste matrix
Gloeirest van de indamprest
Organisch stof gehalte
Voorbehandeling SCG kromme
    Alle componenten
Korrelgrootte voor SCG
    Alle componenten

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Analyserapport

Waternet, TOP
MTW
T.a.v. de heer E. Bontjes
Postbus 94370
1090 GJ AMSTERDAM

Datum:	Rapportnummer:	Uw Kenmerk:
23-02-2023	443069	714355
Project:	**Monstername door:**	**Uw projectcode:**
dooea005/005, Kwaliteit hemelwater en slib	Opdrachtgever	

Geachte heer Bontjes,

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.

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

De resultaten op dit rapport zijn geautoriseerd door de directeur van Stichting Waterproef
J.S.C. Bruin.

Kopie aan:
MTW , t.a.v. mevrouw A. Hoornick

Volgnummer	**Puntcode**	**Monsteromschrijving***
696042	oh080007	Overig Hemelwaterput uitlaat
696043	oh080007	Overig Hemelwaterput hoog
696044	oh080007	Overig Hemelwaterput laag
696045	oh080007	Overig Kolk rustig

Volgnummer	**696042**	**696043**	**696044**	**696045**
Monstercode klant*	UIT	HD	LD	RS
Monstertype*	Overige	Overige	Overige	Overige
Bemonsteringstype*	steekmonster	steekmonster	steekmonster	steekmonster
Monsternemer*	Annemieke Hoornick	Annemieke Hoornick	Annemieke Hoornick	Annemieke Hoornick
Monstername datum*	15-02-2023	15-02-2023	15-02-2023	15-02-2023
Monstername tijd*	09:00	09:00	09:00	09:00
Acceptatiedatum	15-02-2023	15-02-2023	15-02-2023	15-02-2023

Fysisch- Chemische analyses	696042		696043		696044		696045		**Eenheid**
Carbonaat, volumetrisch	170	*a*	20	*a*	90	*a*	70	*a*	g/kg dg
Dichtheid van vaste matrix	1,1659		1,1184		1,2899		1,0947		g/ml
Indamprest van vaste matrix	17,5		19,8		50,5		33,9		%
Gloeirest van de indamprest	72		76		93		76		% van dg
Organisch stof gehalte	39,2	*a*	12,3	*a*	24,2	*a*	19,4	*a*	%dg
Voorbehandeling SCG kromme									
Afval	nb	*a*	nb	*a*	nb	*a*	nb	*a*	%
Grind	< 0,1	*a*	24,3	*a*	< 0,1	*a*	0,2	*a*	%
Grond	96,5	*a*	75,2	*a*	94,0	*a*	76,0	*a*	%
Puin	3,5	*a*	24,8	*a*	6,0	*a*	24,0	*a*	%
Korrelgrootte voor SCG									
Korrelgrootte <2 um, sedigraaf	30,1	*a*	11,4	*a*	40,8	*a*	< 2,5	*a*	% md
Korrelgrootte <16 um, sedigraaf	53,1	*a*	14,4	*a*	69,3	*a*	5,0	*a*	% md
Korrelgrootte <32 um	56,0	*a*	15,4	*a*	86,5	*a*	5,8	*a*	% md
Korrelgrootte <50 um	56,2	*a*	15,9	*a*	91,4	*a*	6,5	*a*	% md
Korrelgrootte <63 um	58,6	*a*	16,6	*a*	96,7	*a*	6,5	*a*	% md
Korrelgrootte <125 um	66,4	*a*	21,7	*a*	97,6	*a*	8,8	*a*	% md
Korrelgrootte <250 um	89,8	*a*	78,5	*a*	98,9	*a*	37,1	*a*	% md
Korrelgrootte <500 um	96,6	*a*	96,2	*a*	99,6	*a*	82,5	*a*	% md
Korrelgrootte <1000 um	98,2	*a*	98,7	*a*	99,9	*a*	96,8	*a*	% md

Opmerkingen

a Analyse uitgevoerd door OMEGAM

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Methodeverwijzingen

Fysisch- Chemische analyses in overige

Carbonaat, volumetrisch	
Dichtheid van vaste matrix	
Indamprest van vaste matrix	
Gloeirest van de indamprest	
Organisch stof gehalte	
Voorbehandeling SCG kromme	
	Alle componenten
Korrelgrootte voor SCG	
	Alle componenten

Analyserapport

Waternet, TOP
MTW
T.a.v. de heer E. Bontjes
Postbus 94370
1090 GJ AMSTERDAM

Datum:	Rapportnummer:	Uw Kenmerk:
20-03-2023	445485	301321 / 301212
Project:	**Monstername door:**	**Uw projectcode:**
dooea005/005, Kwaliteit hemelwater en slib	Opdrachtgever	

Geachte heer Bontjes,

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.

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

De resultaten op dit rapport zijn geautoriseerd door de directeur van Stichting Waterproef
J.S.C. Bruin.

Kopie aan:
MTW , t.a.v. mevrouw A. Hoornick

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

Rapportnummer:
445485

Volgnummer	Puntcode	Monsteromschrijving*
698268	oh080007	Overig Hemelwaterput uitlaat
698269	oh080007	Overig Hemelwaterput hoog
698270	oh080007	Overig Hemelwaterput laag
698271	oh080007	Overig Kolk rustig

Volgnummer	**698268**	**698269**	**698270**	**698271**
Monstercode klant*	UIT	HD	LD	RS
Monstertype*	Overige	Overige	Overige	Overige
Bemonsteringstype*	steekmonster	steekmonster	steekmonster	steekmonster
Monsternemer*	A. Hoornick	A. Hoornick	A. Hoornick	A. Hoornick
Monstername datum*	01-03-2023	01-03-2023	01-03-2023	01-03-2023
Monstername tijd*	10:00	10:00	10:00	10:00
Acceptatiedatum	02-03-2023	02-03-2023	02-03-2023	02-03-2023

