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Master Thesis

Assessment of a Highway Runoff Stormwater Collector System of A Stormwater Treatment Plant: A Focus on Dynamic Responses Within the System

Submitted by

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 06/09/2023 Eliott Jean Robert GABRIEL *(manu propria)*

Preface

It is with immense satisfaction and a sense of accomplishment that I present this master's thesis. This is the culmination of an enriching academic journey that I have undertaken as part of the MSc in Environmental Science (Soil, Water, and Biodiversity). This opportunity would not have been possible without the involvement of the Euroleague for Life Sciences (ELLS) in creating a network of leading European universities which helps institutions and students to collaborate on an European level.

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This work represents the collaborative efforts and support of two esteemed institutions, The University of Natural Resources and Life Sciences of Vienna (BOKU) and the University of Copenhagen (KU), both of which have played an integral role in shaping my academic pursuits.

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Undertaking a double degree has been a remarkable experience, one that has provided me with the unique opportunity to draw from the rich academic resources and distinct perspectives offered by the two universities. This thesis pays a tribute to those who made it possible for students and academics to collaborate with each other as part of the European Master Program in Environmental Science (EnvEuro).

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Abstract

Freshwater ecosystems are threatened by various types of pollution that endanger species, ecosystem services, and human lives. Of particular concern is road runoff, a significant threat that requires attention if we want to prevent further environmental degradation and foster the restoration of aquatic ecosystems. It poses a particular danger, transporting diverse heavy metals originating from vehicles and road surfaces that accumulate and wash into water bodies during rain events. This study aims to evaluate the dynamic flows entering a stormwater collector treatment facility and the system's subsequent response. To achieve this, various sampling methods were implemented and tested to gauge the system's reaction to stormwater runoff from the neighbouring highway. The aim of the study was to compare two sampling strategies -total samplers ("System Der Wasserwirt") and automatic samplers - and assess their ability to detect the first flush phenomenon. To do so, we looked at the time of sampling related to the water flow, the height in the pipe and the height in the shaft. Additionally, different methods for measuring pollutant concentrations were evaluated. The study especially focused at the Turbidity (NTU) and the Total Suspended Solids (TSS) in the runoff.

Laboratory analysis supplemented on-site measurements, revealing challenges in locating an appropriate sampling point due to the intermittent nature of rainfall events. Nevertheless, the study successfully observed the first flush phenomenon when the system initiated sampling at the start of a runoff event. Automatic samplers effectively captured turbidity peaks, while total samplers frequently exhibited a delay in their sampling process. Total samplers also seemed influenced by the interactions with the shaft and the sediments that can accumulate there. Further sampling and investigation are imperative to provide robust recommendations to public authorities and highway management entities.

Kurzfassung

Süßwasserökosysteme sind von Verschmutzungen unterschiedlicher Herkunft bedroht, die die Überlebensfähigkeit von Arten, Ökosystemdienstleistungen und das menschliche Leben gefährden. Straßenabfluss stellt eine erhebliche Bedrohung dar, die bei der Wiederherstellung von Süßwasserökosystemen berücksichtigt werden muss. Besonders gefährlich für Ökosysteme sind Schwermetalle aus Fahrzeugen und Straßenbelägen, die sich bei Regen in Gewässer ansammeln.

Diese Masterarbeit zielt darauf ab, die Zuflüsse in eine Regenwasserbehandlungsanlage und deren Reaktion auf den Abfluss der benachbarten Autobahn zu messen und zu bewerten. Dazu wurden verschiedene Probenahmeverfahren eingeführt und getestet, darunter eine großflächige Gesamtprobenahme ("System Der Wasserwirt") und automatische Einzelprobenahmen, um das "First-Flush"-Phänomen zu untersuchen. Dabei wurden der Zeitpunkt der Probenahme im Zusammenhang mit dem Wasserdurchfluss, der Rohrhöhe und der Schachthöhe analysiert. Unterschiedliche Methoden zur Messung von Schadstoffkonzentrationen wurden ebenfalls bewertet, wobei der Fokus auf Trübung und gesamten Schwebstoffen lag. Zusätzlich zu Vor-Ort-Messungen wurden Laboranalysen durchgeführt, die Herausforderungen bei der Auswahl geeigneter Probenahmepunkte aufgrund unregelmäßiger Niederschläge aufzeigten.

Trotzdem konnte das "First-Flush"-Phänomen erfolgreich beobachtet werden, wenn das System zu Beginn eines Oberflächenabflussereignisses mit der Probenahme begann. In den automatischen Einzelproben wurden Trübungsspitzen effektiv erfasst, während in der Gesamtprobe häufig Verzögerungen auftraten, die durch Wechselwirkungen mit dem Schacht und den dort angesammelten Sedimenten beeinflusst wurden. Weitere Probenahmen und Untersuchungen sind erforderlich, um fundierte Empfehlungen für Verwaltungsbehörden und Autobahnverwaltungen geben zu können

1. Introduction

Freshwater is one of the most important elements for human life as it provides an array of benefits. The main ones include, drinking water, electricity generation, and agriculture; although it encompasses almost every activity that can be performed. Despite their extreme importance, there are many concerns related to the preservation of freshwater ecosystems in Europe and throughout the world. In a recent report, the European Environmental Agency pointed out freshwater water bodies degradation as one of the key challenges to be addressed as part of their River Basin Management Plan (RBMPs) strategies (EEA, 2021). They even pointed out that there was limited progress made between the previous assessment of 2018 and the most recent one of 2021. This highlights the current state of degradation of our freshwater ecosystems, and the urgent need to tackle the sources of the problem.

Among the threats that endanger water bodies and the surrounding environments, urban runoff has emerged as one of the most important contributing sources to the issue. It has especially become prominent as the urbanisation of the European landscapes has continued to expand. Urban runoff refers to the rainwater coming from the surfaces of developed areas such as streets, sidewalks, rooftops, and roads picking up pollutants such as oil, chemicals, and debris along the way (Schiff et al., 2016). Out of the different types of urban runoff, road runoff emerges as an important source of heavy metals and vehicles debris which have the potential to contaminate the water bodies that it enters. The threat is especially high when there is no adequate treatment system in place (Gillis et al., 2022).

There is now a wide range of systems and processes that are available in order to purify road runoff and ensure that the concentration of pollutants in the effluent is as low as possible. While there are still some road runoff treatment systems that are only using a sedimentation basin, it is increasingly becoming the norm to use a combined system composed of a sedimentation area alongside a filter bed (Mooselu et al., 2022). For instance, both treatment process have their own advantages. On one hand, sedimentation areas are quite effective in their ability of settling coarse particles and trapping bigger rubbishes (Rommel and Helmreich, 2018), while filter beds have a better capacity to filter finer particles such as dissolved heavy metals (Hallberg et al., 2022). Moreover, the use of natural filter beds can also have aesthetic reasons and can be easily implemented in the surroundings of road areas. Overall, the efficiency of these treatment systems depends on many factors. For instance, it’s important that they are redesigned over time as the weather conditions and the surrounding environment change as the year passes but also that proper maintenance programmes are in place (Meland, 2016). Having the ability to sample and monitor some systems can also provide us with more knowledge and give use a better capacity to develop similar structures that can be replicated in other areas.

Many researchers have targeted their sampling strategies to capture the occurrence of the first flush. The first flush is a phenomenon characterised by a higher concentration and proportion of pollutants carried by the initial amount of water coming from the runoff (Kayhanian et al., 2012). Its occurrence can mainly be explained by the fact that the beginning of the rainfall event tends to wash out the accumulated sediments and particles off the road surface (Barbosa et al., 2023). As the first flush effect is not a set definition, the way that it is sampled is also very varied in the literature. For instance, while in certain publications, equally-timed samples were taken throughout the whole runoff event, in other cases, the amount of samples taken was high at the beginning of the event with additional ones taken at longer intervals at the end of the runoff event (Huber et al., 2016).

As a whole, these sampling strategies and evaluations of the purification systems can enhance our ability to understand the quantity, timing, and toxicity of the runoff which can then be a good basis for the establishment of policies and regulations to safeguard aquatic environments. Protecting water bodies and their ecosystem is essential for the preservation of the species integrity, ecosystem services, and human lives.

2. Objectives

As part of a project alongside the ASFINAC Bau Management and the local public authority, the University of Natural Resources and Life Sciences of Vienna (BOKU) is taking part in a project aiming at assessing the relevance of urban stormwater collector systems as a treatment solution for highway runoff. The project consists of three different stormwater collector systems located in three regions throughout Austria: one near Vienna, one in Upper-Austria, and one in Styria. The main objective of the project is to evaluate the efficiency of the systems, in order to provide recommendations for policymakers, local and private institutions so they can develop and implement similar structures in the future. This could have beneficial implications for Austrian and even European water bodies and ecosystems, as it would be a potential solution to the threat that highway runoff represents.

In that context, the main goal of this master thesis is to obtain a comprehensive overview of the highway runoff stormwater collector system of a stormwater treatment plant, from the precipitation, the different flows that enter and leave the system to the approach that has been used to sample and monitor what is taking place inside it. Thus, one of the first objective has been to investigate the ability of two different sampling methods to capture and sample relevant rainfall events. As sampling with automatic devices is costly and requires a lot of maintenance, it was essential to look at how it compared to a total sampler and if the latter could potentially be implemented as a good alternative. Then, another closely related objective was to evaluate whether we could detect the first flush phenomenon using the calibration of our automatic sampler, the data analysis derived from the water samples taken, and the on-site measurements transmitted online.

A data analysis on the collected data has been carried out to answer the main research question of this master's thesis:

What is the effectiveness of different sampling methods in capturing relevant rainfall events and detecting the first flush phenomenon in the stormwater collector system?

To facilitate the analysis, it has been further divided into two sub research question:

- How effectively do the two sampling methods employed capture and represent relevant rainfall events in the highway runoff stormwater collector system?
- Do the total samplers provide an accurate picture of the concentration of pollutants?
- Was the automatic sampler effective in identifying the occurrence of the first flush phenomenon?

To fulfill the objectives, water samples were collected from the highway runoff stormwater collector system and some parameters have been measured directly on-site. This has been done both in the influent pipe and in the collection part of the system. Then, laboratory analyses have been carried out on the water samples, in the laboratory of our institute and for some parameters, at an external facility.

The thesis has been structured according to the usual approach used for the writing of scientific papers. Following this objective section, we will start with the fundamentals part, presented in the form of a literature review, encompassing the most important concepts and findings in the field.

The literature review serves as a basis for contextualizing the thesis within the larger research landscape and guiding the fulfillment of the research objectives. In the following section, the methodological approach that has been used will be detailed. This includes a more precise examination of the stormwater collector system, and of the various instruments that have been used to collect data. Moreover, it also includes the details of the calculation that has been used to calculate some hydraulic dynamics taking place in the influent but also the approach that has been chosen to analyse the data to generate the results. Subsequently, the results section will display the most important findings that will be relevant for the interpretation and discussion section that will follow. The final sections aim to evaluate the objectives and task of this master's thesis in the light of the results and their interpretation. This will also be the point at which future recommendations for other researchers and policy maker will be made.

3. Fundamentals

The fundamentals section (also refered as literature review section) of this master's thesis aims to provide a comprehensive overview of the different concepts and technical points related to road runoff and its characteristics. This will be essential to have a better understanding of the analysis that has been carried out in the following chapters.

Moreover, this section has been written in a way to showcase the relevant findings related to the general topic of runoff pollution as well as more specific studies which focus more precisely on highway runoff. Highway runoff being a quite specific area of study, some elements will be discussed in relation to studies looking at different aspects of it, or at least not with the same lens. However, the potential limitations and differences between the studies will be highlighted in order to make the similarities and divergences comparable for our analysis.

This section is divided in multiple sub-sections. The aim is to follow a logical order, starting with an explanation of the phenomena related to highway runoffs, and with an overview of the main pollutants that are contained with them. Then, we will investigate the use of sedimentation areas, as well as the importance of filter beds. Following this, we will look at the first flush phenomenon, from the ways it has been defined to its characterisation. In the final part of this section, we will examine the various sampling and monitoring processes that can be implemented, while also delving into the role that seasonality plays over the whole system.

The concept of runoff is of utmost importance for this master's thesis and therefore needs to be briefly but precisely introduced before going forward. A runoff refers to the movement of water, either from precipitation or other sources, over the land surface and into streams, rivers, lakes, or other water bodies. It occurs when the amount of water reaching the ground exceeds the soil's absorbtion capacity or when the ground becomes saturated (Ramke, 2018). Runoff plays a crucial role in the hydrological cycle and is influenced by various factors such as rainfall intensity, soil characteristics, land cover, and topography (Ke and Zhang, 2022).

As such, runoff is quite a general concept and can be applied to a wide range of situations and environments. It has been studied extensively by a wide range of experts and researchers in many fields where it has a relevance. In that regard, the general kind of runoff that directly relates to our study can be defined as road stormwater runoff. This type of runoff has the characteristic of being potentially problematic both on the hydrologic and on the water quality level. Regarding the hydrological issues, a major concern is the extent to which urban areas lead to highly impervious surfaces, ultimately leading to higher runoff volumes (Kaur et al., 2019). In return, this can have the effect of oversaturating the drainage systems and even overflowing directly to the water bodies that are located nearby. This can be further exacerbated by the changes in the hydrograph, which can lead to an acceleration of when the peak flow occurs (Hung et al., 2018). It therefore poses both a problem of water quantity but also of sediments overloading. Indeed, there are also a wide range of pollution concerns related to urban stormwater runoff as it contains various pollutants such as heavy metals, car residues, fertilizers, pesticides, and various miscellaneous trash items (Werbowski et al., 2021). Due to that, we consider this runoff as being a non-point source of pollution and has multiple pathways through which it can endanger natural ecosystems and human lives (Petrucci et al., 2014).

It is in this setting that we are especially focusing on urban stormwater runoff from highways, or in other terms, highway runoff. Although highway runoff has many common characteristics with other urban stormwater runoffs, it differs in the way that it's more specific to the pollutants that come from the road itself. As such, vehicles are central to the pollution that is contained in highway runoff, as well as road management practices (Mooselu et al., 2022). Indeed, we can find pollutants and disturbances that are more distinct, which is also an element that can help researchers and policy makers to tackle the source of the contamination (Mooselu et al., 2022). The threats that can pose these pollutants can diverge according to the frequency, the quantity but can also be different according to the seasons. Moreover, although there are going to be common issues related to every water body that is nearby a highway, it is critical to bear in mind that each of them will be affected differently. Indeed, some ecosystems are more fragile than others and it's hard to have an accurate general picture that can describe the diversity and complexity of all the ecosystems.

As rainwater and snowmelt in water wash over roads, it accumulates a diverse array of pollutants originating from vehicular emissions, road surface deterioration, and other anthropogenic activities (Müller et al., 2020). The composition and frequency of these pollutants can vary widely based on factors such as traffic volume, weather conditions, road design, and land use patterns (Müller et al., 2020). In this sub-section of the literature review, we will examine the various pollutants that can be found in highway runoff. It will encompass their occurrence and prevalence in different environmental settings, and the potential threats they pose to aquatic ecosystems, human health, and the environment as a whole. By gaining a comprehensive understanding of the pollutants present in highway runoff and their implications, we can develop informed strategies for mitigation and better management of runoffs.

A common parameter that can give us good indications of the potential threats of the runoff is conductivity. It is also something that can be measured with relative ease and that does not require complex technology (Das et al., 2006). Thus, it is an element we will look at in our study. Conductivity refers to the ability of water collected from highways to conduct electrical current. As such, an elevated level of electrical conductivity can be an indicator of the presence of contaminants in the runoff. This conductivity is influenced by many factors. These include dissolved ions such as salts, metals, and other pollutants in the water. Salt has the property of being highly conductive meaning that excluding other potential pollutants, the presence of salt can exacerbate the value of the recorded conductivity that is measured (Makineci et al., 2015). Although salt is not "naturally" high in highway runoff, de-icing salt is often used to ensure road safety in the winter. A high conductivity can also be due to the high ionic content coming from some heavy metals that are deposited on the road (Jaishankar et al., 2014). However, the main threat of heavy metals is not their role in increasing the conductivity, hence why we will discuss their negative impact separately. Furthermore, we could add that when the highway is in the vicinity of cultivated areas, it can also impact the conductivity level according to the amount of the fertilizer that has been applied to the soil (Ghane et al., 2016).

As we have seen, conductivity is an important measurement to appraise in highway runoff analysis. On the other hand, it is rather more an indicator that can indicate that the runoff is polluted but not a parameter that will give us the details of what are the cause of high conductivity. Thus, we need to identify more specific elements which give us more precision on the potential threat of the runoff to human health and the environment.

Out of the array of pollutants carried by highway runoff, turbidity is one of the most crucial to look at. Conveniently, it is also feasible to measure it in most circumstances. Characterized by the cloudiness caused by suspended particles, turbidity not only affects visual clarity but can also bring water quality challenges, thus being a fundamental element to consider for our analysis. Turbidity in highway runoff refers to the presence of suspended particles and sediment in stormwater runoff generated from road surfaces. As rainwater flows over highways, it picks up various pollutants, including sedimenst, road salts, heavy metals, and hydrocarbons, resulting in increased turbidity (Müller et al., 2020). The suspended particles not only impair the clarity of the runoff but also pose environmental and ecological risks. High turbidity levels in highway runoff can negatively impact aquatic ecosystems by reducing light penetration, disrupting photosynthesis, and affecting the health of fish and other aquatic organisms (Bilotta and Brazier, 2008). Furthermore, turbid runoff can clog stormwater management systems, leading to reduced system efficiency and increased maintenance costs. Effective stormwater management strategies, such as sediment basins, filtration systems, and vegetative buffers, play a crucial role in mitigating turbidity and reducing the adverse effects of highway runoff on water quality and ecosystem health. There is a strong correlation between turbidity and total suspended solids (TSS) in runoff. Turbidity is a measure of the cloudiness or haziness of water caused by the presence of suspended particles, including solids (Wakida et al., 2013). These suspended solids can originate from various sources, such as soil erosion, sediment, debris, and pollutants washed off from road surfaces. As the concentration of suspended solids increases in runoff, the turbidity levels also rise, resulting in a murky or opaque appearance of the water (Wakida et al., 2013).

The relationship between turbidity and TSS is generally linear, meaning that as the concentration of suspended solids in runoff increases, turbidity levels will also increase proportionally. This correlation is particularly important because turbidity serves as a practical indicator for suspended solids but can sometimes vary according to the weather conditions and site specificities (Hannouche et al., 2011). Turbidity measurements are easier and quicker to obtain compared to quantifying the actual concentration of TSS, making turbidity a widely used parameter for assessing runoff water quality (Bash et al., 2001). Monitoring and managing turbidity in runoff are crucial as they help to identify the extent of sediment and particle load in stormwater and aids in evaluating the effectiveness of erosion control measures.

Highway runoff can contain various heavy metals that originate from multiple sources. The principal ones are road surfaces, vehicle emissions, and debris alongside the roadside infrastructure (Nixon and Saphores, 2007). The correlation between a high concentration in heavy metals and a high concentration of TSS and turbidity has been highlighted in various papers in the literature like in Nasrabadi et al. (2018), which focused on four different catchments (with varying characteristics. Another study, Nasrabadi et al. (2010) mentioned that thanks to this observation, it was then possible to use online turbidity devices to have an overview of the concentration in heavy metals contained in the runoff events. In that context, it is appropriate to look at metal concentration from data on TSS or turbidity but it can also still be important to look at specific heavy metals according to the objective of the research project. Therefore, we will now examine the most important and most studied heavy metals to understand some of their specificities.

A comprehensive table has been provided with the principal sources of each heavy metal mentioned (Table 1). The aim here is more to highlight the threats of these heavy metals and not to make an exhaustive list of all of them and their specific impact on the ecosystem.

Car tire particles are one element that cause a significant disturbance to the ecosystem, partly due to their concentration in some heavy metals. Car tire particles, also known as tire wear particles or tire debris, can have a significant impact on the toxicity of highway runoff and water pollution (Wik and Dave, 2009). The friction that occurs between the tires and the road generates tiny particles that are then released into the surrounding environment, including the runoff generated during rainfall events (Foscari et al., 2023).

Table 1: Principal heavy metals and their main sources

HEAVY METAL	SOURCES
Lead (Pb)	Gasoline, Tire Wear, Paint on vehicles, Road Infrastructure (Kayhanian, 2012)
Zinc (Zn)	Tire particles (Davis et al., 2001), Motor Oil (Chen et al. 1994), Break Pads, Asphalt (Davis et al., 2011)
Copper (Cu)	Electrical Wiring, break pads
Cadmium (Cd)	Tire Wear, Lubricants, Break Pads (Barber et al., 2006)
Nickel (Ni)	Gasoline, Asphalt, Lubricants, Brake Lining Wear (Barber et al., 2006)
Chromium (Cr)	Concrete Pavement (Kayhanian et al., 2009), Tire wear (Iqbal et al., 2022).

Car tire particles are typically composed of various rubber compounds, such as synthetic polymers, plasticizers, fillers, and other additives (Baensch-Baltruschat et al., 2020). Due to their small size and light weight, they can be easily transported by stormwater runoff and end up into rivers, ponds, streams, and other water bodies (Baensch-Baltruschat et al., 2020). They are a consequent source of concern for highway runoff. Firstly, these particles can contain many chemicals and additives, such as heavy metals, plasticizers, and antioxidants (Panko et al., 2012). Secondly, tire particles can act as carriers for other pollutants present on the road surface, such as heavy metals and fuel residues. As result, they contribute to further exacerbating water contamination and lead to disastrous consequences. To help tires resist degradation, an organic chemical called N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6PPD) is used in the manufacturing of car tires. Although it is particularly helpful to protect tire rubber from cracking, it has disastrous impact on the surrounding environment. Throughout its degradation process with air, 6PPD transforms into a metabolite called N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine-quinone (6PPDQ). It is then this element that is released into the surrounding water environment, thus exposing aquatic species and the ecosystem to its associated threats (Ji et al., 2022). Filters designed to target the reduction TSS will efficiently capture tire particles and any other particulate matter containing absorbed contaminants, including 6PPD-Q (Washington State Department of Ecology, 2022). As it has been highlighted in the paper published by Tian et al. in 2022, 6PPDQ has been found to be more toxic that it had been previously measured. For instance, they made the recommendation to categorise it as being “highly toxic” to showcase its high level of toxicity for the ecosystem (Tian et al., 2022). This element can be highly toxic for aquatic species, although it doesn’t affect each species in the same way (Chen et al., 2023). For instance, it has been found that the presence of 6PPDQ led to acute mortality of coho salmon when exposed to the toxicant (Tian et al., 2022).These results were obtained by exposing the fishes to values from commercial standards, and they found a 100% mortality rate for an exposition ranging from 0.8 to 4.0 µg/L. Tian et al. (2022) also emphasises the rapid intoxication (around 40 minutes) and fast deaths (less than two hours) when exposed to the 4.0 µg/L concentration. On the other hand, a test on Atlantic Salmon and Brown Trout did not find any behavioural change or increase in mortality among the fishes. They found these results by exposing the fishes for a 48-hour duration to various levels of 6PPDQ ranging from 0.095 to 12.16 µg/L (Foldvik et al., 2022). In that regard, it is still needed to have more research done on the potential synergy between 6PPDQ and other contaminants, to see whether its presence could have even more negative implications than is thought for now (Chen et al., 2023).

Tire wear contains lead (Pb) which is a toxic metal that is then found in the highway runoff (Kayhanian, 2012). Lead can also be derived from the paint on vehicles or the surrounding infrastructure. The presence of lead in water can negatively impact both human health and the environment (Kayhanian, 2012). For humans, exposure to lead-contaminated water can lead to severe health issues, including neurological and developmental impairments, especially in children (Levin et al., 2021). At the same time, the release of lead into the environment threatens ecosystems by disrupting aquatic life, destabilising the food chain and negatively impacting the ecological equilibrium (Levin et al., 2021). However, it is worth mentioning that lead levels have notably decreased in the past few decades, thanks to multiple bans of leaded gasoline in many parts of the world. For instance, the European Union completely prohibits the usage of leaded gasoline since 2000. In the United States, there was already a regulation that was published in 1973. While the lead concentration present in highway runoff in California was at around 945 µg/L in 1972, it decreased to 164 µg/L in 1987. This highlights the huge impact that the regulations around leaded gasoline had on the concentration of lead in the runoff (Kayhanian, 2012). A more recent highway runoff study further highlighted this trend in decreased lead concentration. As per the study conducted by Lau et al. (2009), the event means concentration (EMC) of lead averaged 33 µg/L. This was done over a period of three years and encompassed 47 storm events, thereby suggesting that the average concentrations of lead have decreased even more significantly in the 21st century.

Tire particles also contain zinc (Zn), which although having lower health implications for humans, is an important disturbance to the ecosystem if it accumulates in water bodies. This is especially the case as zinc is usually found in higher concentration in stormwater runoff compared to lead (Sakson et al., 2018). While lead upper limit in countries that have phased out leaded gasoline usually stands at around 200 µg/L, the concentration of zinc has been found to attain more than 5000 µg/L, with tire wear being a major source of zinc (Davis et al., 2001). Zinc can also be derived from motor oil, brake pads, and the asphalt of the road. For instance, Chen et al. (1994) found that the concentration of zinc was around the double for used oil compared to new oil. A particularity of zinc is that it is highly soluble, meaning that it will dissolve quickly in the water and can be a significant threat towards the aquatic environment (Zakharova et al., 2020).

Another heavy metal that is often found in a quite high concentration is cooper. It is present in vehicles components like brake pads and electrical wiring. As zinc, it poses a lower threat to humans that lead but is already quite toxic for the environment at relatively low concentrations. According to Davis et al. (2001), brake emissions was the largest contributor to the load of copper, according to their assumptions based on tire, engine oil, and brakes samples. Copper has notable impacts on fish behaviours and olfaction. For instance, it affects fishes' ability to smell which is an essential function for their navigation, food finding and mate recognition (DeForest et al., 2018).

Finally, among the most prominent heavy metals, we could also mention Cadmium. It's especially found in highway runoff because it is released by the combustion of fossil fuels, tire wear, and lubricants (Barber et al., 2006). Cadmium particles can settle onto the asphalt before being washed out during precipitation events, ultimately entering water bodies if no treatment is in place. The corrosion of the materials needed for the road infrastructure can also lead to leaching over time and therefore represents and additional source of pollution from Cadmium (Sakson et al., 2018). Human health can be threatened if Cadmium contaminated aquatic species are consumed but also if it has penetrated soils used for agricultural purposes (Rahimzadeh Rafati et al., 2017). Similarly, the threat can also come from the utilisation of irrigation water that has a high concentration of Cadmium. However, it is important to mention that the concentration of Cadmium has overall been found to be much lower than the one of lead, zinc, and copper. For instance, Davis et al. (2021) reported that across the papers it looked at, the concentration of Cadmium never went beyond 12 µg/L. This is way lower compared to the standard value measured for the three other heavy metals. Barret et al. (1998), further emphasized that Cadmium was even often not present above detection limits. As a result, Cadmium is an important element to analyse as part of a road runoff study but is not the main threatening heavy metal for water bodies and human lives.

While these environmental impacts are still being studied, they definitely have adverse effects on aquatic ecosystems and human health. Efforts are being made to mitigate the release and transport of car tire particles into highway runoff (Baensch-Baltruschat et al., 2020). This includes developing innovative tire technologies to reduce tire wear, implementing improved road surface materials, and employing effective stormwater management practices such as sedimentation basins and filtration systems to capture and treat runoff before it enters water bodies. Additionally, raising awareness about tire maintenance, proper inflation, and tire recycling can also help reduce the origination and then dispersal of tire particles into the environment (Baensch-Baltruschat et al., 2020). Effective stormwater management practices, such as sedimentation basins, filtration systems, and green infrastructure, are important for minimizing the transport of heavy metals and other pollutants from highway runoff into water bodies (Pereira et al., 2019). One of the ways to proceed is to implement a system from the source and to establish a purification system that can lead to an effluent that is as clean as possible. By monitoring the water quality in the effluent, it can give us an indication on whether it is safe to be released into the nearby water bodies. The next sub-sections will evaluate the effectiveness of sedimentation areas and filter beds as a mean to reduce pollution threats.

There are a wide range of methods and types of sedimentation processes that have been implemented with different aims according to each specific design situation. In our case, it has two main objectives. The first one is that it breaks the velocity of the incoming runoff, especially when intense rainfall events occur leading to large amount of water transported in a short amount of time (Li et al., 2008). It's also a useful storage facility when we observe recurrent rainfall events over a few days or on a weekly timeframe. The second utility of this sedimentation area is to help with the settling of the particles and sediments removal. According to Andersson et al. (2018), sedimentation basins are very effective in removing suspended solids (75%) but also zinc (65%) and copper (60%). However, the overall efficiency of sedimentation basins is hindered during the winter period, mainly due to the density differences caused by the number of de-icing salts entering the system (Rommel and Helmreich, 2018). They further emphasised the seasonal difference by highlighting that the reduction in temperature also affects the sedimentation removal by up to 8%. Furthermore, highway runoff contains some larger particles that are sometimes hard to deal with and when there is a filter bed after the sedimentation area, these larger particles could even clog the filter bed in some cases (Al-Nasra, 2013). For instance, bigger rubbishes, coarse sediments, or cigarettes can be contained within the sedimentation area. As a result, it serves the purpose of ensuring that the purification part will function well later on when the water reaches the filter bed. As it is hard to always predict what kind of material could end up in the system, it is critical to sustain a good maintenance of the sedimentation tank over the time. It is especially important when extreme rainfall events occur, and a high number of sediments and particles enter the system.

Although sedimentation areas are useful for sediments removal and is sometimes the only pollutant removal system in place, implementing a filter bed ensures that there are even more sediments that are removed from the runoff (Palermo et al., 2023). Indeed, while in the sedimentation tank, the particles are mainly settling at the bottom, the filter bed has this capacity of directly reducing the number of sediments and particles (Palermo et al., 2023). As a result, it relies less heavily on human maintenance compared to the sedimentation tank. It is critical to understand that each filter media has different hydraulic conductivity properties and purification capacities. For instance, coarse filter materials have proved to be very effective in dealing with high flow of water but are not as potent for fine particles removal. The contrary applies for fine filter materials which are good at removing the fine particles that go through it but cannot handle high flow effectively (Haile, 2018). It has also been found that using filter beds are particularly effective in enhancing the removal of highly soluble elements. For instance, zinc is present in a significant proportion within the dissolved phase (Huber et al., 2016), meaning that some of it can be captured by a sedimentation basin but the removal might not be sufficient to meet environmental standards (Hallberg et al., 2022). In their study using sand filter bed material, Hallberg et al. (2022) found that 93% of total zinc and 87% of dissolved zinc was removed as well as a large proportion of total suspended solids (TSS), suggesting a high removal capacity of the filter bed. The efficiency was also fairly good for total copper but not very effective for dissolved copper. A Swedish study on motorway runoff also found a higher percentage of removal for zinc compared to copper using polonite as a filter media (Rodríguez-Gómez et al., 2021). While both studies did not explicitly mention the potential reasons explaining these finding, it could be due to the higher affinity for adsorption that zinc has onto solid surface, therefore adhering more to the filter media and hence, making it easier for zinc particles to be removed as the water passes through the filter bed. However, other studies in the literature such as Cherono et al. (2021) and Banat et al. (2002) have indicated that many indicators could also affect the filtration capacity of different metals, pH variation being one of them.

Secondly, another important feature of filter beds is that they are also actively breaking the velocity of the water coming in, which provides an additional velocity slow down with the sedimentation tank area that is located before (Pereira et al., 2019). This is especially important when substantial storm events occur, meaning that there is an important quantity of water that reaches the system in a small amount of time. In this context, we should consider the impact on the purification process when the system is flooded with a vast quantity of runoff or an excessive sediment load. When pollutants have a distorted distribution at the start of the runoff event, we can refer to it as the first flush phenomenon.

What is commonly referred as being the “First Flush”, is the time at which the concentration of sedimentation in the discharge is extremely high. It can usually be observed at the initial stage of a runoff event (Gao et al., 2023). However, there is no clear consensus in the scientific literature on what can be ultimately considered to be the first flush phenomenon (Mamun et al., 2020). In fact, there are various definitions that differ according to the types of rainfall events, the size of the catchments but also other parameters such as the season in which it takes place. For instance, Stahre and Urbonas (1990) defined it as being 80% of the pollutant mass carried in 20 % of the volume. This is close to the ratio that was proposed by Bertrand-Krajesky et al. (1998) at 70% of the pollutant mass for 20% of the volume. On the other hand, Wanielista and Youssef (1993) mentioned a value of 50% of the pollutants mass in the first 25% of the volume, being therefore more conservative on the peak of concentration that occurs. However, we can highlight than in their paper, Bertrand-Krajesky et al. (1998) mentioned that an 80/30 first flush can be considered as a “significant first flush”, thereby emphasising that the ratio cannot be precisely set with fixed values and that it is also important to consider system and rainfall characteristics as well as if we are dealing with separated or combined sewer system. Nonetheless, the main common element is that the first flush corresponds to the part of the runoff that has a high concentration of pollutants (Maniquiz-Redillas et al., 2022). It is usually observed in the first 30 minutes to 1 hour of a storm event (Huber et al., 2016)

As we are now more familiar with what entails the first flush phenomenon, the objective is here to get a comprehensive overview of the phenomenon and to define it more precisely for our specific case study so we can use it appropriately later on for our analysis and discussion. Many studies have highlighted the presence of a higher concentration of pollutants in the runoff during the initial stage of a rainfall event. For instance, one paper looked at the highway runoff from a busy road in the UK, and especially focused on the pollution caused by heavy metals (Zakharova, et al., 2023). In their study, they looked at the proportion of heavy metals in the initial stage of the event to see whether they could observe the first flush phenomenon. Overall, they observed that every parameter was in a higher concentration at the initial stage of the rainfall event. On the other hand, the proportion varied considerably, and some metals were in a huge proportion whereas some others had lower concentration, although it was always a higher percentage that the percentage of the water volume (Zakharova et al., 2023). An additional interesting finding from this study is that they found out that the local conditions of the catchment can heavily influence the concentration of a particular pollutant or metal. Another study which also investigated road runoff, also found a pronounced first flush effect (He, 2019). Moreover, they also highlighted that the phenomenon varied according to each heavy metals, with a stronger first flush of copper and Cadmium compared to zinc and lead (He, 2019). This suggests that it is also essential to analyse how each individual pollutant is transported in the runoff, as they are not present in the same quantity at different stage of the runoff event. A factor that is regularly being discussed, is whether the antecedency of dry days before the collected runoff from a given rainfall event influences the concentration of pollutants that is measured. In the scientific literature, some papers argue that if there are many dry days occurring before a rainfall event, the concentration of pollutants might be higher than during a continuous wet period. For instance, a statistical analysis performed by Iqbal et al. (2022), concluded that there was an increase in the event mean concentration in lead when there was an accumulation of dry days between stormwater events. One of the drawbacks of this study is that the dry periods ranged from 10 to 31 days and did not cover short dry periods within one day or over a two-day period. On the other hand, a 28-month long study conducted in South Korea between 2006 and 2008 found that there was not positive correlation between the antecedency of dry days and the event loads (Maniquiz et al., 2010). This was also the case if compared to the event mean concentration. As such, they concluded that the rainfall duration, total rainfall, and average rainfall intensity were more important to predict event loads and the event mean concentration (Maniquiz et al., 2010).

In this master's thesis, the literature on first flush acts as an indicative role in order for us to better understand the phenomenon and its occurrence. On the other hand, it is not really possible to make direct comparison with other examples and situation that have been used to describe this phenomenon in other studies. Indeed, the hydrograph of each study area can be considered as unique due to multiple factors (Mamun et al., 2020). For instance, the diameter of the pipes, rainfall patterns, length of pipe connectivity to the system and the area covered are all factors that will considerably influence the hydrograph (Mamun et al., 2020). Moreover, specific traffic conditions or the requirements to wear special tyres for snow that vary according to the countries can also affect our ability to directly refer to other paper. Nevertheless, we have now obtained a comprehensive overview of how we can characterise the first flush, ultimately enabling us to draw appropriate results and discuss them later on in this paper.

The identification of pollutant concentration, load, and quantity is heavily reliant on the sampling methods used for the runoff (and first flush) analysis. Thus, comparing results from different studies may be challenging due to significant variations in these methods. It may also be difficult to compare findings from one paper to another. However, it is important to understand which approaches are commonly used and what are the benefits and drawbacks of them. An informative comparison has been carried out in a review paper published by Huber et al. in 2016. Based on the paper's study compilation, it can be noted that random sampling is rarely employed. The most often used sampling strategies were the first flush, the flow-proportional and the time-proportional strategies. The latter relies mainly on time but can also be adapted in order to capture the first flush if it is one of the research objectives. Thus, we talk about "first flush-enhanced sampling" because we sample more at the beginning of the event than at later stages. For instance, Han et al. (2016), conducted this type of sampling based on time by collecting 5 samples every 15 minutes for the first hour of a monitored rainfall event with a subsequent one sample for every hour until seven hours was reached. On the other hand, the interval of sample taking varies greatly in the literature and can sometimes exceed more than 60 minutes (Gäth et al., 1990).

If one delves into the complexities of first flush sampling, differences in its implementation by various researchers and within different contexts can be identified.. For instance, Huber et al. (2016), mention three different types of "triggering signals" that have been used in the review paper. These include time, volume, and rain depth. The volume approach can especially be good for smaller systems that receive a low amount of discharge. On the other hand, collecting water samples for the early stages of the rainfall event can provide us with more precise data, especially related to the changes in pollutants between each sample when we are able to have precise timestamps for each water sample that is taken. The main barrier to collecting an important amount of samples in a short amount of time can be related to technical and labour requirements as a lot of devices are quite constrained in the number of samples that they can take but also need to be collected by a worker (Maniquiz-Redillas et al., 2022). Moreover, the approach of sampling also differs purely based on the common practices of the country, the available funding or the specificities of each study site (Maniquiz-Redillas et al., 2022). A general overview of the various ways of sampling would be even more relevant if all the studies published were detailing how they sampled, which interval of sampling was used and all the other parameters that are essential to understand the whole context in which the research took place (Huber et al., 2016)

Furthermore, it’s also critical to have an understanding of what we consider as being a “rainfall event”. Indeed, while a one-hour long precipitation occurrence in one day can easily be characterised as being a distinct rainfall event, it’s more complicated to make the same assumptions when it rains with intermittence throughout a day or even multiple days. For instance, Barret et al. (1998) used a 10 hour dry period to separate two event, which is quite a long period of time. On the other hand, Molina-Sanchis et al. (2016) suggested a minimum inter-event time of one hour to distinguish two rainfall event, although there could be some variations between wet soil and dry soil. Finally, there are other elements that we need to bear in mind such as the holding time of samples after collection which should not exceed a certain number of hours. The preparation of the samples that occurs before carrying out the analysis also needs to be specific. However, as highlighted by Huber et al. (2016), not a lot of paper describes the processes for these two elements which makes the comparison harder between the studies.