Fysisch- Chemische analyses									**Eenheid**
Carbonaat, volumetrisch	25	a	39	a	14	a	22	a	g/kg dg
Dichtheid van vaste matrix	1,1969		1,2183		1,306		1,0759		g/ml
Indamprest	18,9		30,6		25,9		23,7		%
Gloeirest van de indamprest	75		89		78		71		% van dg
Organisch stof gehalte	31,7	a	11,6	a	23,3	a	6,4	a	%dg
Voorbehandeling SCG kromme									
Afval	nb	a	nb	a	nb	a	nb	a	%
Grind	1,2	a	1,0	a	< 0,1	a	< 0,1	a	%
Grond	98,8	a	90,5	a	90,0	a	81,3	a	%
Puin	1,2	a	9,5	a	10,0	a	18,7	a	%
Korrelgrootte voor SCG									
Korrelgrootte <2 um, sedigraaf	24,8	a	5,3	a	6,1	a	14,0	a	% md
Korrelgrootte <16 um, sedigraaf	35,6	a	8,0	a	10,8	a	24,2	a	% md
Korrelgrootte <32 um	38,6	a	8,6	a	13,3	a	25,3	a	% md
Korrelgrootte <50 um	39,6	a	8,8	a	13,5	a	27,9	a	% md
Korrelgrootte <63 um	41,8	a	9,6	a	14,6	a	29,2	a	% md
Korrelgrootte <125 um	49,0	a	15,2	a	22,8	a	36,1	a	% md
Korrelgrootte <250 um	77,1	a	71,9	a	66,0	a	71,5	a	% md
Korrelgrootte <500 um	95,2	a	93,9	a	92,9	a	95,7	a	% md
Korrelgrootte <1000 um	97,9	a	97,6	a	97,2	a	99,1	a	% md

Opmerkingen
a Analyse uitgevoerd door OMEGAM

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Methodeverwijzingen

Fysisch- Chemische analyses in overige

Carbonaat, volumetrisch
Dichtheid van vaste matrix
Indamprest
Gloeirest van de indamprest
Organisch stof gehalte
Voorbehandeling SCG kromme
    Alle componenten
Korrelgrootte voor SCG
    Alle componenten

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Analyserapport

Waternet, TOP
MTW
T.a.v. de heer E. Bontjes
Postbus 94370
1090 GJ AMSTERDAM

Datum:	Rapportnummer:	Uw Kenmerk:
06-04-2023	447705	301321 / 301212
Project:	**Monstername door:**	**Uw projectcode:**
dooea005/005, Kwaliteit hemelwater en slib	Opdrachtgever	

Geachte heer Bontjes,

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.

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

De resultaten op dit rapport zijn geautoriseerd door de directeur van Stichting Waterproef
J.S.C. Bruin.

Kopie aan:
MTW , t.a.v. mevrouw A. Hoornick

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

Volgnummer	Puntcode	Monsteromschrijving*
699314	oh080007	Overig Kolk park
699315	oh080007	Overig Kolk druk
699316	oh080007	Overig Kolk rustig

Volgnummer	699314	699315	699316
Monstercode klant*	IN-1	IN-2	IN-3
Monstertype*	Overige	Overige	Overige
Bemonsteringstype*	steekmonster	steekmonster	steekmonster
Monsternemer*	A. Hoornick/H. Nieuwenhuis	A. Hoornick/H. Nieuwenhuis	A. Hoornick/H. Nieuwenhuis
Monstername datum*	14-03-2023	14-03-2023	14-03-2023
Monstername tijd*	13:00	13:00	13:00
Acceptatiedatum	15-03-2023	15-03-2023	15-03-2023

Fysisch- Chemische analyses	699314	699315	699316	Eenheid
Carbonaat, volumetrisch		16 a		g/kg dg
Fosfor na ontsluiting	1,5	0,33	1,1	g/kg P dg
Dichtheid van vaste matrix		1,5425		g/ml
Indamprest	17,1	52,9	22,0	%
Gloeirest van de indamprest	27	92	43	% van dg
Organisch stof gehalte		3,0 a		%dg
Voorbehandeling SCG kromme				
Afval		2,1 a		%
Grind		8,8 a		%
Grond		89,1 a		%
Puin		10,9 a		%
Korrelgrootte voor SCG				
Korrelgrootte <2 um, sedigraaf		3,5 a		% md
Korrelgrootte <16 um, sedigraaf		7,3 a		% md
Korrelgrootte <32 um		7,9 a		% md
Korrelgrootte <50 um		9,2 a		% md
Korrelgrootte <63 um		11,0 a		% md
Korrelgrootte <125 um		17,5 a		% md
Korrelgrootte <250 um		56,9 a		% md
Korrelgrootte <500 um		88,9 a		% md
Korrelgrootte <1000 um		96,8 a		% md

Metaal analyses	699314	699315	699316	Eenheid
Koper na ontsluiting	50	170	70	mg/kg dg
Zink na ontsluiting	370	410	870	mg/kg dg

Organische analyses	699314	699315	699316	Eenheid
Minerale olie in vaste matrix	2100	1400	3900	mg/kg dg
PAK EPA in vaste matrix				

** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Rapportnummer:
447705

Pagina

Volgnummer	699314		699315		699316		
Acenafteen	< 0,05	b	< 0,05	b	0,20		mg/kg dg
Acenaftyleen	< 0,1	b	< 0,1	b	< 0,1	b	mg/kg dg
Anthraceen	< 0,05	b	0,07		0,34		mg/kg dg
Benzo(a)antraceen	< 0,1	b	0,36		1,6		mg/kg dg
Benzo(a)pyreen	< 0,1	b	< 0,2	b	1,6		mg/kg dg
Benzo(b)fluorantheen	0,22		0,38		2,5		mg/kg dg
Benzo(g,h,i)peryleen	< 0,1	b	0,23		1,4		mg/kg dg
Benzo(k)fluorantheen	< 0,1	b	< 0,3	b	0,73		mg/kg dg
Chryseen	0,13		0,38		1,6		mg/kg dg
Dibenzo(a,h)antraceen	< 0,15	b	< 0,3	b	0,81		mg/kg dg
Fenanthreen	0,18		0,62		1,9		mg/kg dg
Fluoreen	< 0,05	b	0,07		0,20		mg/kg dg
Fluorantheen	0,25		1,7		2,7		mg/kg dg
Indeno(1,2,3-c,d)pyreen	< 0,15	b	< 0,3	b	1,2		mg/kg dg
Naftaleen	< 0,05	b	0,08		0,14		mg/kg dg
Pyreen	0,26		1,4		2,3		mg/kg dg
Som 16 PAK EPA	1,7	c	6,2	c	19	c	mg/kg dg

Opmerkingen

a Analyse uitgevoerd door OMEGAM
b De rapportagegrens is verhoogd in verband met matrixstoring.
c Door de verhoogde rapportagegrens van een of meerdere componenten is het resultaat van de sommatie verhoogd.

Methodeverwijzingen

Fysisch- Chemische analyses in overige

Carbonaat, volumetrisch	
Fosfor na ontsluiting	Eigen methode
Dichtheid van vaste matrix	
Indamprest	
Gloeirest van de indamprest	
Organisch stof gehalte	
Voorbehandeling SCG kromme	
Alle componenten	
Korrelgrootte voor SCG	
Alle componenten	

Metaal analyses in overige

Koper na ontsluiting	
Zink na ontsluiting	

Organische analyses in overige

Minerale olie in vaste matrix	
PAK EPA in vaste matrix	
Alle componenten	

Analyserapport

Waternet, TOP
MTW
T.a.v. de heer E. Bontjes
Postbus 94370
1090 GJ AMSTERDAM

Datum:	Rapportnummer:	Uw Kenmerk:
26-04-2023	449934	301321 / 301212
Project:	**Monstername door:**	**Uw projectcode:**
dooea005/005, Kwaliteit hemelwater en slib	Opdrachtgever	

Geachte heer Bontjes,

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.