Through an analysis of different research studies and methodologies, it has become evident that highway runoff is a significant environmental concern, with the contamination of heavy metals being particularly problematic. To lessen the detrimental effect of such pollutants on our water ecosystems, we have outlined different systems that can be adopted, including sedimentation basins and filter beds. However, our ability to design and ensure the efficiency of these systems depends on our understanding of the phenomenon behind the first flush effect and our ability to design effective sampling strategies accordingly.

4. Material and Methods

The methods that have been used in this master's thesis have been derived from both theoretical knowledge and field experience. A wide range of material has been used such as the technical report from the project, literature on the topic, lectures from professor at the University, and other miscellaneous sources.

A large number of samples from different rainfall events and sampling methods have been used for the analysis. Therefore, two comprehensive table (one for the automatic sampler and one for the total samplers have been created in order to enable every reader to decode the data.

The tables can be found in the Appendix section of the master's thesis (Appendix 1 and Appendix 2).

General overview of the system:

A good starting point was to identify the study site, looking at where it was located and the different roads that surrounded it. As we can see on Figure 1, the stormwater treatment plant is located near a highway, with also some secondary roads passing nearby. It is also in the vicinity of a commercial and industrial area. Figure 1: Overview of the sampling site

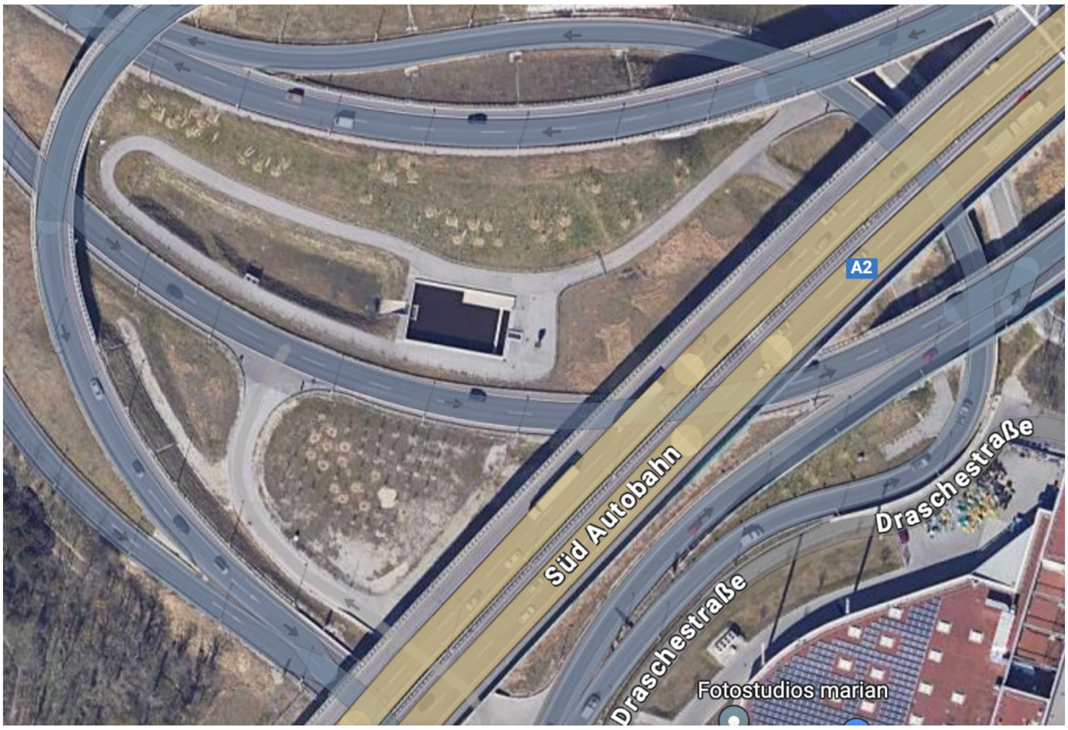

Figure 1: Overview of the sampling site

Our stormwater treatment plant is composed of two main different part: the sedimentation basin, and the filter bed. There are both essential components that aim to purify the runoff before it is released in the nearby river Liesing (functions have been highlighted in the previous section of the master's thesis). In this sub-section, the objective is to mention the system specificities, as well as highlighted intermediary parts of the whole system that are important to know for the calculations and analysis that will follow.

Firstly, multiple pipes from the surrounding areas are leading to the influent pipe which enters the sedimentation basin. To be more precise, the runoff first arrives in the shaft before going further. Measurements devices and water samplers have been placed in both the shaft and the influent pipe.

A long concrete structure has been built to start the slowing down of the velocity and to prevent water overflow in case of heavy precipitation events. Afterwards, we can say that runoff enters the main sedimentation basin (Figure 2).

Another prominent structure that has been built to break the velocity is a horizontal rock element that has been positioned just before the water goes into the filter bed (Figure 3). When this type of structure is used, it can prove to be quite effective to retard the water flow. It's especially a great addition to the system when sizeable storm events occur, leading to a great quantity of runoff coming into the system in a short period of time. By retarding the flow, it also allows suspended solids and other particles to start settling at the bottom of the sedimentation area. As a result, it further leads to a decrease in the total pollutant loads that the filter bed has to deal with. However these benefits can be hindered if the sedimentation tank is not well cleaned and maintained over time.

Figure 2: Overview of the sedimentation tank

Figure 3: Rectangular stone structure installed to break the velocity and trap bigger sediments

After the sedimentation process took place, the principal purification process of the water occurs in the filter bed area of the system. In this system, a nature-based solution has been chosen composed of a soil mixture (Figure 4). The soil filter layer has a thickness of around 40cm and is followed by a gravel layer. The area is in fact bigger than the one on the picture but most of the time, only this small part is mobilised.

Figure 4: Main area of the filter bed that is mobilised to filter the runoff

Underneath the filter bed area, there is a receiving pipe which further leads to the shaft of the effluent section. Similarly, to the influent, we have also installed measurements devices and water samplers in that part of the system. This has principally been implemented to assess whether the purification system was effective in removing pollutants from the initially contaminated runoff.

As this master's thesis focuses on the influent part of the system, the following parts of the methods section will only be related to what has been especially studied for this thesis. The previous information was a contextualisation to understand the general context in which samples have been taken and how the overall system functions.

Collection of Water Samples:

As we are now more familiar with the layout and purpose of this kind of system, we can now talk about the collection of the water samples. As part of the monitoring and analysis processes, multiple types of sampling are being carried out by workers from the University but also by partners from the project. It means that some of the devices in use have been designed or installed by our partner and others by the University. The collection of samples can only be done after the occurrence of a rainfall event, which can be detected thanks to an on-site weather station as well as the various on-site measurements tools.

We can distinguish two main locations at which we have chosen to install our sampling equipment: at the influent point and at the effluent point. This allows us to estimate the reduction in pollutants between the runoff that enters the system and after the purification process took place. There is a differentiation in the type of samples that are taken. Some devices collect a single and quite large quantity of water ("System Der Wasserwirt") while there are devices that collect single sample when triggered by the sensor ("Einzelprobe"). We can talk about total samples versus automatic samples.

While some of the parameters can be directly transmitted online, it is necessary for someone to go and collect the water samples before bringing it to the laboratory for further analysis. Data collection at the beginning of the system is essential as it allows us to capture the quantity of runoff that comes into the structure at a given time but also to collect data related to the water level or various parameters linked to the water quality. In the influent, data is collected in the pipe but also in the shaft depending on the device and the parameter that is being measured.

At the beginning of the system, there is a Nivus device to help us with the flow measurement and height of the water in the pipe (Figure 5). Nivus is a company that produce reliable and robust measurement systems. In this project the "NIVUS PCM Pro Device"has been used. The device is always on-site to track and record measurements and is just being taken out when the battery needs to be recharged. In the influent, there is also a single sample taker as well as another device that can take up to x measurements.

In the pipe, there is also a turbidity measurement device that can transmit real-time data. It is activated when submerged, which is at about 6 cm of water height within the pipe. Thus, it is not able to capture very small rainfall event or events which have a very small intensity even for a long time span.

The pipe is also the location where we have placed our automatic sampler. The samples are being taken directly in the pipe where the influent arrives. After carrying out tests in the shaft, we decided that it was more appropriate to place the automatic sampler in the pipe so the sediments in the shaft could not influence the value of the parameters measured. The device collecting the automatic samples is a WaterSam “WS Porti” device. The device can take up to 24 individual samples before collection. In an ideal scenario, it would have been even better to have multiple samplings occurring in various parts of the system so we can obtain data using different sources and compare it. However, system restrictions, equipment limitations and funding often limit the possibilities of establishing this kind of multi-source sampling. In the shaft, we have a device that measures the water level as well as the conductivity. This data is also transmitted to us online. In that part of the system, there is also a total sampler which gets filled once the water reaches a certain height. When the water enters the total sampler, we get a message that states the day and the time at which it started to fill. Then, we can use it for our analysis alongside the samples that have been collected automatically. There is no proper name available for the total sampler as it is a device still in its experimentation process. In Table 2, it is indicated where which sample was taken and with whick kind of devices.

Figure 5: Influent pipe where the automatic sampler takes water samples and where the nivus device takes measurements and shaft area where the total sampler is placed (attached to the orange rope)

Table 2: Overview of where the parameter where the parameters where taken and which which type of devices.

Name of the Parameter	Point of Sampling	Type of Measurement
Water Flow (l/s)	Pipe	Nivus Device – On Site
Height (m)	Pipe	Nivus Device – On Site
Turbidity (NTU)	Pipe	Device – On Site (Online)
Total Suspended Solids (TSS)	Pipe	Automatic Sampler / Laboratory
Conductivity (µS/cm)	Pipe	Automatic Sampler / On Site and Laboratory
pH	Pipe	Automatic Sampler / Laboratory
Conductivity (mS/cm)	Shaft	Device - On site and Total Sampler / Laboratory
Height (m)	Shaft	Device – On Site
Turbidity (NTU)	Shaft	Total Sampler / Laboratory

Preparation and Analysis of Water Samples:

Once the samples have been collected from the field, we need to carefully process and prepare them. Although some of the analysis is carried out directly by the person collecting the samples like the pH or the conductivity, the rest of the analysis is conducted by someone else from the laboratory. Thus, it is important to label every sample according to the day and date it has been sampled but also collected. In that way, we do not lose track of the date and location and when we delegate the analysis to other person in the laboratory, it ensures that we have reliable and tracked data to use. One of the things to bear in mind is that, sometimes the water sampler captures multiple event that occurred at different times during during a given day or even across multiple days. As a result, it is important to double check the information that has been recorded to not label different events as being from the same one.

It is also at that stage that we create Mixed Samples that can give us an overview of the overall rainfall event that occurred in terms of water quality and the pollutants. For instance, if we have 10 samples, we can take 100 mL for each of them into a container and in that way, we have the same percentage of each individual sample into the new mixed one. However, it occurs that the quantity of water collected is not sufficient to create a mixed sample. Indeed, the priority is given to the analysis, and we usually need a volume of at least 200 mL for the laboratory analysis. As a result, we use the mixed samples as an addition to our main analysis but the lack of them for some events is not a considerable prejudice.

Discharge calculation:

The first calculation aimed at finding the discharge that enters the system (the DN800 pipe as shown on Figure 5). The objective was to look at a design rainfall event that could occur in the surrounding of the stormwater collector system in order to calculate how much water would go into it. It was with the aim of compare our sampled events to this specific design event.

Moreover, finding the discharge for this given rainfall event will also enable us to carry out further calculations that need this variable as an input. We chose to look at the 1-year flood events as it was the most representative of what a strong rainfall event could look it. More specifically the 15-minute duration was the one that was the most central to our study. The discharge equation is the same as the one that was used in the technical document of the project. It has been decided to keep the same one to maintain some sort of consistency and to make it more comparable.

The equation that has been used to find the discharge is the following:

$$Q = rt,n * A * \psi$$

Where:

Q: Discharge (l/s)

rt,n: Rainfall Intensity

A: Area (ha)

Ψ: Flow coefficient

The area is composed by the surrounding of the storm collector system, in the proximity of the highway. All the pipes located in this area which eventually leads to the entrance of the system has been accounted for. The area had a value of 6.5 hectares.

The flow coefficient has been decided based upon the literature search and recommendation from various professors. The value of 0.9 was the most suitable due to the fact that we could assume the overall homogeneity of the type of soil.

The rainfall intensity had to be calculated using another equation that had been found in the literature. The equation is the following:

$$rt,n = (H(r,t) * F) / D$$

Where:

rt,n: Rainfall intensity (l/s.ha)

H(r,t): Height of precipitation (mm)

F: Conversion Factor

D: Duration of the rainfall event (seconds)

The duration of the rainfall event was just the one that we decided for our design rainfall event of 15 minutes, one year event. In the calculation, the duration was expressed in seconds, so it was just needed to do the conversion

To find the height of precipitation, we looked at the average height of precipitation for this specific rainfall event. The data was obtained using the EHYD database which is a national database regarding hydrological data in Austria. On the website, we could select the suitable location and get this information. While EHYD has been used to find this specific event, it was needed to look at another database for smaller rainfall events. Indeed, EHYD could provide data for 1-year events at the minimum whereas we also wanted to look at rainfall events that occur more frequently. To do so, the meteorological data for smaller rainfall occurrences has been found on the ZAMG database.

All the parameters of these equations have been inputted into an Excel file, with one sheet for each equation. The objective was to facilitate the calculation and diminish potential errors. Moreover, it also allowed for a rapid analysis when we looked at different rainfall events later on.

Finding the height of the water (at partial filling) for our design event:

After obtaining the discharge, we decided to find the height that is reached by the water level in the pipe during our chosen design rainfall event. The aim was to have an understanding of the height at which we should place the sensor to sample this event.

Indeed, the height is a fundamental element of the analysis because it ensures that the sampling is done accurately and according to the experimental design. If the sensor is placed at a height that is too high, we will end up not having any sample taken by the machine when we go to collect after a rainfall event. On the other hand, by placing it too low, we could have a situation where small rainfall instances trigger the collection of samples for an event that was not correct according to the design. Thus, an accurate sensor position makes it more reliable to have the number of samples we want according to the chosen rainfall event.

To do the calculation, it was needed to look at appropriate calculation methods related to pipe partial filling in a circular tube. The calculation has been carried out according to German and

Austrian standards (Binder et al., 2023). Based on the information provided by the technical document, some of the variables were known, which enabled us to further calculate to find the height for any given rainfall event. The book of Lautrich (1976) has been used to make the assumptions of the calculations as well as internal lectures notes from the university (Binder et al., 2023). Moreover, the help of Ass.Prof. Dipl.-Ing. Dr.nat.techn. Gerhard Kammerer was also very precious in the process.

The given variables were the following:

Q_p: Discharge at partial filling

K_o: Operational roughness of the pipe material

d: inner diameter of the pipe

s: slope

The objective is to find h_p which is the height of the water in the pipe for the discharge Q_p.

In order to calculate h_p, we first need to find the discharge when the pipe is full, which is Q_f.

The discharge at partial filling is the one that has been calculated using the first equation mentioned in the Method section. As aforementioned, the weather data to proceed with the calculation has been obtained on the EHYD database.

The operational roughness of the pipe material has been directly obtained from the technical document corresponding to the project. It has a value of 1.0 mm. The value for the inner diameter of the pipe has also been found on the same technical document and has a value of 800 mm. On the same technical report, the slope has been obtained. It has a value of 0.3%.

a) Discharge when running full

The classical formula for the calculation of the friction slope for turbulent flow is the equation of Darcy and Weisbach, which constitutes a quadratical relationship between the velocity head and the friction slope:

$$I_f := \frac{\lambda}{d} \cdot \frac{v^2}{2\,g}$$

Where:

I_f: Friction slope

λ: Friction factor

v: mass conserving average velocity

v2/(2g) is an average velocity head (although not energy conserving). The mass conserving average velocity is the ratio of the discharge *Q* and the cross-sectional area *A* (at full filling), which can be calculated for a circular tube on the basis of the only-one geometry parameter *d*:

$$A(d) \coloneqq \frac{d^2\pi}{4}$$

$$\mathrm{v} \coloneqq \frac{Q}{A}$$

When supposing uniform and steady-state flow in the pipe, the friction slope or the slope of the energy line must be equal to the slope of the water table (for partially filling) and also equal to the bottom slope of the pipe. Therefore we can simply write *I* instead of I_f.

For a very small flow velocity of water the flow condition can be laminar, whereas in almost all practical cases it is turbulent. The criterion whether the flow in the pipe is laminar or turbulent is the comparison of the Reynolds number Re with a threshold value for pipe hydraulics, which is 2320 in the Austrian and German norms. *Re* is a "dimensionless" (to be more precise, its dimension is 1) model parameter which represents the ratio of inertia forces and the viscous friction forces in the pipe:

$$Re \coloneqq \frac{\mathrm{v} \cdot d}{v}$$

v – the symbol in the numerator – is again the average (mass conserving) velocity in the pipe, *d* the inner diameter and *v* – the greek symbol in the denominator – the kinematic viscosity of the fluid depending on the temperature.

For laminar flow the friction slope is strongly proportional to the velocity head. For turbulent flow it is proportional to the squared velocity head and the friction factor *λ*, and the flow behavior is either smooth, transitional or rough. For smooth flow the inner friction dominates, and *λ* depends on the viscosity of the fluid. For rough flow the outer friction dominates and *λ* depends on the relative roughness of the pipe $\varepsilon = k_O/d$. For transitional behavior *λ* depends on both, and it is calculated with the formula of Prandtl and Colebrook:

$$\frac{1}{\sqrt{\lambda_{tr}}} = 2 \cdot \log\left(\frac{2.51}{Re \cdot \sqrt{\lambda_{tr}}} + \frac{\varepsilon}{3.71}\right)$$

There are a lot of other forms of this equation used. The upper version is the predominant one in Germany and Austria. When neglecting the term with ε, the equation goes over in that for smooth flow, whereas for rough flow, the first term in the argument for the logarithm function becomes negligible.
The formula of Prandtl and Colebrook cannot be solved explicitly for λ (whereas its adaptation for smooth or rough flow could), its evaluation requires a numerical procedure.

The basic cases of circular pipe dimensioning comprise the 4 quantities *d*, *v*, *Q* and *I*, and 2 out of the 4 and also the fluid property *v* and the material property and k_O must be given.