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

De resultaten op dit rapport zijn vrijgegeven onder de verantwoordelijkheid van de directeur van Stichting Waterproef J.S.C. Bruin.

Kopie aan:
MTW , t.a.v. mevrouw A. Hoornick

Volgnummer	Puntcode	Monsteromschrijving*
703743	oh080007	Overig Kolk druk
703744	oh080007	Overig Kolk rustig

Volgnummer	703743	703744
Monstercode klant*	IN-2	IN-3
Monstertype*	Overige	Overige
Bemonsteringstype*	steekmonster	steekmonster
Monsternemer*	A. Hoornick/ H.van Nieuwehuizen	A. Hoornick/ H.van Nieuwehuizen
Monstername datum*	12-04-2023	12-04-2023
Monstername tijd*	13:00	13:00
Acceptatiedatum	13-04-2023	13-04-2023

Fysisch- Chemische analyses	703743		703744		Eenheid
Carbonaat, volumetrisch	11	*a*	< 1	*a*	g/kg dg
Dichtheid	1,5555		1,1896		g/ml
Indamprest	49,8		20,2		%
Gloeirest van de indamprest	90		42		% van dg
Organisch stof gehalte	5,5	*a*	54,6	*a*	%dg
Voorbehandeling SCG kromme					
Afval	< 0,1	*a*	< 0,1	*a*	%
Grind	< 0,1	*a*	< 0,1	*a*	%
Grond	88,4	*a*	86,1	*a*	%
Puin	11,6	*a*	13,9	*a*	%
Korrelgrootte voor SCG					
Korrelgrootte <2 um, sedigraaf	3,5	*a*	4,3	*a*	% md
Korrelgrootte <16 um, sedigraaf	7,5	*a*	12,9	*a*	% md
Korrelgrootte <32 um	8,8	*a*	15,2	*a*	% md
Korrelgrootte <50 um	9,7	*a*	18,1	*a*	% md
Korrelgrootte <63 um	10,0	*a*	18,8	*a*	% md
Korrelgrootte <125 um	15,8	*a*	23,6	*a*	% md
Korrelgrootte <250 um	50,8	*a*	46,6	*a*	% md
Korrelgrootte <500 um	83,3	*a*	76,6	*a*	% md
Korrelgrootte <1000 um	93,7	*a*	91,2	*a*	% md

Opmerkingen

a Analyse uitgevoerd door OMEGAM

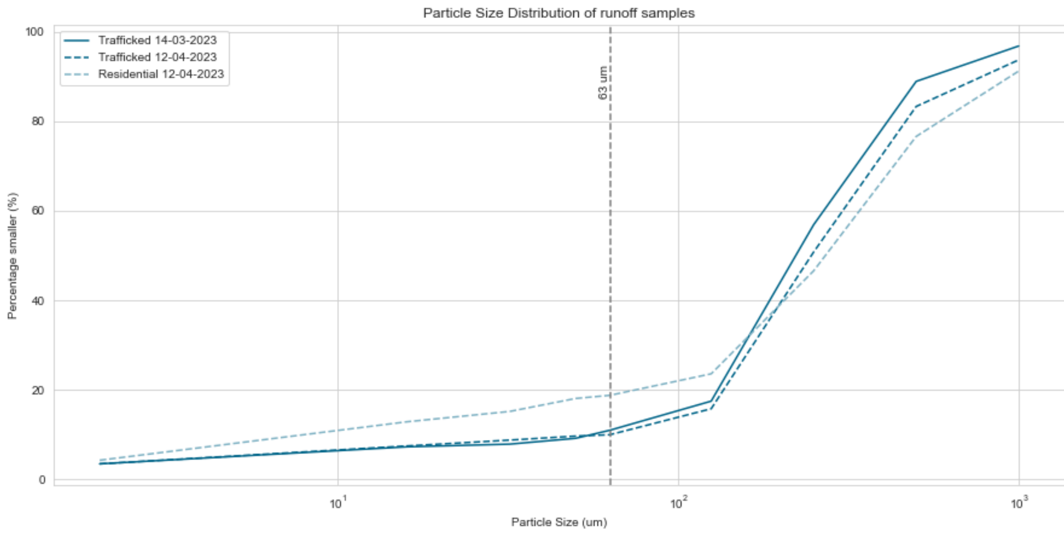
** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*

Methodeverwijzingen

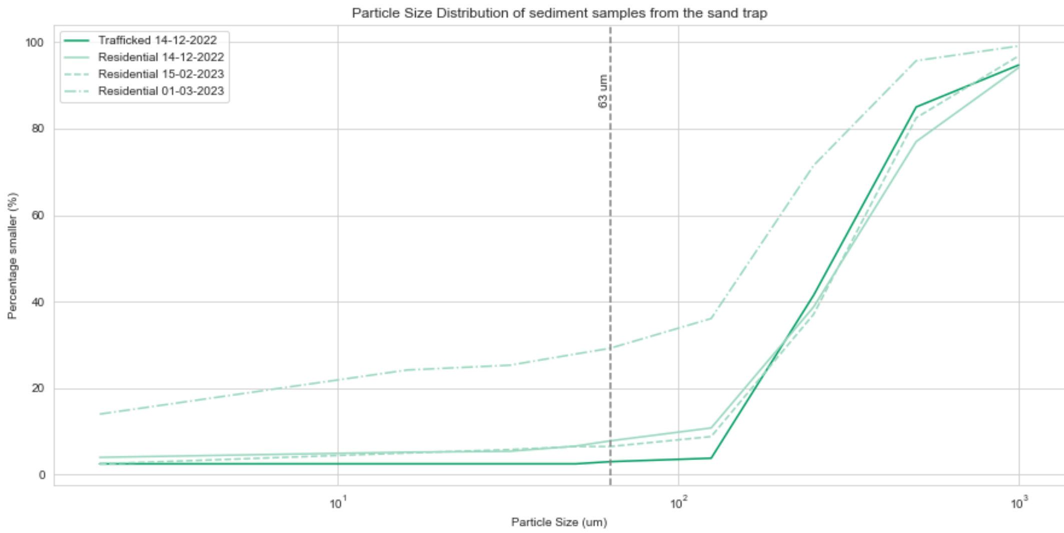
Fysisch- Chemische analyses in overige

Carbonaat, volumetrisch	
Dichtheid	
Indamprest	
Gloeirest van de indamprest	
Organisch stof gehalte	
Voorbehandeling SCG kromme	
	Alle componenten
Korrelgrootte voor SCG	
	Alle componenten