Whereas those out of the 6 cases in total can be calculated straightforward, when *I* is asked, there is an iterative solution required when *I* is given.
Our case with given *d* and *I* is the case number 4. Fortunately, when assuming turbulent flow in the transition zone, there is an explicit formula available, combining the formulae of Darcy and Weisbach and Prandtl and Colebrook (obtained from internal lectures note from the university by Binder et al. (2023):

$$v_{fCi} := \left(-2 \cdot \log \left(\frac{2.51\nu}{d \cdot \sqrt{2g \cdot I \cdot d}} + \frac{k_o}{3.71d} \right) \right) \cdot \sqrt{2g \cdot I \cdot d}$$

Because $Q = v \cdot A$, this formula can be easily reformulated to give the discharge:

$$Q_{fCi} := \left(-2 \cdot \log \left(\frac{2.51\nu}{d \cdot \sqrt{2g \cdot I \cdot d}} + \frac{k_o}{3.71d} \right) \right) \cdot \sqrt{2g \cdot I \cdot d} \cdot \frac{d^2 \cdot \pi}{4}$$

The inner diameter of the pipe is d := 800mm

The Kinematic viscosity of water at 10°C is $\nu := 1.31 \times 10^{-6}\ \mathrm{m}^2 \cdot ^{-1}$

The operational surface roughness of a concrete tube for wastewater transport is k0 := 1mm

The slope is I := 3%

$$Q_f := \left(-2 \cdot \log\left(\frac{2.51\nu}{d \cdot \sqrt{2g \cdot I \cdot d}} + \frac{k_o}{3.71d}\right)\right) \cdot \sqrt{2g \cdot I \cdot d} \cdot \frac{d^2 \cdot \pi}{4}$$

In order to check the compliance of the prerequisites, we need to calculate.

$$v_f = (-2 \cdot \log\left(\frac{2.51\nu}{d \cdot \sqrt{2\,g \cdot I \cdot d}} + \frac{k_0}{3.71\,d}\right)) \cdot \sqrt{2\,g \cdot I \cdot d}$$

$$Re := \frac{\mathrm{v_f} \cdot \mathrm{d}}{\nu}$$

The relative roughness ε is the ratio of the absolute roughness and the pipe diameter d:

$$\varepsilon := \frac{k_0}{d}$$

The friction factor can be numerically calculated with a simple recursive iteration:

$$\lambda_{tr}(\lambda_o, Re) := \left| \begin{array}{l} \lambda_n \leftarrow \dfrac{1}{4 \cdot \log\left(\dfrac{2.51}{Re \cdot \sqrt{\lambda_o}} + \dfrac{\varepsilon}{3.71}\right)^2} \\ \textit{while} \ \left|\lambda_n - \lambda_o\right| > 10^{-7} \\ \quad \left| \begin{array}{l} \lambda_o \leftarrow \lambda_n \\ \lambda_n \leftarrow \dfrac{1}{4 \cdot \log\left(\dfrac{2.51}{Re \cdot \sqrt{\lambda_o}} + \dfrac{\varepsilon}{3.71}\right)^2} \end{array} \right. \\ \lambda_n \end{array} \right.$$

b) Filling head for the discharge at partial filling

Hydraulic quantities when the pipe does not run full are calculated in Germany and in Austria based on the assumption of Franke and Schmidt relating the friction factors for partial filling and for running full to the ration of the hydraulic radius R_f and R_p:

$$\sqrt{\frac{\lambda_f}{\lambda_p}} = \left(\frac{R_p}{R_f}\right)^{\frac{1}{8}}$$

The hydraulic radius R is the ratio of the flow area A to the wetted perimeter U.

$$\mathrm{R} := \frac{A}{U}$$

This gives for a circular pipe fully filled:

$$R_{fCi} = \frac{\frac{d^2 \cdot \pi}{4}}{d \cdot \pi} = \frac{d}{4}$$

For partial filling of a circular tube R_P is given by an explicit function depending on the filling head. When defining dimensionless quantities discharge ratio $P_Q = Q_p / Q_f$ and filling degree $p_h = h_p/d$, the assumption of Franke and Schmidt leads to a unique relationship between both:

$$p_Q(p_h) := \frac{\left(2 \cdot \operatorname{acos}(1 - 2p_h) - \sin\left(2 \cdot \operatorname{acos}(1 - 2p_h)\right)\right)^{\frac{13}{8}}}{2 \cdot \pi\left(2 \cdot \operatorname{acos}(1 - 2p_h)\right)^{\frac{5}{8}}}$$

Similarly for $p_v = \frac{v_p}{v_f}$

$$p_v(p_h) := \left[1 - \frac{\sin\left(2 \cdot \operatorname{acos}(1 - 2p_h)\right)}{\left(2 \cdot \operatorname{acos}(1 - 2p_h)\right)}\right]^{\frac{5}{8}}$$

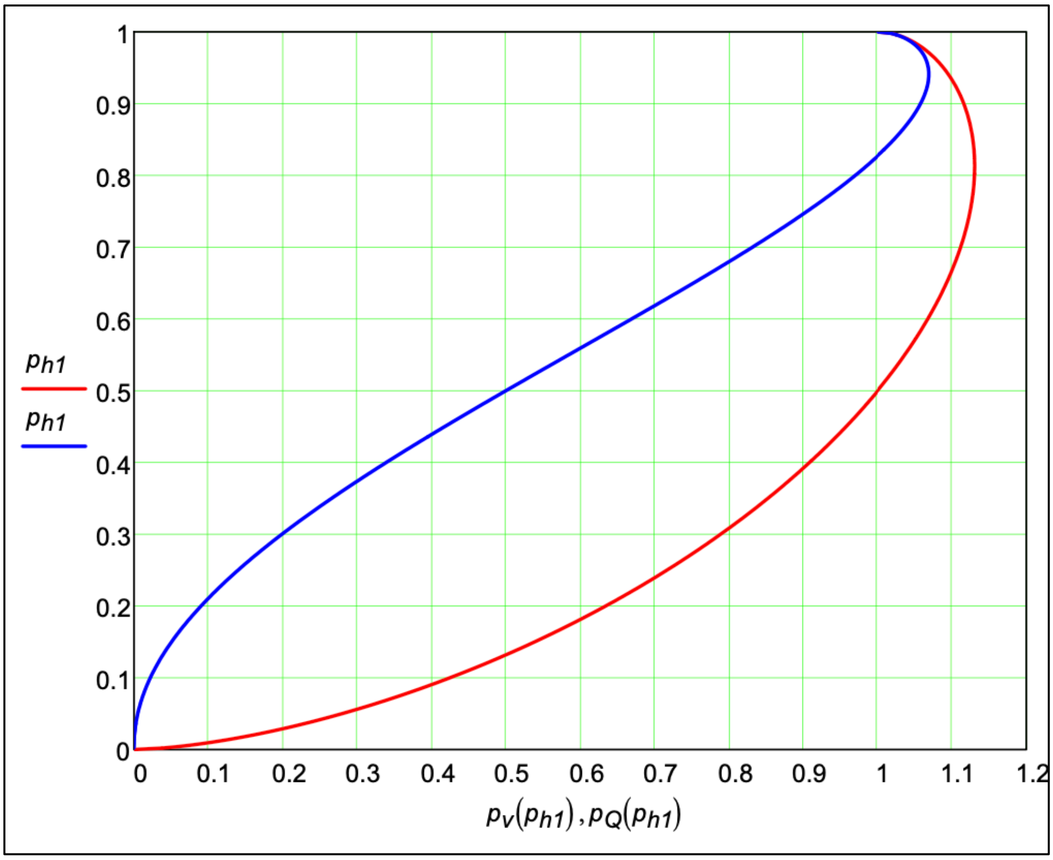

Figure 6: Partial filling diagram curve

Unfortunately, in our case, we must solve the inverse problem p_h (p_Q), but the functions above cannot be inverted analytically. Therefore, it needs either a graphical solution with the help of the diagram above or a numerical solution (Figure 6).

We can see from the curve that for values p_v >= 1 or p_Q >= 1, there are 2 solutions for p_h, the smaller one given by the function p_h respectively $p_{Q\,v}$ and a larger one for $p_{h\,v1}$ respectively $p_{h\,Q1}$:

$$p_{h\,v}(p_{v0}) := \left| \begin{array}{l} p_{h\,vmax} \leftarrow 0.812803127 \\ p_{h\,u} \leftarrow 0 \\ p_{h\,o} \leftarrow p_{h\,vmax} \\ \text{while } \left|p_{h\,o} - p_{h\,u}\right| > 10^{-7} \\ \quad \left| \begin{array}{l} p_{h\,new} \leftarrow \dfrac{p_{h\,u} + p_{h\,o}}{2} \\ p_{v\,new} \leftarrow p_v(p_{h\,new}) \\ p_{h\,u} \leftarrow p_{h\,new} \quad \text{if } \; p_{v\,new} \le p_{v0} \\ p_{h\,o} \leftarrow p_{h\,new} \quad \text{otherwise} \end{array} \right. \\ p_{h\,new} \end{array} \right.$$

$$p_{h\,v1}(p_{v0}) := \left| \begin{array}{l} p_{h\,vmax} \leftarrow 0.812803127 \\ p_{h\,u} \leftarrow p_{h\,vmax} \\ p_{h\,o} \leftarrow 1 \\ \text{while } \left|p_{h\,o} - p_{h\,u}\right| > 10^{-7} \\ \quad \left| \begin{array}{l} p_{h\,new} \leftarrow \dfrac{p_{h\,u} + p_{h\,o}}{2} \\ p_{v\,new} \leftarrow p_v(p_{h\,new}) \\ p_{h\,u} \leftarrow p_{h\,new} \quad \text{if } \; p_{v\,new} \ge p_{v0} \\ p_{h\,o} \leftarrow p_{h\,new} \quad \text{otherwise} \end{array} \right. \\ p_{h\,new} \end{array} \right.$$

$$p_{h\,v}(1.112) = 0.700$$

$$p_{h\,v1}(1.112) = 0.910$$

$$
p_{h\,Q}(p_{Q0}) := \left|
\begin{array}{l}
p_{h\,Qmax} \leftarrow 0.940883830 \\
p_{h\,u} \leftarrow 0 \\
p_{h\,o} \leftarrow p_{h\,Qmax} \\
\textit{while} \ \left|p_{h\,o} - p_{h\,u}\right| > 10^{-7} \\
\quad \left|
\begin{array}{l}
p_{h\,new} \leftarrow \dfrac{p_{h\,u} + p_{h\,o}}{2} \\
p_{Q\,new} \leftarrow p_Q(p_{h\,new}) \\
p_{h\,u} \leftarrow p_{h\,new} \quad \textit{if} \ \ p_{Q\,new} \le p_{Q0} \\
p_{h\,o} \leftarrow p_{h\,new} \quad \textit{otherwise}
\end{array}
\right. \\
p_{h\,new}
\end{array}
\right.
$$

$$
p_{h\,Q1}(p_{Q0}) := \left|
\begin{array}{l}
p_{h\,Qmax} \leftarrow 0.940883830 \\
p_{h\,u} \leftarrow p_{h\,Qmax} \\
p_{h\,o} \leftarrow 1 \\
\textit{while} \ \left|p_{h\,o} - p_{h\,u}\right| > 10^{-7} \\
\quad \left|
\begin{array}{l}
p_{h\,new} \leftarrow \dfrac{p_{h\,u} + p_{h\,o}}{2} \\
p_{Q\,new} \leftarrow p_Q(p_{h\,new}) \\
p_{h\,u} \leftarrow p_{h\,new} \quad \textit{if} \ \ p_{Q\,new} \ge p_{Q0} \\
p_{h\,o} \leftarrow p_{h\,new} \quad \textit{otherwise}
\end{array}
\right. \\
p_{h\,new}
\end{array}
\right.
$$

$$p_{h\,Q}(0.831) = 0.700$$

Now, we would like to know the filling degree for a discharge at partial filling.

$Q_p := 0.389\ m^3.\ s^{-1}$

Then the discharge ratio is $p_{Q0} := \frac{Q_p}{Q_f}$

The filling head $h_p :=\ p_{h\,Q}(p_{Q0}) \cdot d$

The filling head corresponds to the height in the pipe of the design event of 1 year – 15 minutes

Identifying the rainfall events:

To start with the data analysis, it was essential to do a characterisation of the rainfall events that occurred during the sampling period we were looking at. Moreover, it was also better to have a yearly overview to identify potential seasonality in rainfall occurrence and intensity. In that context, we chose to look at the rainfall data from the 30th June 2022 to the 1st July 2023.

The rainfall data has been collected by the Austrian Ministry of Geology, Geophysics, Climatology and Meteorology. It has been published on the geosphere.at website and it is available for anyone to download. As such, there is no restriction on who can access the data that I had access to.

Rainfall precipitation data can be displayed on various scales. I have chosen to look at daily, hourly and 10-minute rainfall data. As aforementioned, the daily data is important to get an overview of the rainfall events over the year, while the hourly data has been used to look at the development of rain throughout a one or two-day period. On the other hand, the 10-minute data is the lowest interval that was possible to obtain. It was especially useful to look at it with the data coming from the individual water samples as they were often collected over a short time span.

General process of the analysis:

Considering the data that we obtained from the water samples and on-site measurements, we were subsequently able to investigate and analyse this data to find correlations and make appropriate conclusions. For some of the parameters, it was very straightforward to identify and therefore, easier to extrapolate whereas we have also noticed more subtle correlations for others.

Microsoft Excel (Version 16.76) has been used extensively to first sort out the data. Owing to its functions, we were able to clean up the data for any anomalies or inaccuracies. The most important functions than have been used are the following (without any specific order): AVERAGE, SUM, TIME, DATE, and OFFSET.

Afterwards, we could create graphs on different scales and for various rainfall events. Indeed, the procedure and the timespan we were looking at varied according to the parameter and for the specific element that we were pointing at. Two graph types have been used: XY Scatter Graphs and Line Graphs. The following sub-sections

Overview of the sampled events:

After getting the overview about the rainfall events throughout the year, and carrying out the calculations that has been mentioned previously, we wanted to get an overview of the event we sampled. To do so we created one line graph with the rainfall event over the 3 days preceeding and the 2 days following the recorded runoff event. On this graph, we also indicated the time at which the automatic sampler started sampling. To supplement this graph, another one has been created that portrays an overview of the Water Flow (l/s), TSS, and Turbidity measured in real time in the pipe (NTU). For the 02/02, no turbidity measurements were available so this parameter was not included on the graphics for this date. This overview related more to the automatic sampler as there were more sample taken and as it would not have been as relevant to also do this overview for the total samplers. However, a closer look will be taken to the total sampler in the analysis of our sampling taking strategy.

We obtained reliable data for the 02/02/2023, 12/05/2023, and 05/06/2023, which are the three events that have been selected for the analysis. The details related to these events have been displayed in Table 3 (automatic sampling) and Table 4 (total sampling).

Table 3: Overview of Automatic Sampling

DATE	02-Feb	12-May	05-Jun
TIMEPERIOD	00:50 to 01:05	08:25 to 09:34	17:22 to 18:31
INTERVAL	3 minutes	3 minutes	3 minutes
NUMBER OF SAMPLE TAKEN	6	24	24

Table 4: Overview of Total Sampling

DATE	02-Feb	12-May	05-Jun
TIME	00:54	11:14	18:34
NUMBER OF SAMPLE TAKEN	1	1	1

<u>Sample taking evaluation:</u>

This analysis focuses especially on looking at whether we manage to sample at the right time. This element was also essential to our objective to measure the first flush. For this evaluation, data on the Water Flow (l/s), precipitation (mm), height in the pipe (m), and height in the shaft(m) were particularily important.

Looking at how the water level changes based on the rainfall precipitation is an important element to understand the dynamic that takes place once the runoff reaches the system. Indeed, we could have many different scenarios that could happen. For instance, we could have a shaft that reacts very rapidly to any input that comes into the system, like when a small rainfall occurs. On the other hand, we could also observe a case where it takes quite a lot of rain to impact the water level or a sustained rainfall period over multiple minutes or even hour to see a change. To do so, we used the 10-min rainfall data that has been previously introduced in this section.

With the objective to have a comprehension overview of the conditions in which the samples were taken, we also decided to combine the data between the water level in the pipe with the water flow and the water level in the shaft with the flow. On these graphics, we also indicated the interval of sample taking for the automatic samplers (green line) and the time at which the total sampler was filled (purple line). These elements can provide us with more details to see how the water level reacts to an increase in flow and to understand at which point the samples were taken. By using this data with the precipitation data, we were able to draw observations that were then used in the interpretation part.

Comparison of the pollutant parameters:

In the literature, it has been previously highlighted that there was a strong correlation between the Turbidity and the TSS. In other words, there are slightly different measurements to explain a similar and showcase a similar matter.

As we measured both parameters in the water samples, we decided to make some comparison to see whether the curves would be as similar as it had been observed in other studies or if we could notice major differences. As the On-Site Online Turbidity Measurements were only available from the 12th May, the comparison has only been made for the 12/05 and the 05/06 (excluding the 02/02). For the automatic sampelrs, we created graphics where we used the timeline provided by the automatic sampler and just added the Turbidity (NTU) from the pipe device on one axis, and the TSS derived from the water samples on another axis.

The approach that we took for the total samplers was not the same due to the diverging way it had been sampled. Firstly, we compared the Online Turbidity from the Pipe with the Turbidity measured in the total sampler (value obtained in the laboratory). It is displayed in a way that shows the online turbidity values at a 1 – minute interval for the whole recorded runoff (duration that includes the start of sampling until the last sample is taken), alongside the Water Flow (l/s), and the single value of the Turbidity (NTU) of the total sampler. In that way we could investigate whether the value obtained in the total sampler was reprensentative of the turbidity as measured by the online turbidity device.

The exact same process has been done subsequently but for TSS. This time we used the value of TSS from the water samples taken by the automatic sampler alongside the TSS value measured in the total sampler.

Determining the first flush:

Once we had done the in-depth analysis of the general rainfall context, how we sampled, and how the different parameters interact with each other, we were able to carry out our analysis of the first flush phenomenon.

Being able to define the first flush event with more accuracy has been an important objective of this master’s thesis. The approach that has been used draws upon the findings that have been found in the scientific literature before having been applied to the data obtained. The literature is very important to understand how our events compare to what other researchers have found but it also critical to remember that individual environmental and sampling conditions need to be accounted for.

The most sensible way to have a comprehensive understanding about our first flush events was to plot a graph using the data on TSS and on the water volume (Liter). The data for the suspended solids was obtained from the laboratory analysis of the samples and the water volume was derived from the Water Flow (l/s) from the NIVUS device. It was plotted against a scale from 0% to 100% where each 10% increments represented 10% of the total volumetric flow and 10% of the volume of suspended solids.

To do so, we used the data collected from the WaterSam device, so we can have a precise times stamp for each unit of water sample that has been collected. It also enables us to see the evolution in volumetric flow and total suspended solids between each interval (taken within 3 minutes of each other).

Once we have the data, we summed it up for the given parameter and the targeted runoff event. We then obtained a value that we could use to express the individual samples in terms of percentage of the total summed value (whether for the volume or the total suspended solids). Then, we just have to addition the percentage of the previous sample to the next one so we can see the amount in % that has gone through the system over time.