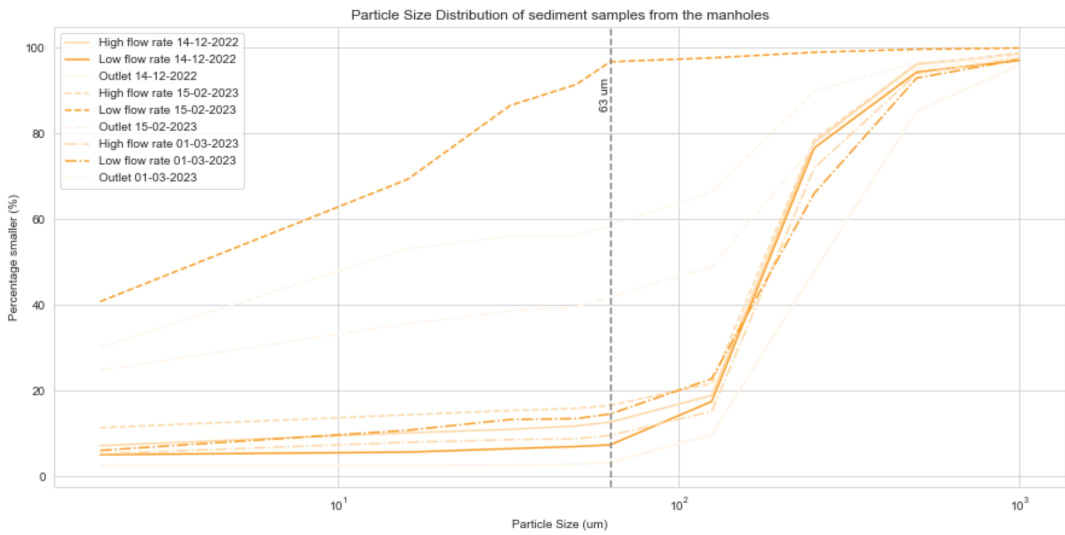
** Door de klant aangeleverde gegevens zijn gemarkeerd en vallen buiten de verantwoordelijkheid van het laboratorium. De gerapporteerde analyseresultaten hebben slechts betrekking op het aangeboden monster.*



(a) The particle size distribution of solids collected using a filter bag placed in the gully pot located alongside a highly trafficked road and one sample collected using a filter bag placed in the gully pot located in a residential neighborhood



(b) The particle size distribution of sediment collected from sand traps, located in a trafficked area and residential area.



(c) The particle size distribution of sediment collected from the sediment bed at the bottom of manholes.

Figure C.2: Particle size distribution analysis of all samples

Appendix D

Dynamics

This appendix provides a detailed analysis of the dynamics observed during selected rainfall events within the study period. Only events with a duration longer than 1 hour and an average intensity higher than 0.4 mm/hour are included for evaluation.

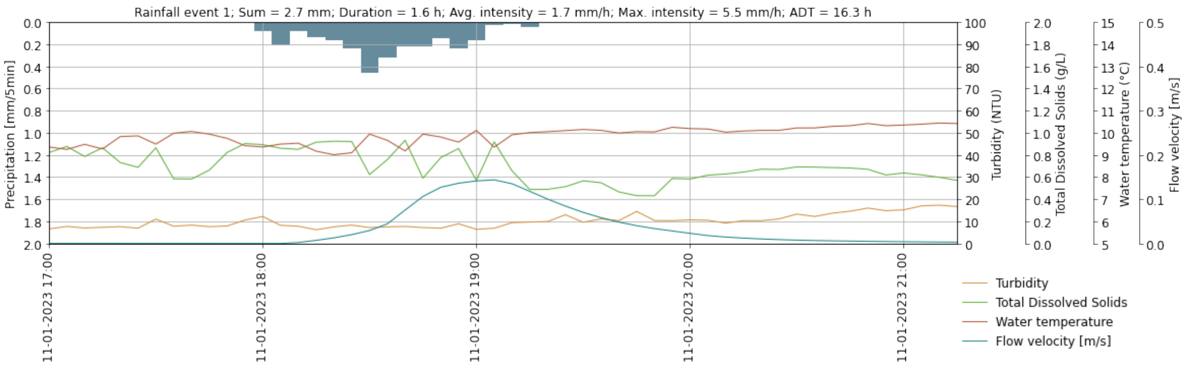


Figure D.1: **Rainfall event 1**: This event was characterized by relatively light rainfall. Turbidity showed no significant response, while total dissolved solids (TDS) exhibited variations with intermittent peaks. The water temperature also displayed minor fluctuations.

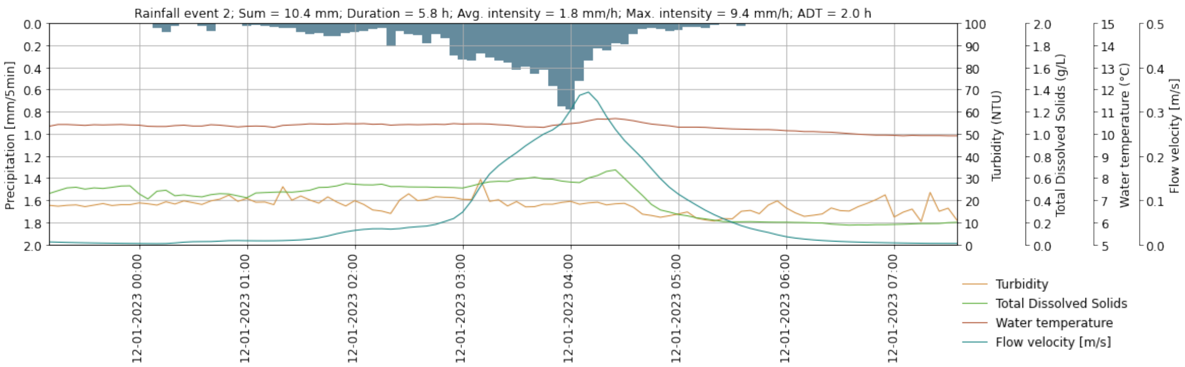


Figure D.2: **Rainfall event 2**: Compared to the rest of the study period, this event was relatively heavy. Following the peak intensity of 9.4 mm/hour, the TDS initially increased slightly from 0.6 to 0.7 g/L before decreasing to 0.2 g/L approximately 20 minutes after the peak. The turbidity graph showed minimal changes, except for some small peaks during the event. It is worth noting that there was only one dry hour prior to the event, which may have influenced the limited parameter response.

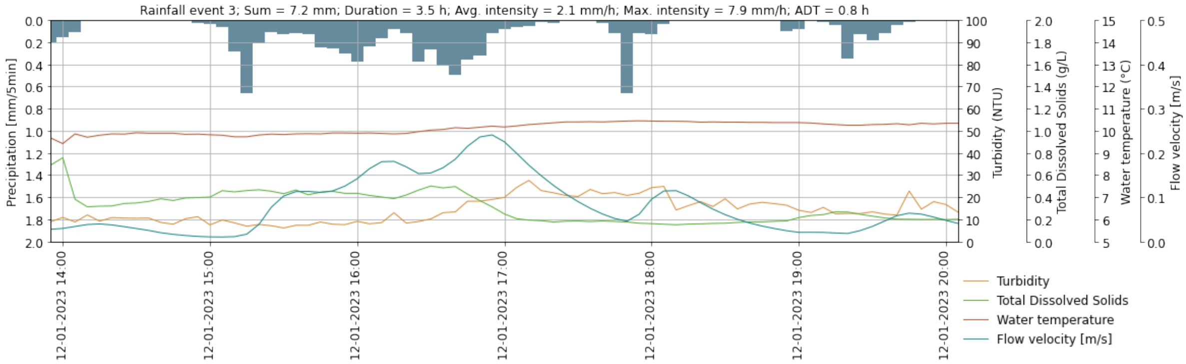


Figure D.3: **Rainfall event 3**: Occurring on the same day as event 2, this event demonstrated a delayed response in the TDS graph, with a slight increase from 0.4 to 0.6 g/L followed by a decrease to 0.2 g/L. The turbidity graph exhibited an increase from 10 to 25 NTU during the flow velocity peak. The last peak of the event, with an intensity of 7.9 mm/hour, induced a minor response in turbidity but did not significantly impact TDS levels.

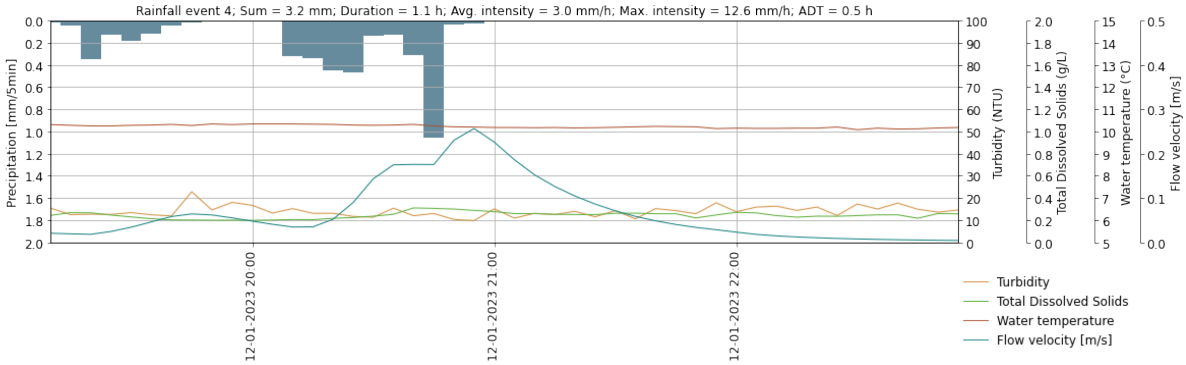


Figure D.4: **Rainfall event 4**: Despite a high maximum intensity, no noticeable response was observed in the three parameters. This lack of response may be attributed to the short dry period prior to the event.

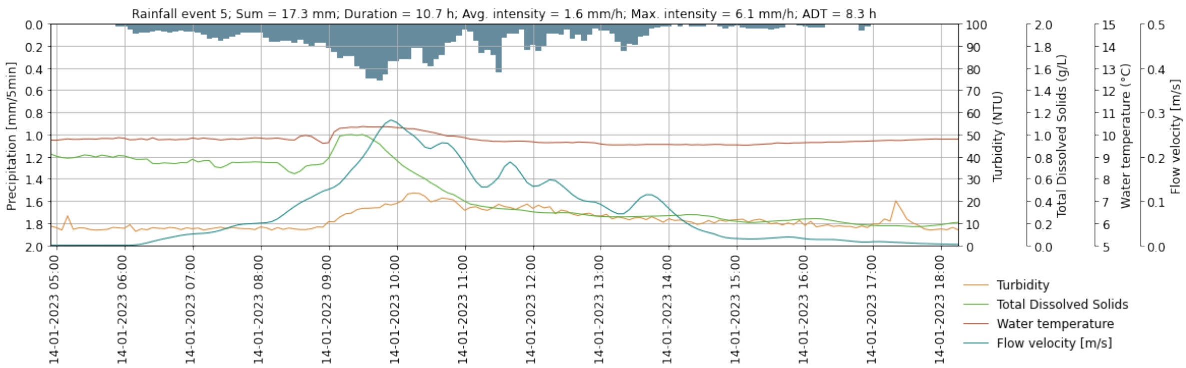


Figure D.5: **Rainfall event 5**: This event was characterized by a long duration and a substantial total precipitation amount. Although the maximum intensity was not exceptionally high, the parameter graphs displayed clear responses. TDS initially increased from 0.7 to 1 g/L and then decreased to 0.2 g/L. The water temperature first increases a bit and slowly decreases. The turbidity showed an increase during the increase of the flow velocity and slowly decreased again. Notably, the response began before the peak of the event, suggesting that even low-intensity rainfall over an extended period can initiate the movement of solids. The delayed response can also be attributed to the reliance on precipitation data derived from radar, which can lead to variations in flow patterns within the sewer system.

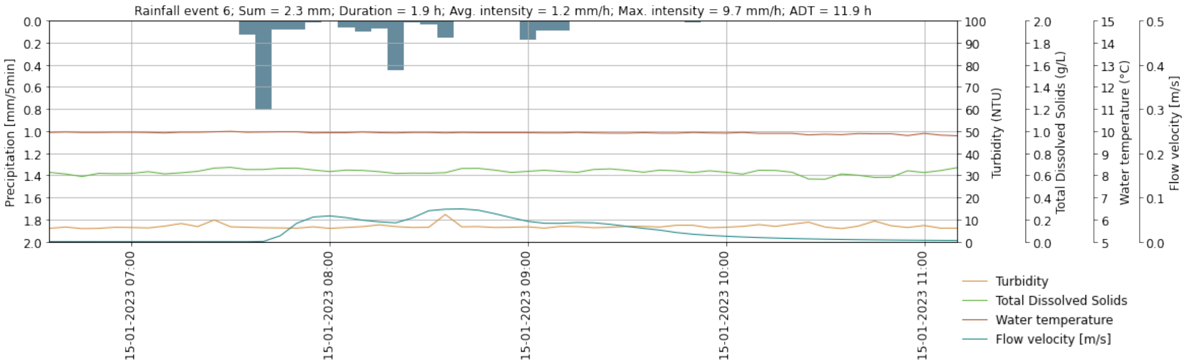


Figure D.6: **Rainfall event 6**: This event consisted of several short peaks with relatively high intensities. However, no observable response was detected in the parameter graphs. It appears that insufficient precipitation occurred to generate runoff and reach the sewer system. It is assumed that the initial 2-3 mm of precipitation may not contribute to runoff, explaining the absence of parameter responses.