Finally, we transformed the numerical data into graphics in order to have a better visualisation of it and to make it easier to identify the first flush. If we want to know precisely how much of the total suspended suspended solids have been flushed away for a given amount of the water volume, we could just draw a line to find it.

5. Results and Discussion

The results section aims to present the results of the investigation that has been done throughout this master's thesis. Thus, it will cover all of the aspects that have been displayed in the Methods section with the objective to answer the research questions and to fulfil the objectives that have been introduced at the beginning of the thesis.

Having this in mind, this section will encompass a wide array of matters, ranging from a general overview of the rainfall patterns throughout the year, an analysis of the sampling strategies, a comparison between the different parameters measured to assess the concentration in pollutants, and finally the analysis of the first flush phenomenon. While this section has been purposedly written in a descriptive way, these results will be interpreted in the following section, and the limitations outlined.

After having collected the data from the GeoSphere Austria database, the following graphs have been made to showcase the general rainfall context that has influenced the results that will be presented in the section. These include an overview of the overall daily precipitation that occurred (Figure 7), and the days where more than 10mm of precipitation were recorded (Figure 8).

5.1 Overview of the Rainfall

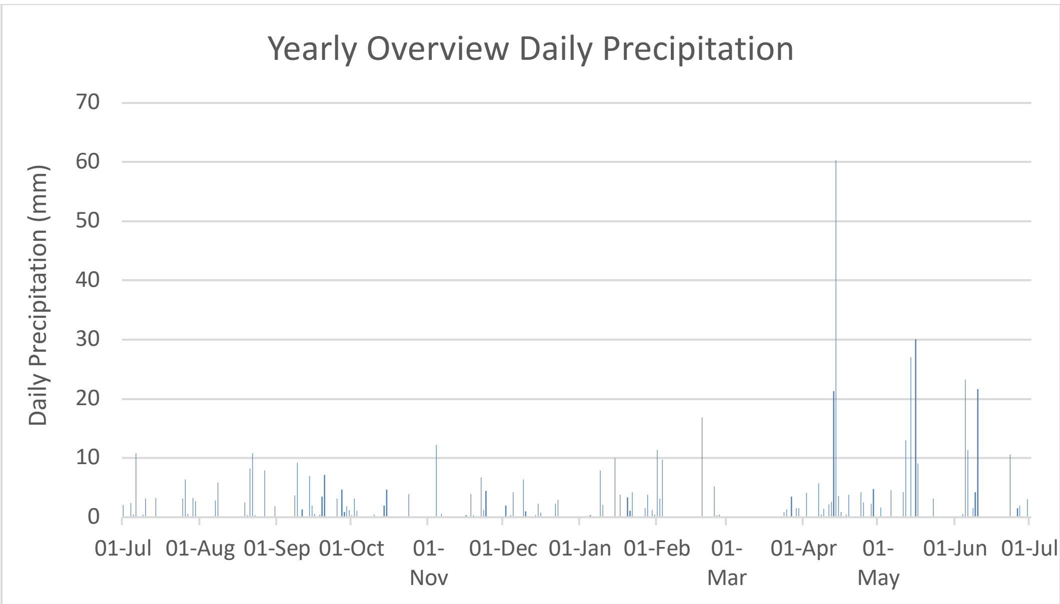

Figure 7: Overview of the Daily Precipitation from 01/07/2022 to 31/06/2023 (ZAMG)

The area surrounding our stormwater collecter systems received rainfall throughout the year, meaning that we can expect activity and an inflow of runoff on a year-round basis (Figure 7). Most of the recorded daily rainfall does not exceed 10mm of rain depth, while we can notice a distinguishable number of days where the 5mm threshold is passed. Furthermore, there are only a handful number of days that received more than 20mm of rain.

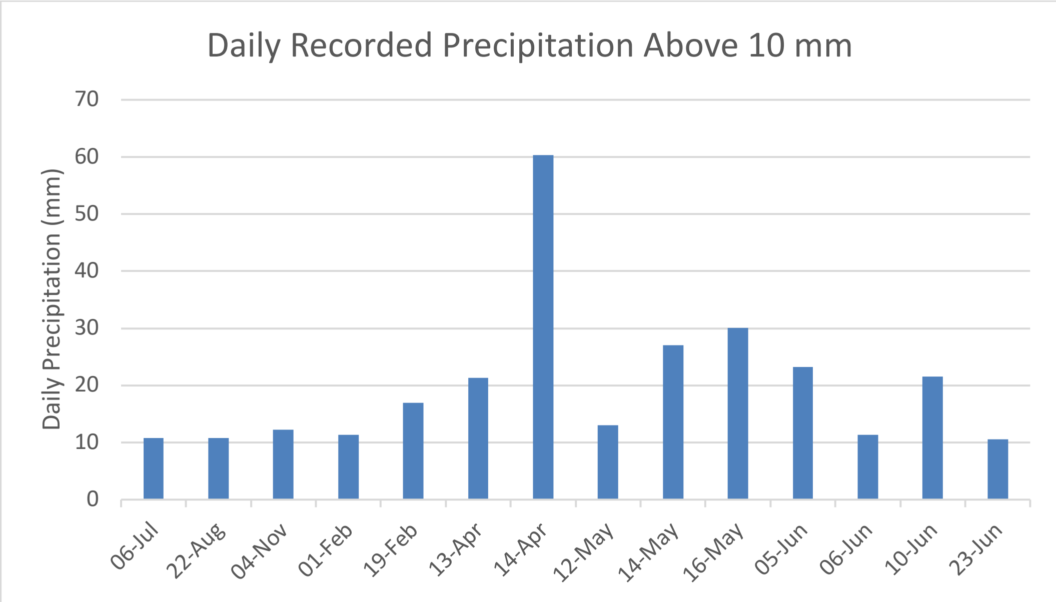

Figure 8: Overview of the days where the precipitation recorded was over 10 milimeters (ZAMG)

Over the course of one year, there have been only 14 instances where the daily recorded precipitation equalled or exceeded 10 millimeters of rain depth. If we look at Figure 8 in more detail, we can even observe that sometimes the rainfall is high over a two day period. This is the case with the 13/04-14/04 and the 05/06-06/06. Moreover, we can see that only one day (14/04) recorded an extremely high amount of precipitation with over 60mm recorded. However, it's important to mention it does not necessarily reflect the amount of inflow as it was an event that stretched for a long period of time. Moreover, this is the data used from Brunn am Gebirge, which is the weather station that was the nearest to our stormwater collection system. Overall, we did not record way more than 20mm on most days, with only a few days where it has gone beyond this threshold.

The general overview of the rainfall conditions surrounding our system is important to outline the overall environmental conditions that will influence our system and the way we sample. Overall, we can observe that it has rained throughout the year and there were no long periods of time without rain. On the other hand, extreme precipitation occurrence has been especially noticed between April and June. In that context, we sampled rainfall events that occurred on the 02/02, 12/05, and 05/06. These three events will be investigated in detail after the results of the calculations.

5.2 Results Calculation

Assessing the design event:

By diving into the meteorological data, we have been able to see whether the design rainfall event of 1-year 15 minutes event had been reached or not. According to the precipitation data ranging from 01/07/2022 to 31/06/2023, we never observed such an event. Indeed, according to EHYD Data, this 1-year 15 minutes event corresponds to around 10.6mm of rain over this duration for this area (and over 15 minutes). Now, according to the 10-min precipitation data from ZAMG Geosphere Data, the maximum rain over a 10-minute period was 6.4mm. This was between 13:30 and 13:40 on the 10^{th} of June 2023. If we add half of the rain of the 13:40-13:50 timeframe (corresponding to an approximation of 5 minutes), we obtained a total of 7.35mm for the 15 minutes event.

As a result, the maximum value for a rainfall event that has been observed over the last year is considerably lower than the amount for the 1-year 15 minutes event. This also means that the maximum observed is far lower from the 5-year 15 minutes event upon which the system had been built on back in 2012.

Nevertheless, it's still relevant to look at the results of the calculation related to the discharge of this 1-year 15 minutes event and how it affects the height in the pipe. Indeed, although this event has not been recorded in the previous year, it could happen in the years to come. Therefore, having an appraisal of it now can help us to make appropriate changes in the future.

Results of the discharge and height in the pipe calculations:

At present, we will look at the results of the calculation for the discharge of the 1-year (15 minutes) event and how it translates to the height in the pipe. These were detailed in the method section.

Firstly, we found that the maximum discharge Q_f that could come for the pipe was 752 liters per second. As a result, we dived into the Nivus data to see whether this limit had been reached or not. As far as we can see from the available data that we had at the time of writing this paper, the maximum discharge that has been measured in the pipe was 660.5 liters per second. This corresponds to around 87.8% of the maximum discharge when the pipe is running full.

However, it happened only once more that the pipe reached a significant percentage of this maximum value, at around 74.6%. In most cases, the discharge measured for sizeable rainfall event was below 200 liters per second.

For the height in the pipe reached during the design event, we found hp= 40.8cm. This gives us an indication of the magnitude of height that can be reached with a strong rainfall event over a short time period. The height found will be relevant when we will observe stronger event in the future and we can also keep it in mind to compare with other events that have a similar magnitude.

5.3 Overview of the sampled events

The aim of this sub-section is to portray and characterise the rainfall event and the associated runoff that have been sampled in the influent part of the system. To do so, three graphics have been selected for each date. The first one is an overview of the rainfall conditions three days before and two days after the recorded rainfall event with the green cross indicating the time at which we started sampling (which was always the automatic sampler first). The second one gives an indication of the flow conditions, the online turbidity measurements (from the device in the pipe) and the laboratory measured suspended solids. The interval of sampling from WaterSam has been used for these figures.

The combination of these two graphics will give us some general data that will be important for the following sub-sections investigating the sampling and the first flush effect.

<u>02/02/2023:</u>

The days preceding the 02/02 were not dry as it rained on multiple occasions. Overall, the hourly rain did not exceed 1mm during the previous days (Figure 9). A relatively small rainfall event was recorded in the hour the automatic sampler was triggered. It started sampling at 00:50 and while there was an hourly recorded rain of 0.4 mm between 00:00 and 01:00, the rain became very intense in the following hour (7mm).

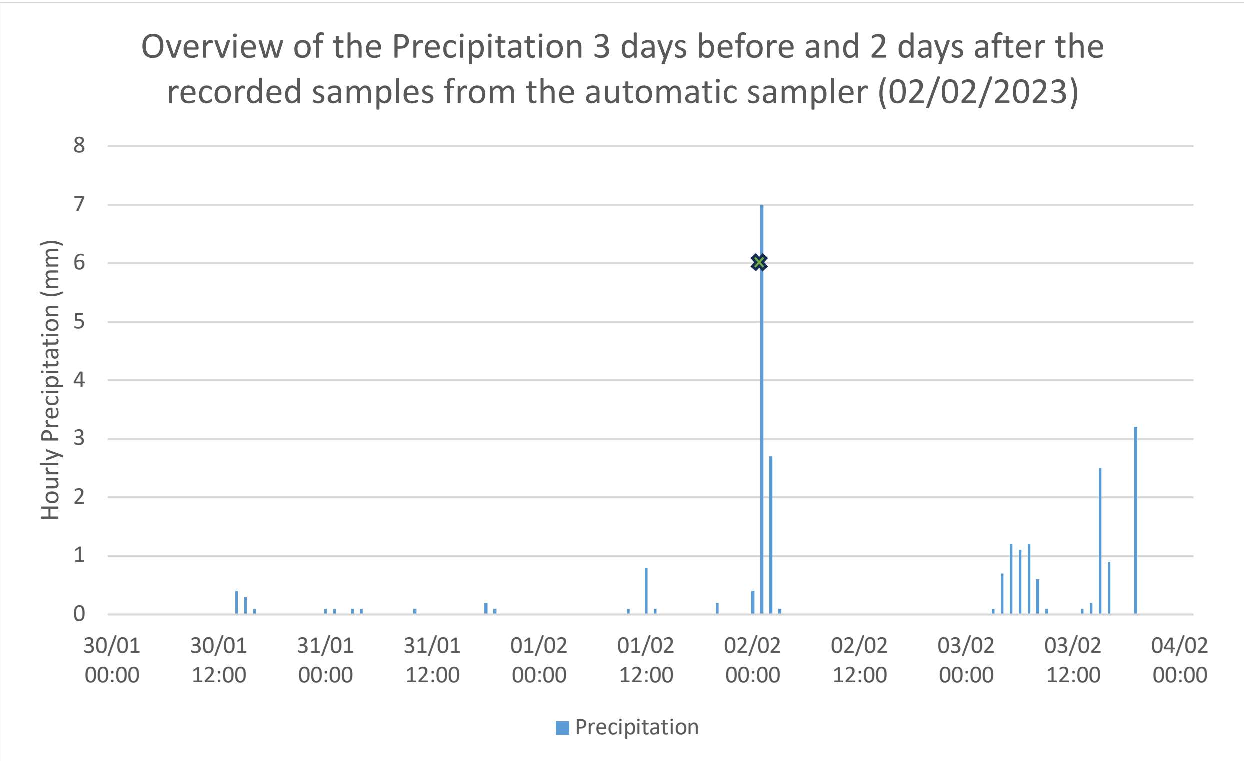

Figure 9: Precipitation occurrence three days prior and two days after the recorded event of the 02/02/2023

Regarding the automatic sampler, we can observe that only 6 samples were taken by the water sampler for this event. The water flow starts at a very low level, then it increases at a rapid pace before reaching its peak after 9 minutes. We can also see that there is still a relatively high water flow for the last sample taken, suggesting that the runoff event was not finished (Figure 10). The TSS curve did not follow a linear evolution. Indeed, the first sample recorded the highest concentration of total suspended solids, and while it decreased quite considerably until the third sample, it went back up at a value close to the peak before ending up at around half of the highest value observed.

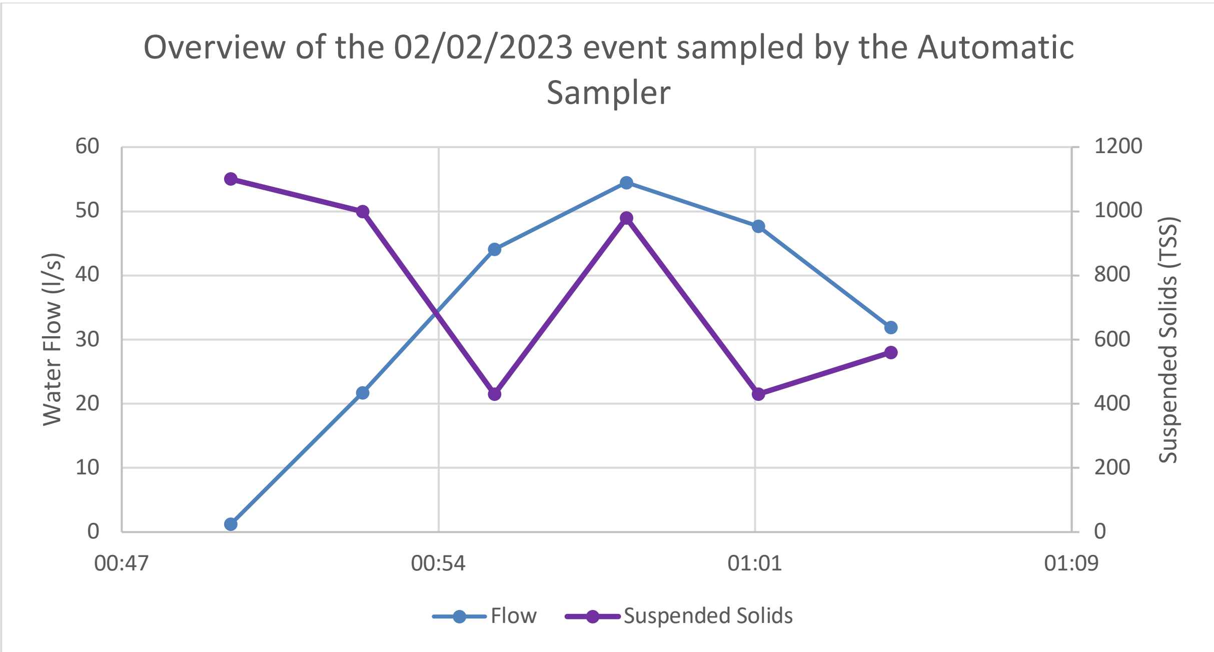

Figure 10: Overview of the water flow (l/s) and the suspend solids (TSS) for the samples taken (02/02/2023)

12/05/2023:

For the 12/05, we can see that the rainfall context was quite different (Figure 11). The previous days were entirely dry as the precipitation started on the 11/05 during the evening. It rained during the seven previous hours preceding the start of the automatic sampler (which occurred at 08:25). Moreover, it rained for most of the 12/05 although the hourly rainfall precipitation did not reach any value close to the 7mm value that had been recorded for one hour during the 02/02.

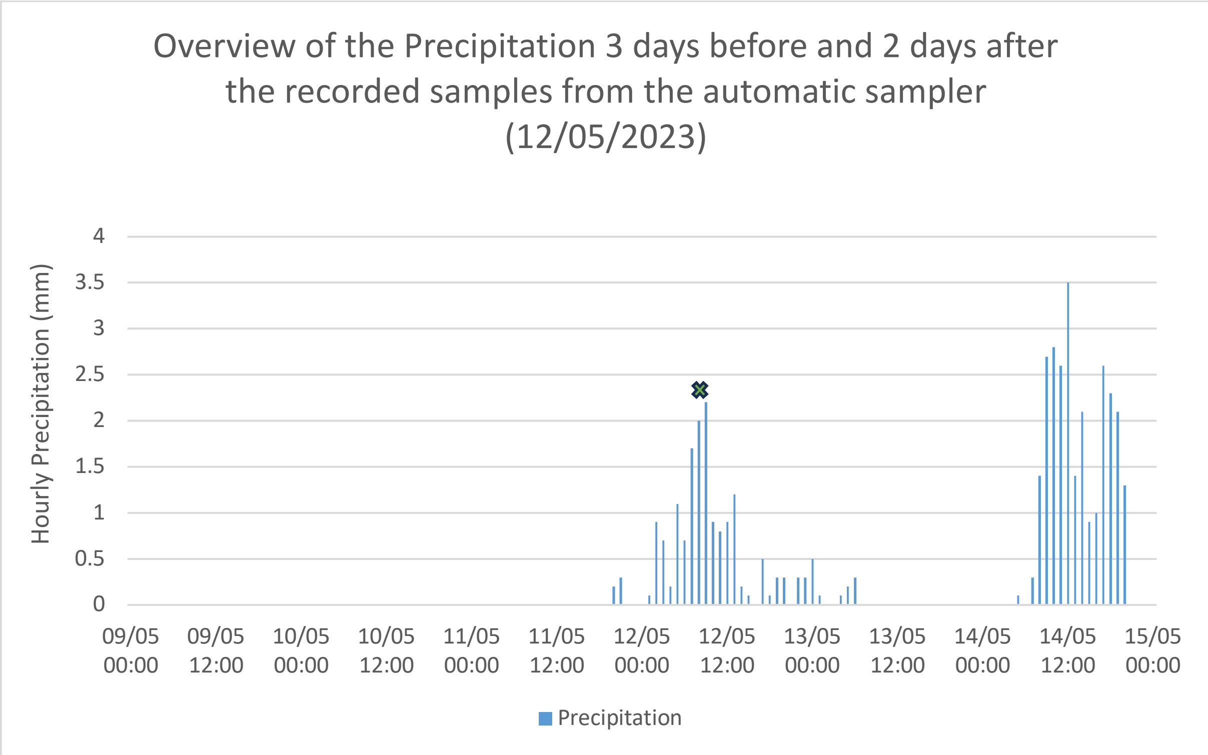

Figure 11: Precipitation occurrence three days prior and two days after the recorded event of the 12/05/2023

For the 12/05, we have recorded a larger amount of samples compared to the 02/02 (Figure 12) By having 24 individual water samples instead of 6, it also enables us to cover a longer time period and therefore, potentially observe elements that we would not have been able to otherwise. Every parameter dipslay a downward linear line, while we can see two increases in water flow during a few samples before decreasing again. Generally, the turbidity and TSS curves kept going down throughout the recorded event without a very noticeable increase. The water flow is also significantly lower throughout the event than for the 02/02. The pollutants were also in a lower concentration compared to the first event.

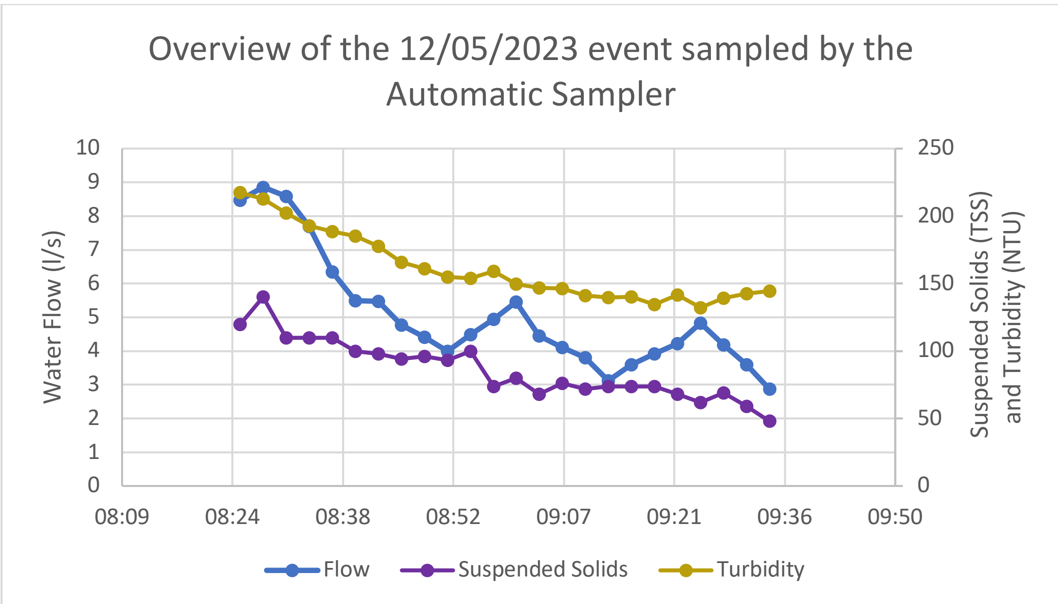

Figure 12: Overview of the water flow (l/s) and the suspend solids (TSS) for the samples taken (12/05/2023)

05/06/2023:

As we can see in Figure 13, the days before the sampling were also dry, as only two hours were recorded in the 04/06 evening. However, what is important to consider is that there was a strong rainfall event of 5.2mm between 15:00 and 16:00 which was not a long time before the start of the automatic sampling which started at 17:22. On the other hand, only 0.1mm of rainfall was recorded between 16:00 and 17:00, meaning that the intense rainfall event did not continue up to the sampling started.

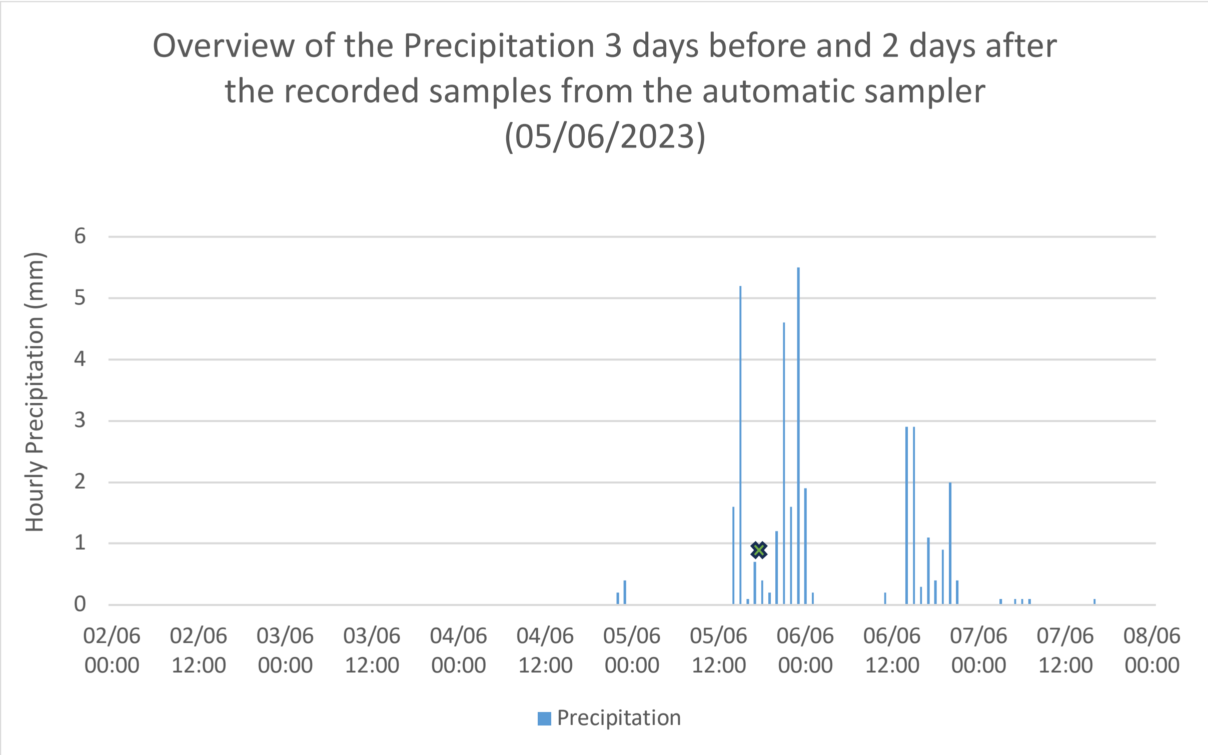

Figure 13: Precipitation occurrence three days prior and two days after the recorded event of the 05/06/2023

In Figure 14, we can observe that the water flow follows a different trajectory compared to the 02/02 and 12/05 , meaning that for every recorded rainfall event, we have been able to observe a different direction.This time, the water flow was at its lowest at the beginning, like we saw for the 02/02. However, it did not follow a downward direction throughout the whole sampling. Indeed, the peak is attained after 24 minutes before going down considerably and slightly increasing again. On the other hand, the flow but also the two other parameters end up being very low at the end of the sampled event. For the 05th June, the water flow was higher compared to the one observed on the 02nd February and even higher in contrast to the very low flow that was sampled on the 12th May. It’s also on the 05/06 that the highest value of suspended solids has been reached.

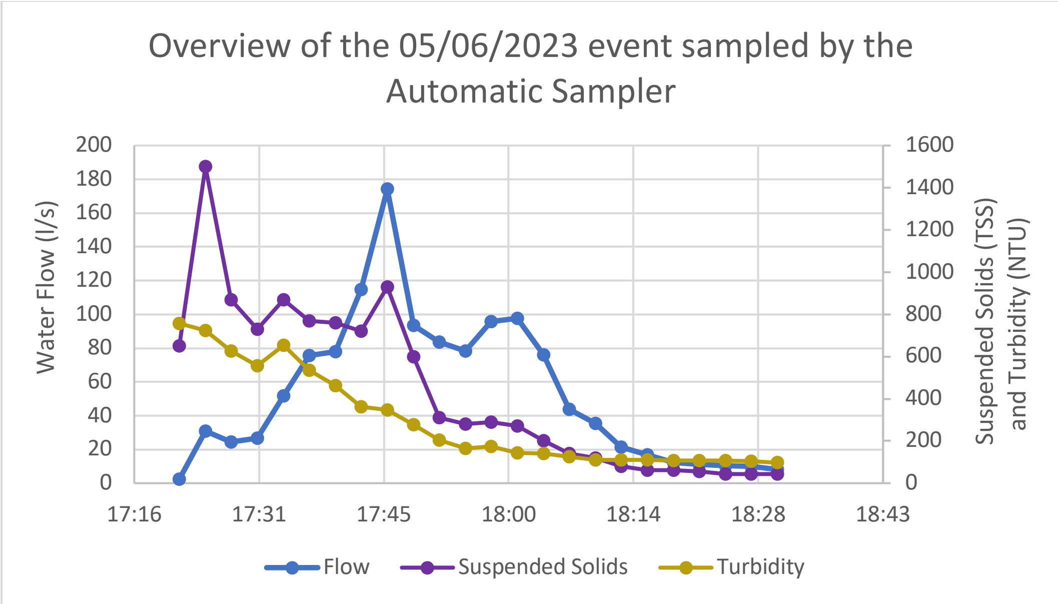

Figure 14: Overview of the water flow (l/s), the suspend solids (TSS), and the turbidity (NTU) for the samples taken 05/06/2023).

5.4 Sample taking results

As we now had an overview of the rainfall context and of the parameters, we can now look more in depth at how we sampled. To do so, we have added the height of the pipe (for the automatic sampler), and the height of the shaft (for the total sampler) to the water flow and the precipitation (10 minutes interval).

As mentioned in the methods, two green lines have been displayed to showcase the start and the end of the water sampling for the automatic sampler while for the graphics looking at the total samplers, it is the purple line that indicates the time at which the total sampler started to get filled.

<u>02/02/2023:</u>

For the recorded event of the 2nd February, we can notice a concordance between the start of the elevation of the water level in the pipe and the start of the automatic sampler. It is also at that same time that flow starts increasing. Thus, we can observe that the height in the pipe follows the increase in flow coming from the incoming runoff. As we can see in Figure 15 and similarly to what has been observed in Figure 10, we did not manage to sample all of the event. Indeed, the flow takes around 20 more minutes to go back to the initial level.

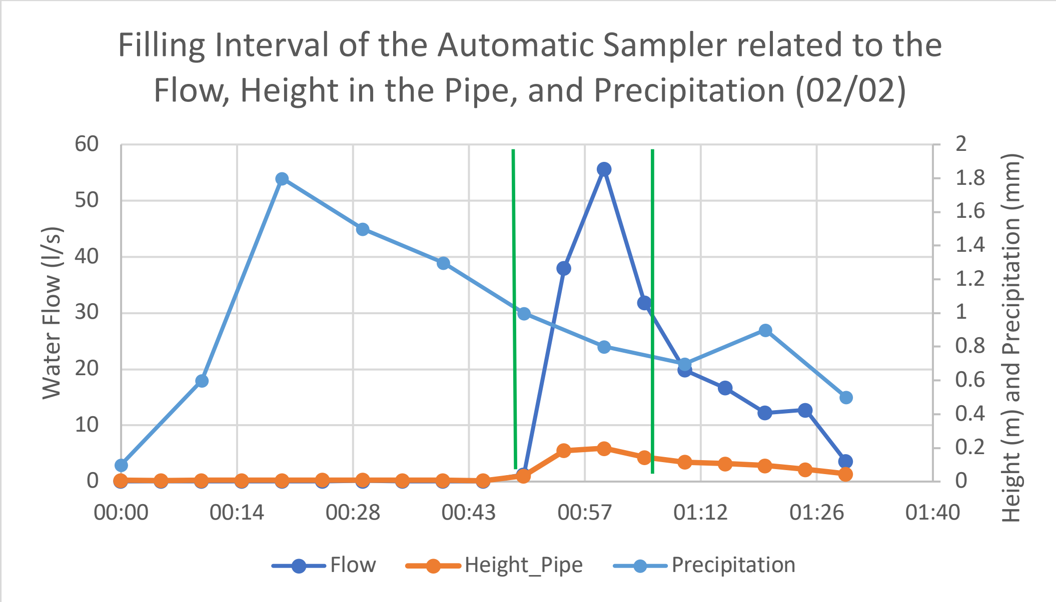

Figure 15: Overview of the Automatic Sampling process (02/02/2023)

The start of filling of the total sampler also corresponded well to the recorded increase of the height in the shaft (Figure 16). Likewise, it is also the time at which the flow started to increase. Therefore, if we only consider how we sampled from a hydraulic point of view, it seems that we have been able to start the sampling at the right time. For the 02/02, we could only point out that the main issue was the low amount of automatic samples that was taken, which did not cover all of the runoff event.

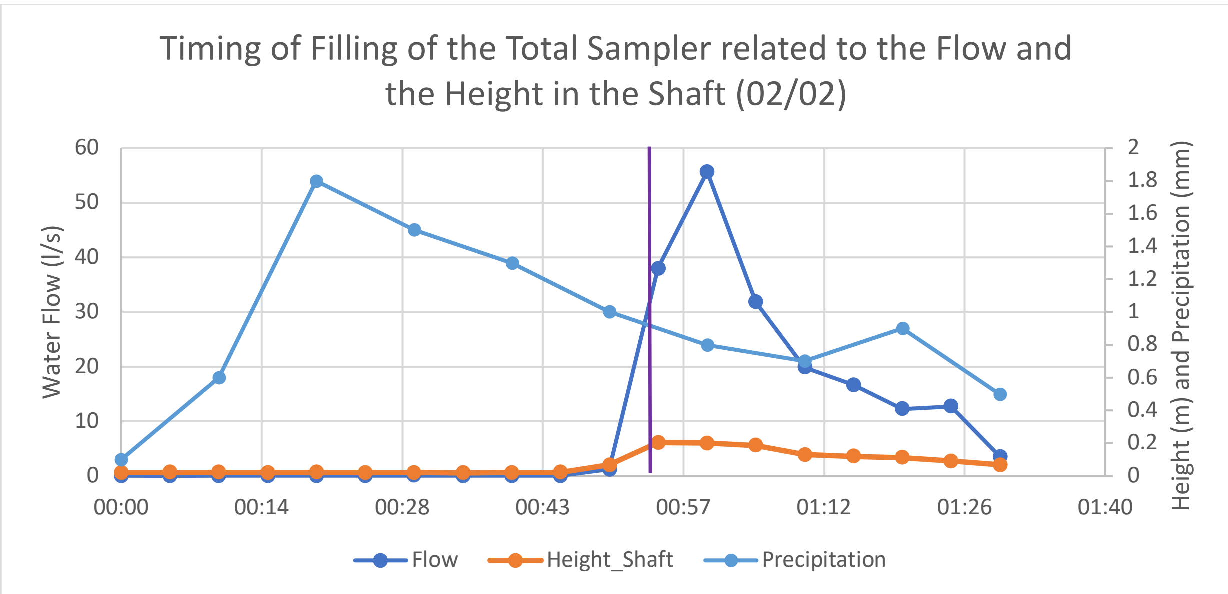

Figure 16: Overview of the Total Sampler filling process (02/02/2023)

12/05/2023:

As far as it is indicated by Figure 17, it seems that we sampled quite a bit of time after the increase of the water flow, and a few minutes after the height in the pipe started to elevate (the visualisation of the height in the pipe is hindered by the relatively high value of precipitation on the same axis).

While for the 02/02 (Figure 15), the flow curve was not varying prior to the sampling event, we can see that the water flow decreased before increasing again before the automatic sampler started to be activated. As a result, looking only one hour prior to the start of the sampling might not be enough, as there might have been another rainfall event before that. This will be looked at more closely in the first flush part of the results section.

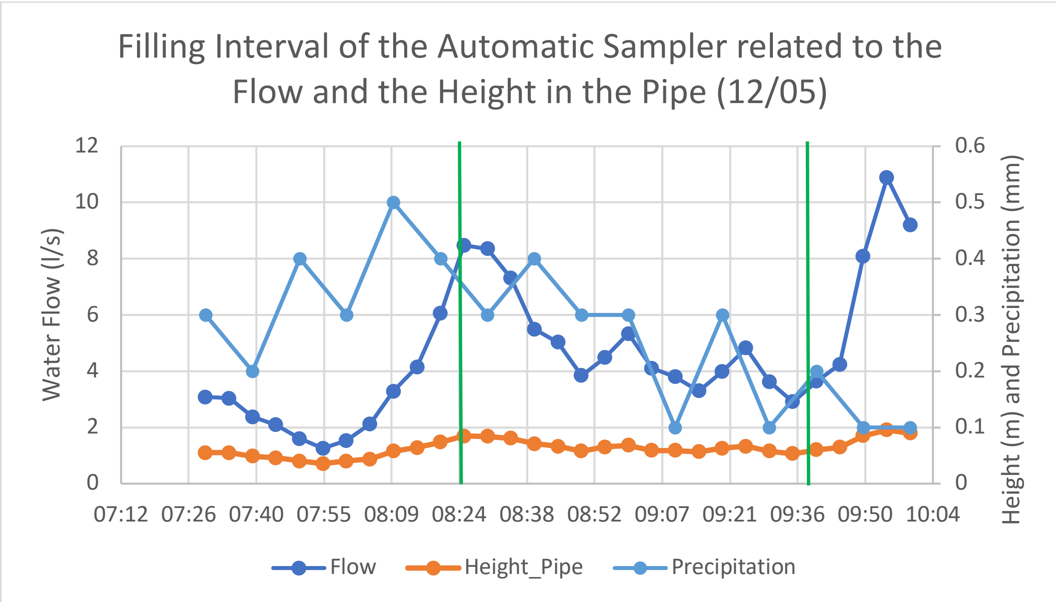

Figure 17: Overview of the Automatic Sampling process (12/05/2023)

The first noticeable element that we can see in Figure 18, it is the time at which the total sampler has been filled. Indeed while the automatic sampler finished sampling its 24th and last sample at 09:35, the total sampler was filled at 11:14. On the other hand, we can see that the height in the shaft increases as there is more flow coming from the influent, thereby reinforcing that there is a relationship between the flow and the change of height in the shaft. Furthermore, it does not seem that the height of filling was very appropriate as it has been filled when the height was going down. This can suggest either an error related to the time information that we got or also coming from the water level data. It could also be the case that there was an equipment failure. However, it is not possible to have a definite answer of why it has been sampled at that point in time.