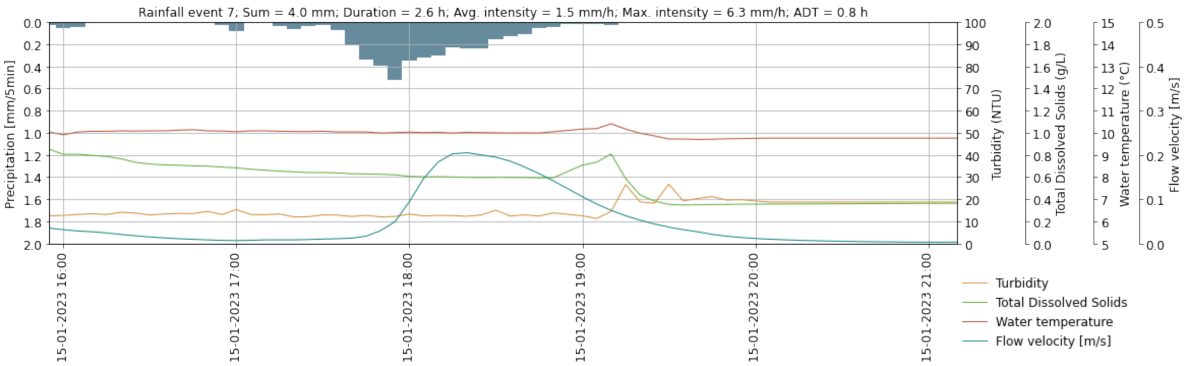


Figure D.7: **Rainfall event 7**: Responses were observed approximately 1 hour after the peak of this event. TDS levels increased slightly from 0.6 to 0.8 g/L before decreasing to 0.4 g/L. The water temperature exhibited a similar pattern, with a slight increase and subsequent decrease. Turbidity, on the other hand, increased from 10 to approximately 20 NTU, with two short peaks reaching 28 NTU.

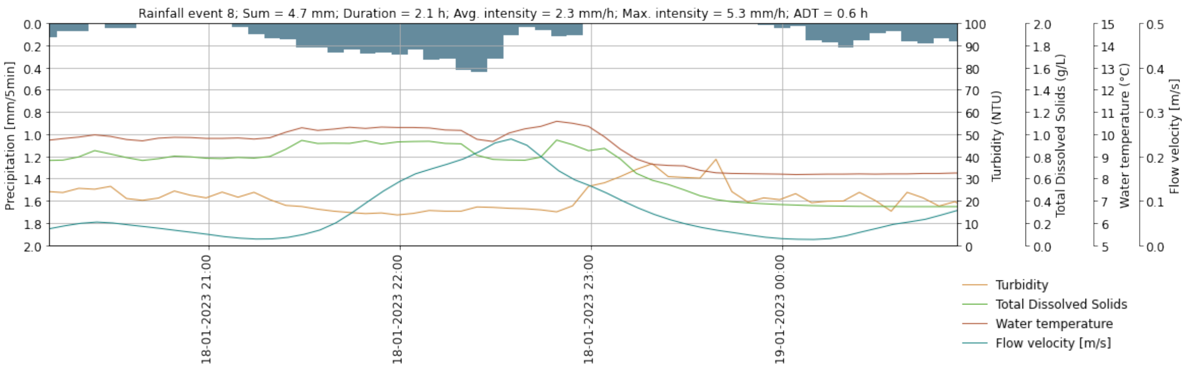


Figure D.8: **Rainfall event 8**: Despite not having a very high intensity, variations were observed in all parameters during this event. The relatively short duration of dry hours before the event may have contributed to the observed response. Initially, a slight increase in TDS and water temperature was observed, followed by a subsequent decrease. Additionally, there was an increase in turbidity.

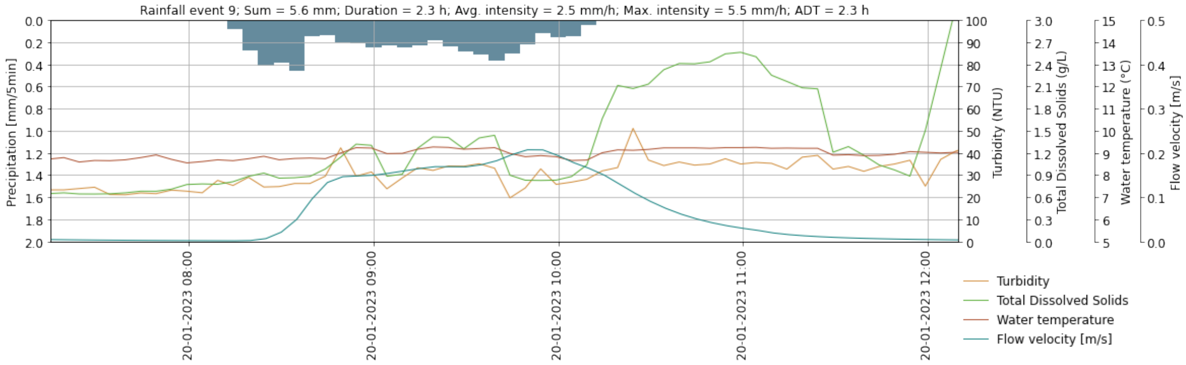


Figure D.9: **Rainfall event 9**: This event was similar to event 8, but with a slightly longer dry period before the event. Variations in all parameters were observed throughout the event and towards the end, there was a relatively significant response in conductivity. The exact explanation for this response requires further investigation.