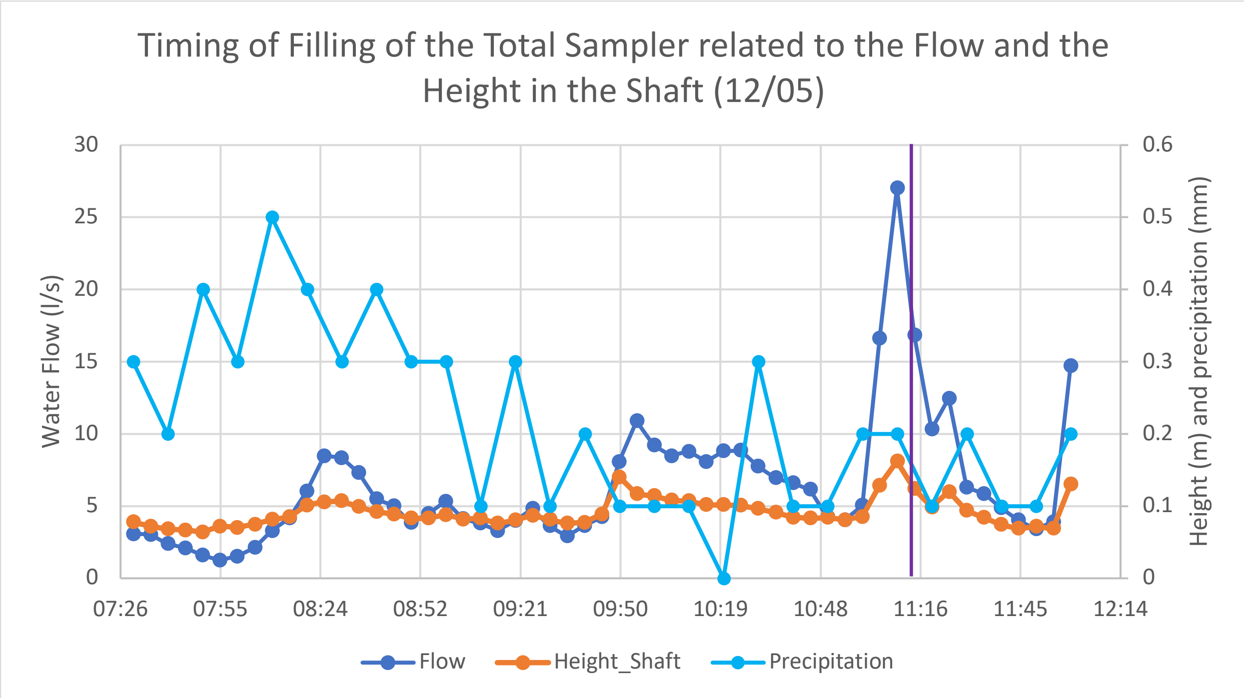

Figure 18: Overview of the Total Sampler filling process (12/05/2023)

<u>05/06/2023</u>

For the 5th June, the situation is similar to the first recorded event. Indeed, prior to the sampling, the flow and the height in the pipe were at very low level, with variations that are almost not perceivable (Figure 19). From the moment the height in pipe started rising, it triggered very quickly the automatic sampler which is what was meant to happen according to the set up. Overall, we managed to capture the beginning of the runoff coming into the system while we almost covered the entire flow increase. The water flow and the height in the pipe were close to their initial level for the last sample we took. We can also observe that although the precipitation almost reached 1mm over a 10-minute period around the middle of the sampled events, it did not seem to have a considerable impact on the amount of flow and on the height in the pipe. At around 18:00 we can see that there was a slight increase in water flow for only one sample and the same can be seen for the height in the pipe. However, both curves continued their downward trajectory after this small increase.

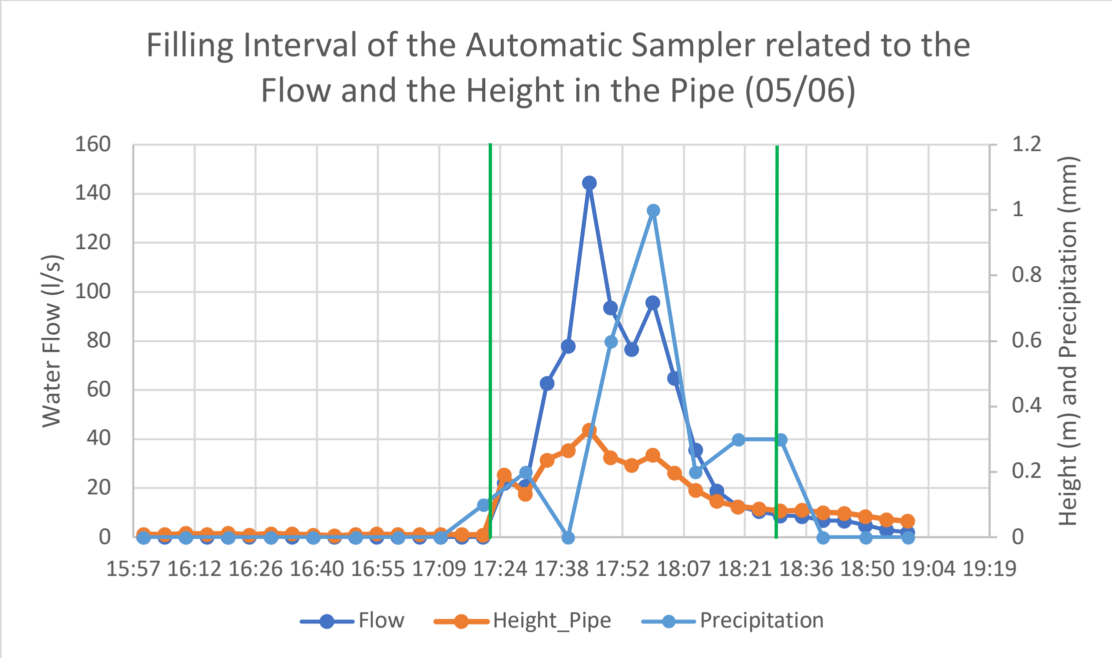

Figure 19: Overview of the Automatic Sampling process (05/06/2023)

As it is shown in Figure 20, there is again an issue with the filling of the total sampler. This is still an issue even though the time of filling is very close to the end of sampling of the total sampler (unlike what we saw for the 12/05). Although the height of sampling is higher than the one observed before the runoff started coming into the system, it is still at a point where the height is decreasing. Indeed, we were aiming to sample at a higher height that would be more reprensentative of the flow coming into the system in order to capture the concentration of pollutants of the rainfall event (and compare it with the data from the automatic samplers). Thanks to the data on turbidity and suspended solids, we will be able to identify a bit more what could be the cause of these inaccuracies from the total samplers. We will look at this in the following sub-section.

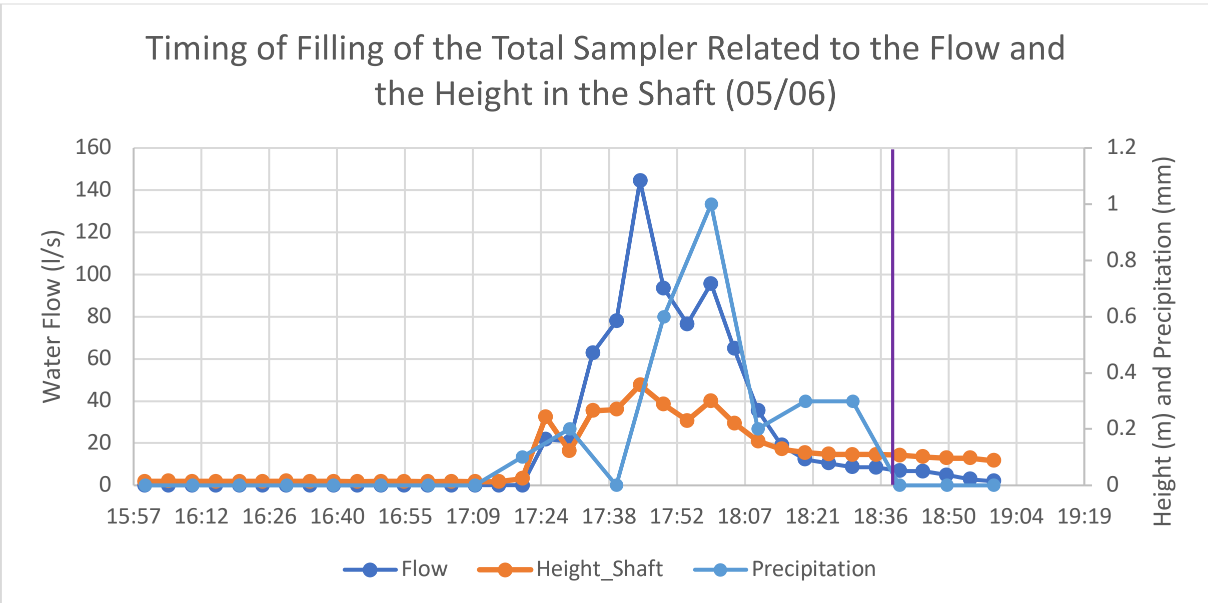

Figure 20: Overview of the Total Sampler filling process (05/06/2023)

5.5 Analysis of the different pollutant parameters

In this sub-section, we will start by looking at how the curve of Turbidity (NTU) obtained in real-time with the device in the pipe and compare it with the TSS measurements obtained in the laboratory. Then we will look at these parameters separately to evaluate the ability of the total samplers to measure these pollutants.

<u>12/05/2023:</u>

In Figure 21, we can observe with more clarity the overall concordance between the turbidity and the TSS curve. Although both have been measured in different ways (online on-site versus laboratory), we can say that for this event, it is relevant to use one or the other for any further analysis. This is especially relevant if we consider that it is sometimes complicated to have the capacity to collect water samples from the field and analyse them in the laboratory. In this case, the turbidity measurements would have proven to be good enough.

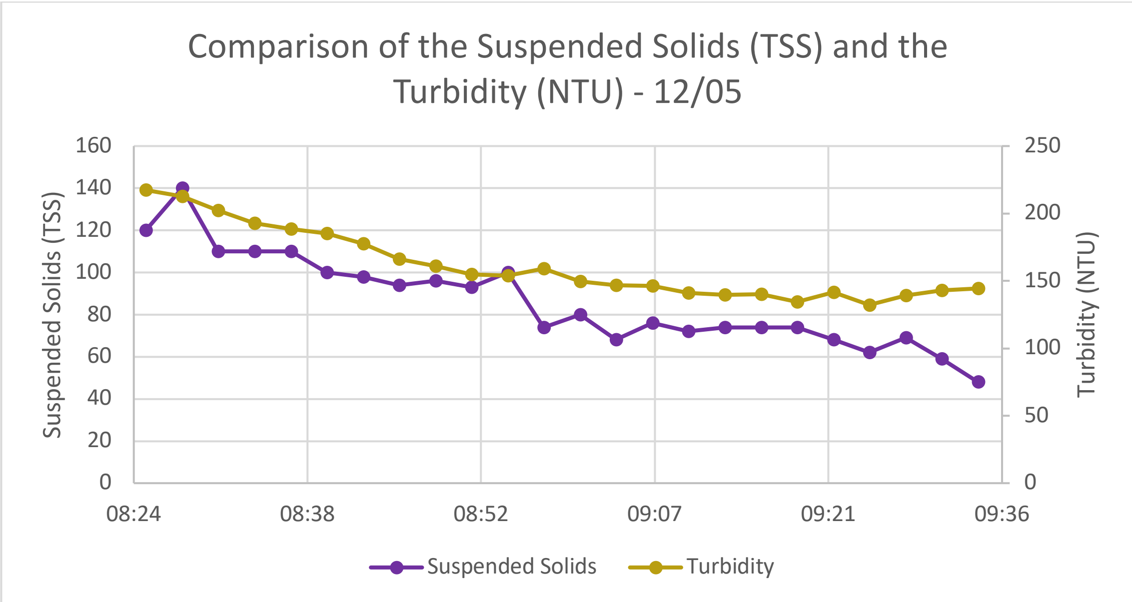

Figure 21: Comparison between the Suspended Solids (automatic) and the Turbidity (Pipe) – (12/05/2023)

A similar observation has been found for the 05/06, as shown in Figure 22. The two parameters peak at the same time and follow a similar downward direction with some increases along the way. It is critical to bear in mind that the turbidity measurements give data minute by minute meaning that the highest peak could have been higher. On the other hand 3 minutes intervals have been chosen to concordate with the suspended solids values that were derived from the automatic sampler. One element that can be highlighted, is that the concentration in TSS decreased quite rapidly after reaching its peak compared to the turbidity. This could also be due to the settling of particles in the collected sample and the lack of mixing prior to the sampling. One of the challenges of collecting samples relates to the handling and preparation time as it has been discussed in the literature review.

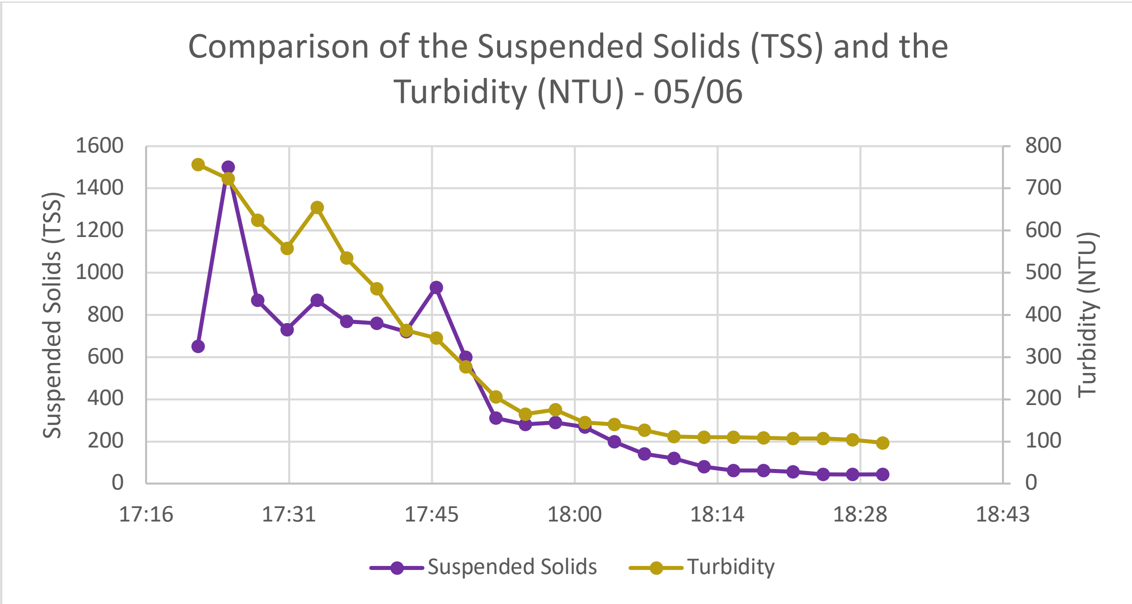

Figure 22: Comparison between the Suspended Solids (automatic) and the Turbidity (Pipe) – (05/06/2023)

As we have now established that the turbidity (from the pipe) TSS were comparable in terms of general trajectories, we are now going to look at the differences between the turbidity measurements from the pipe and the turbidity derived from the total samplers (measured in the laboratory). Indeed as we have observed some issues related to the sampling with the total samplers, it is relevant to identify whether we have been able to detect a similar level of turbidity across the two ways of sampling.

The two following figures, Figure 23 and Figure 24, highlight that the turbidity in the total samplers (Turbidity_Shaft) is considerably lower than the one that was observed during most part of the recorded runoff event. For the 12/05, this low turbidity in the shaft was recorded at the same time at which an important increase of the turbidity in the pipe was taking place (Figure 23). For the 05/06, it was sampled at a moment where the turbidity in the pipe was already at an almost 10 times lower value than at its peak. According to this data, we can say that the total samplers were not able to capture the concentration of pollutants of their event of reference. If we had only used this mean of sampling, we would have thought that the runoff contained fewer pollutants than in reality.

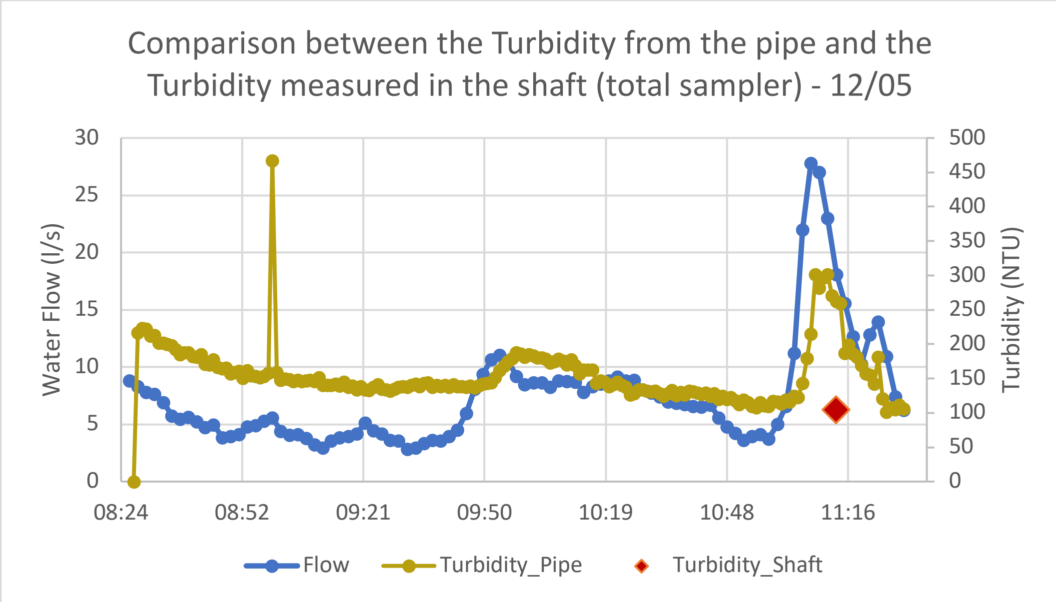

Figure 23: Comparison between the Turbidity (pipe) and the Turbidity (shaft – total sampler) – (12/05/2023)

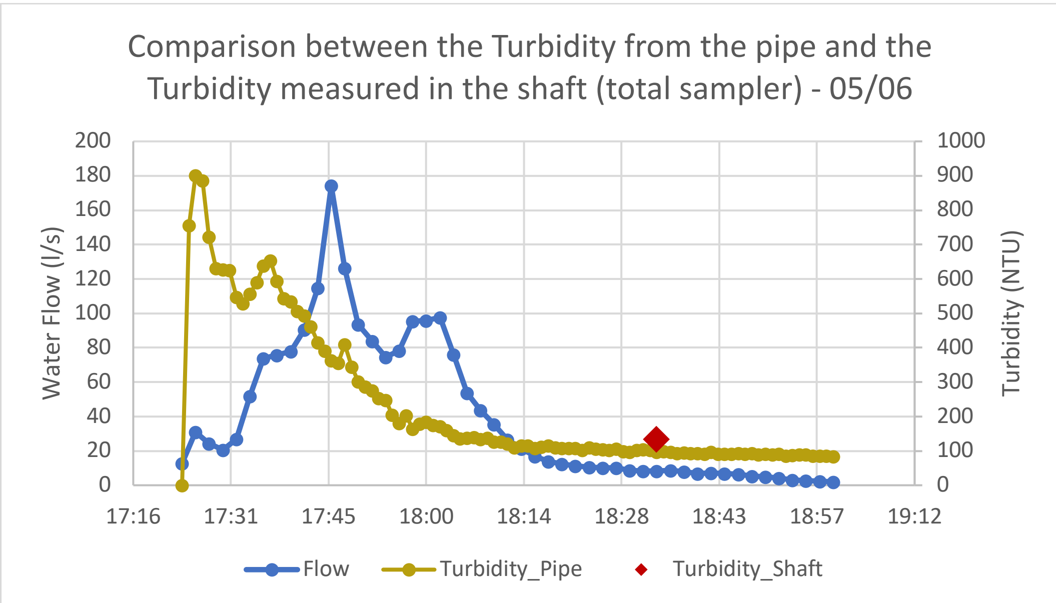

Figure 24: Comparison between the Turbidity (pipe) and the Turbidity (shaft – total sampler) – (05/06/2023)

At present, we chose to use the same approach to look at the difference between the TSS values obtained from the samples collected automatically and the total suspended solids value derived from the total sampler in the shaft.