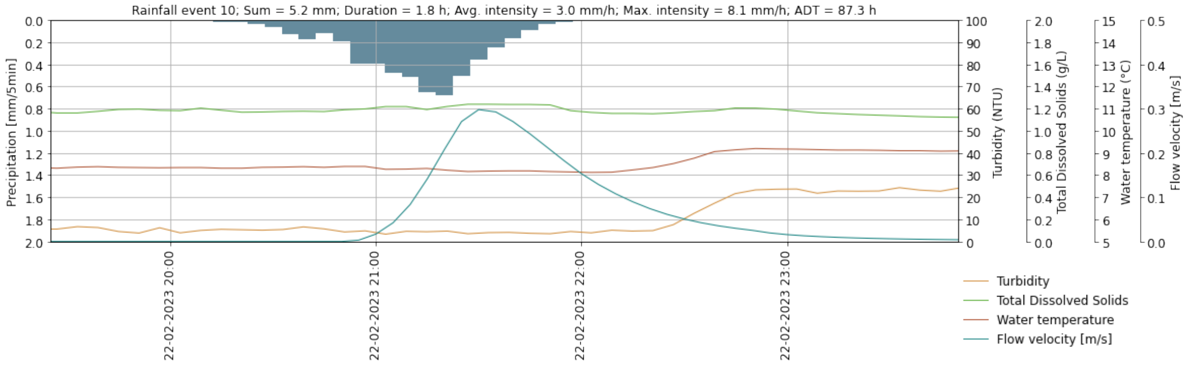


Figure D.10: **Rainfall event 10**: With a long period of dry hours before the event, this rainfall event had a relatively high maximum intensity. The response, however, occurred considerably later after the peak. The only significant response was observed in turbidity, which increased from approximately 5 to 23 NTU. A slight increase in water temperature and a shallow decrease in TDS were also noted.

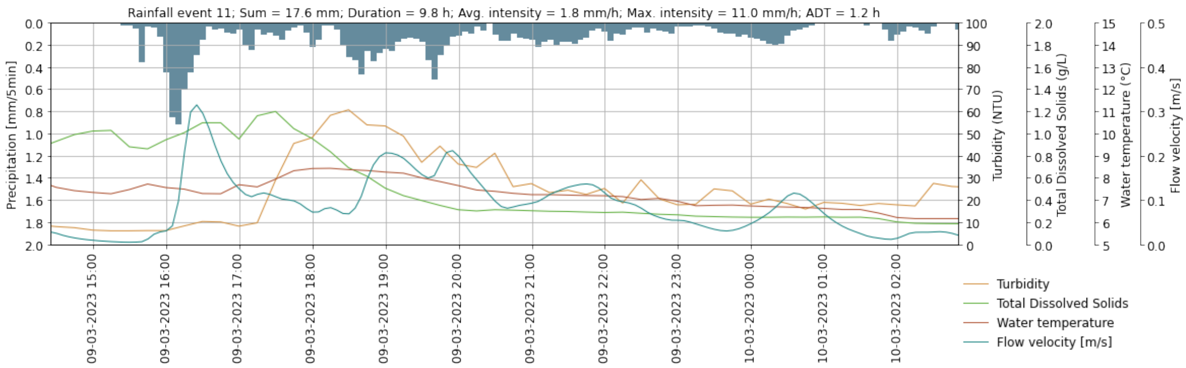


Figure D.11: **Rainfall event 11**: This event was characterized by relatively heavy rainfall, with the peak intensity occurring early in the event. Approximately 1 hour after the peak, clear responses were observed. TDS levels initially increased slightly from 1 to 1.2 g/L, followed by a significant decrease to 0.2 g/L. The water temperature displayed a gradual increase and subsequent decrease. The turbidity exhibited a sudden increase from 10 to 60 NTU approximately 1 hour after the peak, followed by a gradual decrease.

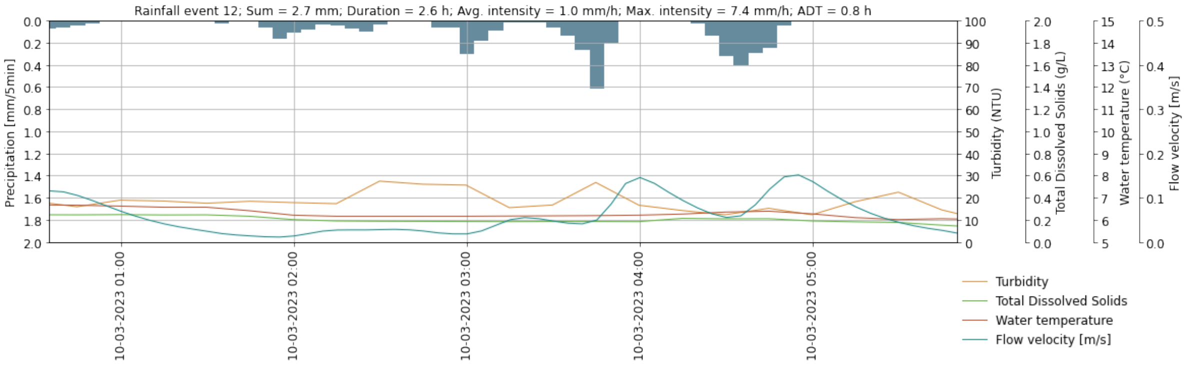


Figure D.12: **Rainfall event 12**: Little response could be seen during this event, with only minor variations in turbidity. This could be attributed to the short duration of dry hours before the event or the possibility that insufficient precipitation occurred to generate flow in the sewer system.

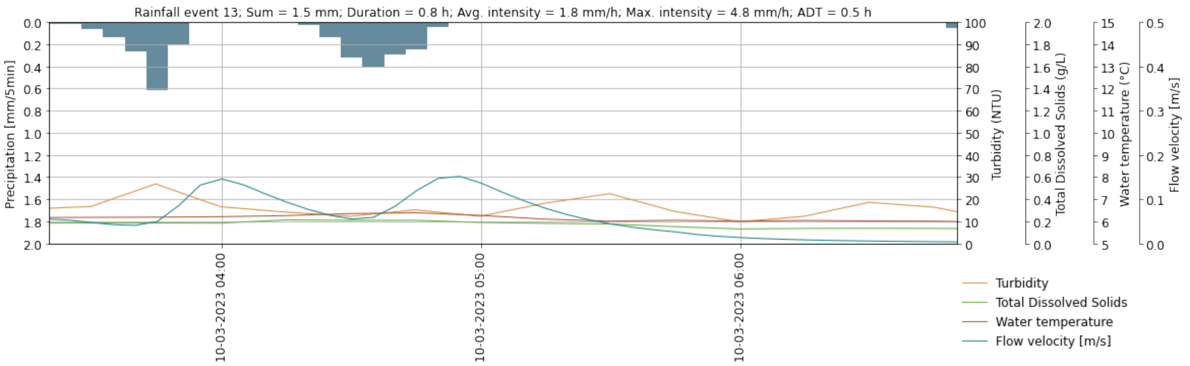


Figure D.13: **Rainfall event 13**: Similar to rainfall event 12, no significant response was observed. Some variations in turbidity were noted, but they were not substantial. Again, this lack of response may be due to the short duration of dry hours or insufficient precipitation.

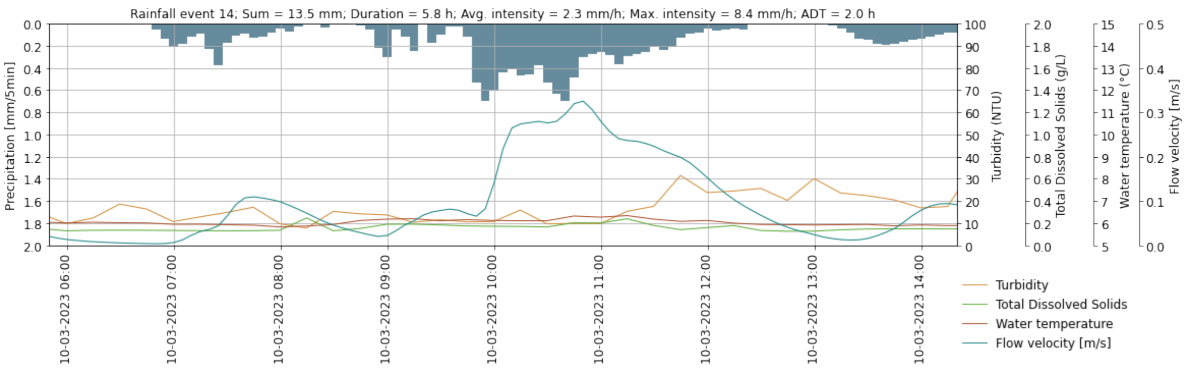


Figure D.14: **Rainfall event 14**: Approximately 1 hour after the highest peak of 8.4 mm/h, a minor increase in turbidity could be observed. However, there was no significant response in TDS or water temperature. The reasons for this lack of response require further investigation.

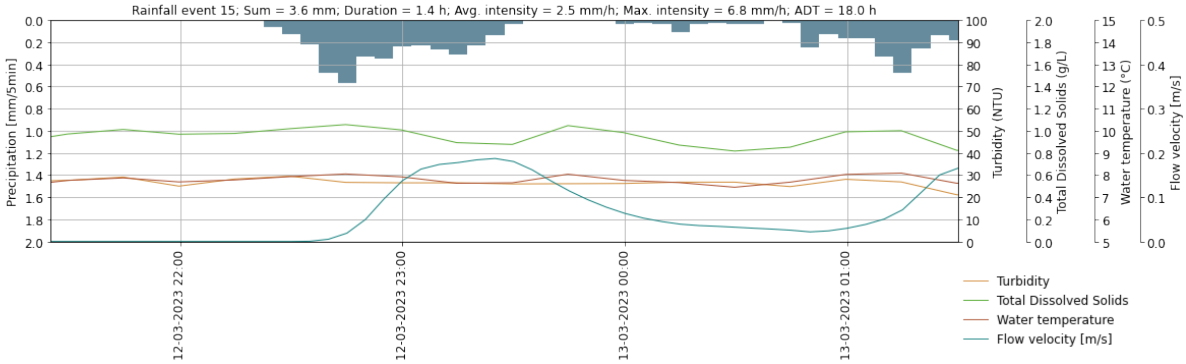


Figure D.15: **Rainfall event 15**: Some minor variations were observed in all parameters during this event, but they were not significant. The event itself was relatively light, which may explain the limited responses observed.

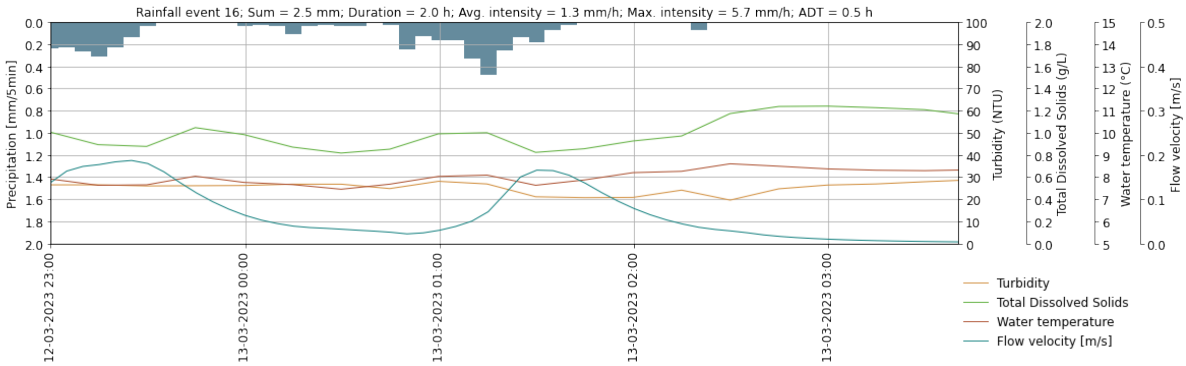


Figure D.16: **Rainfall event 16**: Similar to event 15, minor variations in all parameters were observed, with a slightly more noticeable response in TDS. Despite the peak of the event being less than event 15, the response occurred relatively soon after event 15.

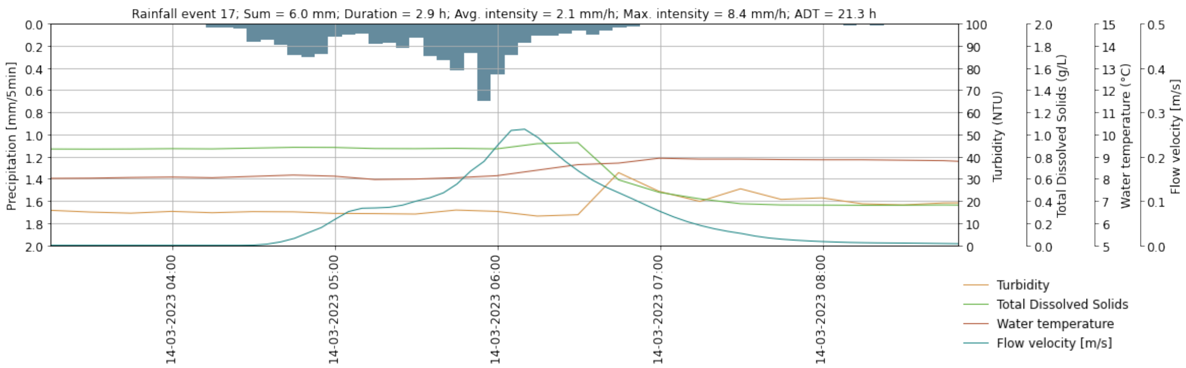


Figure D.17: **Rainfall event 17**: Clear responses were observed during this event, with a slight increase in TDS followed by a larger decrease. There was also a minor increase in water temperature. Turbidity displayed an increase and a gradual decrease afterward. These responses occurred approximately 40 minutes after the peak of the event.