Firstly, we can see in Figure 25 and Figure 26 that the dynamic between both samplers is very different than the one that has been observed for the turbidity. For the 12/05, the value measured by the total sampler is almost two times higher than the peak of TSS that was seen in the samples from the automatic sampler. This could be due to the remobilisation of the suspended solids in the shaft that came from an earlier rainfall event close to the one recorded. Moreover, it could also relate to a later event as there is an important delay between the end of the automatic sampling and the filling of the total sampler. The average value of TSS measured by the Automatic Sampler was of 86.2 which is a value three times lower that the single value of TSS measured by the total sampler.

On the other hand, the value of the total suspended solids parameter for the 05/06 can be considered as quite representative of the one derived from the automatic samples. Indeed, although it does not reflect the peak that was reached, the value falls within the ones that were measured once the TSS went down from the peak but still before decreasing considerably. As a result, the total sampler can give us a relatively good approximation of the total suspended solids, although it was not able to record a value close to the peak. If we look at the average TSS measured by the automatic sampler, we have a value of around 433 which is a bit less than half the 950 value measured by the total sampler. As a result, even though the total sampler did not capture the peak in TSS, it was still able to indicate a value that was already quite high and a bit more representative of the runoff event (compared to the 12/05).

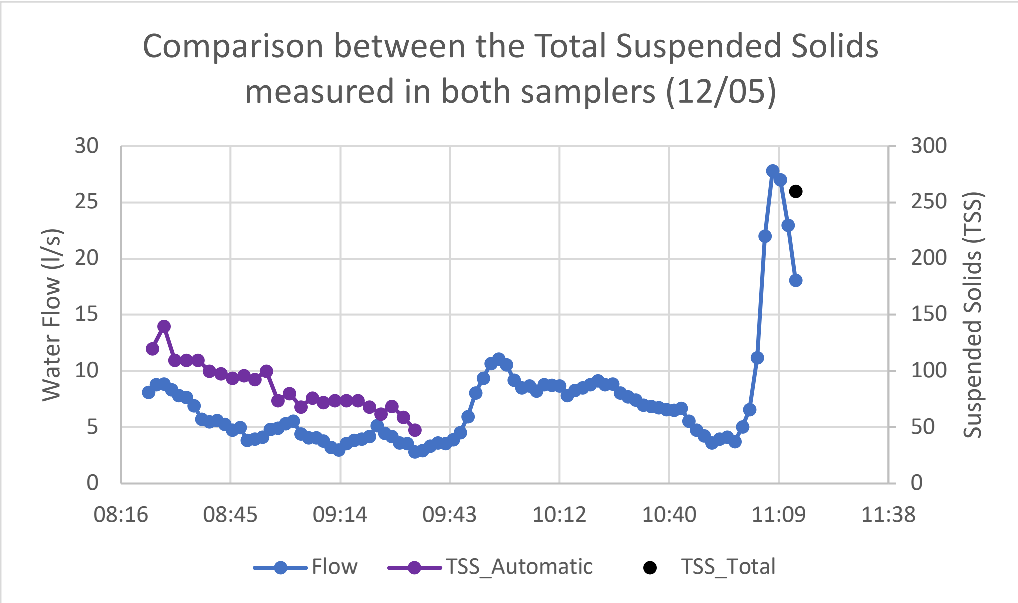

Figure 25: Comparison between the Total Suspended Solids (TSS) of both types of samplers (12/05)

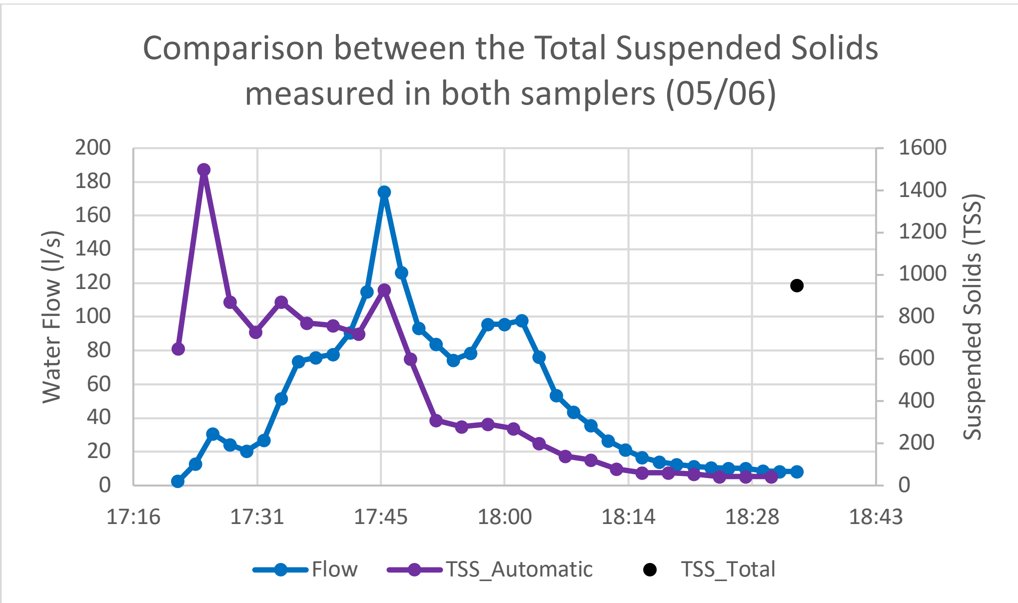

Figure 26: Comparison between the Total Suspended Solids (TSS) of both types of samplers (05/06)

5.6 First Flush

The previous sub-sections were mainly covering the sampling strategies and also the different ways of measuring the pollutants parameters. As we have now a better picture related to these areas of the results, we can at present dive into the first flush phenomenon. Thus, this part of the results aims to investigate the occurrence of the first flush for our three recorded runoff events. For each date, two graphics have been chosen, with the first one portraying the percentage of volume and TSS as the sampled event goes on; while the second one showcases the water flow and the height in the pipe by looking at how it evolves over the hours preceeding the sampling (7 hours prior).

<u>02/02/2023:</u>

The first event shows a relatively important first flush phenomenon as it can be seen in Figure 27. Firstly, it is quite striking that there is already more than 20% of the TSS in only 0.63% of the recorded volume. After the second sample 3 minutes later, we have more than 45% of the suspended solids for around 11% of the total measured volume. Going further, the gap starts to narrow but nonetheless, the first flush phenomenon is quite noticeable for this event. The main limitation is that we only have 6 samples covering a total of 15 minutes, which is definitely not the entirety of the event as highlighted in Figure 15.

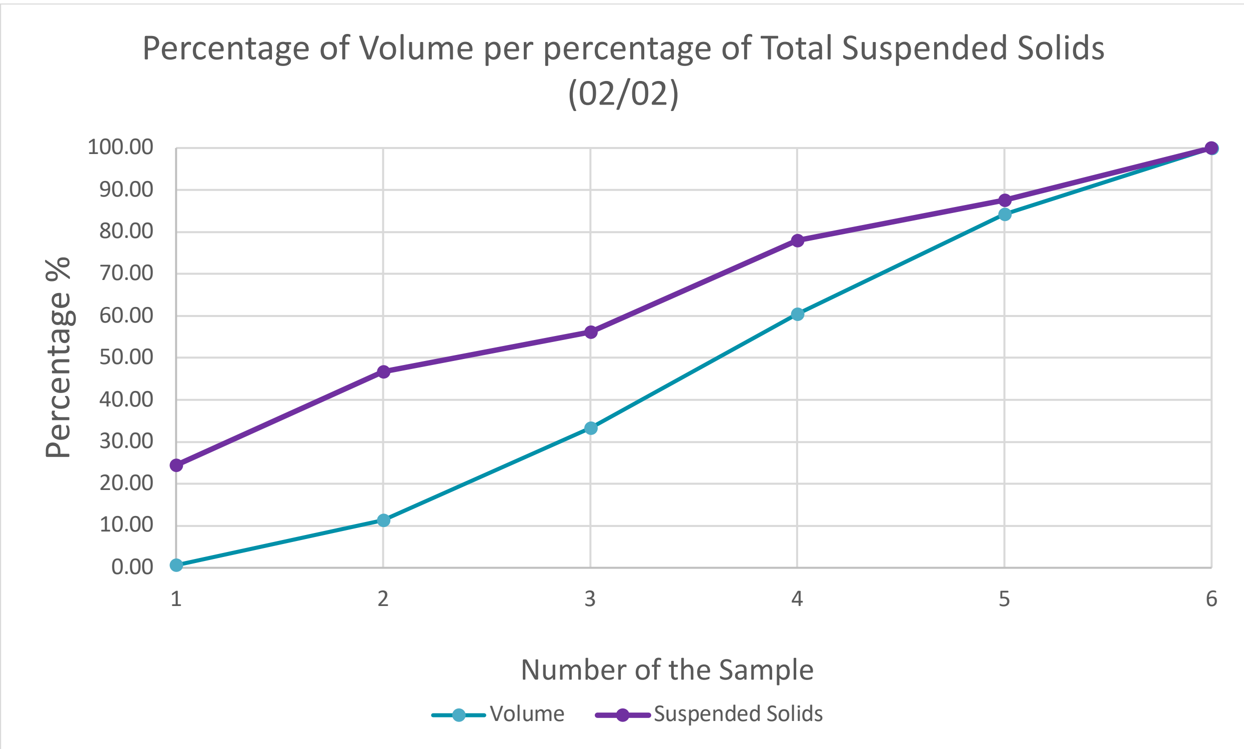

Figure 27: Proportion of Volume and Suspended Solids present in each sample out of the total sampled (02/02/2023)

When looking at the 7 hours preceeding the recorded event, we can see that there was almost no alteration of the Water Flow and of the Height in the Pipe (Figure 28). This suggests that there was not the possibility for previous pollutants and sediments to be carried before the automatic sampler started collection samples. As a result, and according to what has been seen before, we can say that we managed to sample the first flush accurately.

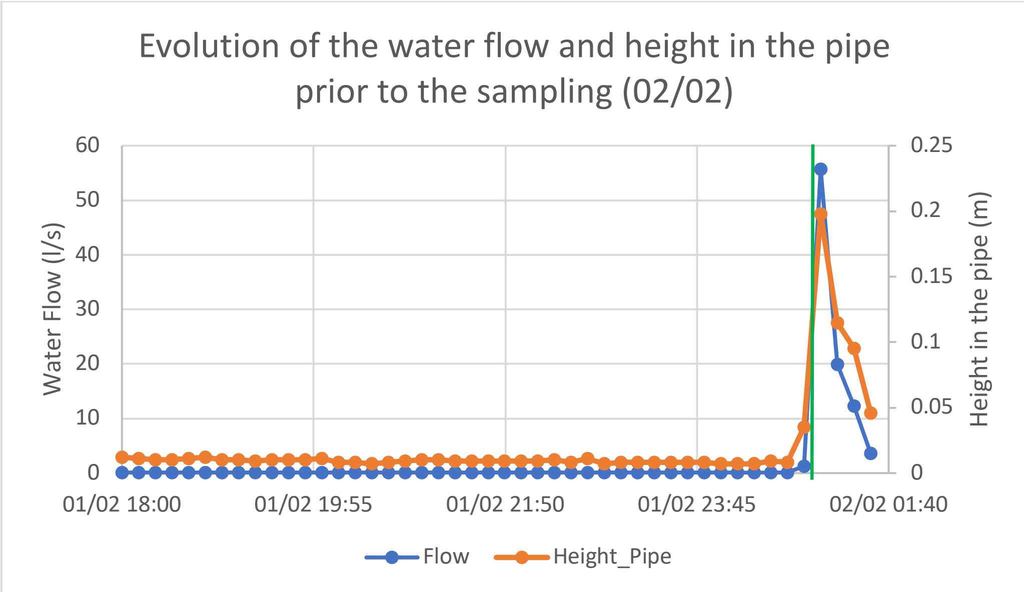

Figure 28: Variations in Water Flow and Height in the Pipe the hours preceeding the sampling (02/02/2023).

<u>12/05/2023:</u>

Earlier, we have mentioned that there were some issues with the automatic sampling for the 12/05. According to Figure 29, we were not able to observe any kind of first flush phenomenon for this event. Indeed, both curves can be considered as following almost the exact same trajectory (overlapping), suggesting that the same percentage of sediments is carried with the same percentage of volume, and this throughout all the recorded event.

This can be explained by the fact that there was already an increase in water flow and height in the pipe, around 90 minutes before the start of the automatic sampler (Figure 30). Due to this, we could emit the hypothesis that the sediments were already flushed at that moment in time, while the 90 minutes gap (or even 60 minutes if we consider the time at which this increase went back down) did not allow for another accumulation of the sediments on the road surface. Therefore, it seems to be the reason explaining why no first flush effect was noticeable for this runoff event.

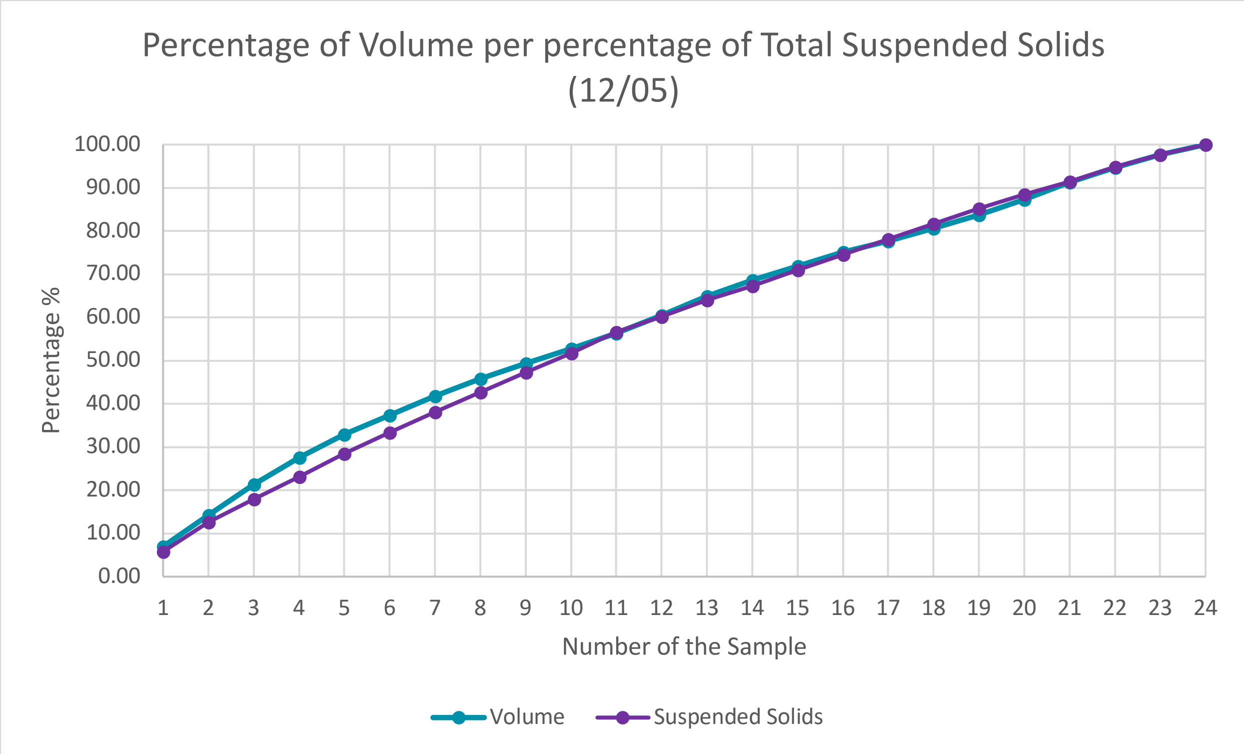

Figure 29: Proportion of Volume and Suspended Solids present in each sample out of the total sampled (12/05/2023)

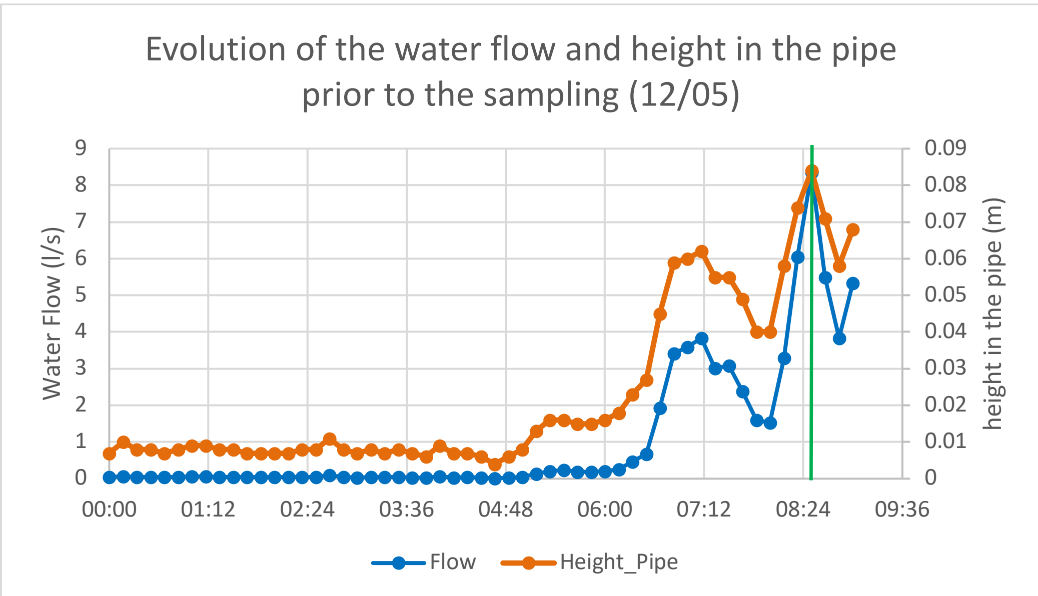

Figure 30: Variations in Water Flow and Height in the Pipe the hours preceeding the sampling (12/05/2023).

05/06/2023:

For the 5th June, we can notice the first flush phenomenon, which unlike the 2nd February, has been based on 24 samples, over more than one hour (Figure 31). This time, the first sample is not as highly concentrated as for the 02/02, but over the first 8 samples, the gap between the percentage of total recorded volume and the percentage of TSS gets wider. At the 8th sample (after 24 minutes), there was 66% of the suspended solids for only 32% of the total volume measured. This suggests that the first flush phenomenon waq quite pronounced. By looking at the seven hours prior to the sampling, we can observe that there were also no real movements (life for the 02/02) in water flow before the start of the automatic sampling (Figure 32). Moreover, we could add that for the 5th June, we were able to capture the majority of the flow increase as it has been highlighted in Figure 19. As a result, we can say that we managed to sample the first flush and the overall runoff event effectively for the 05/06.

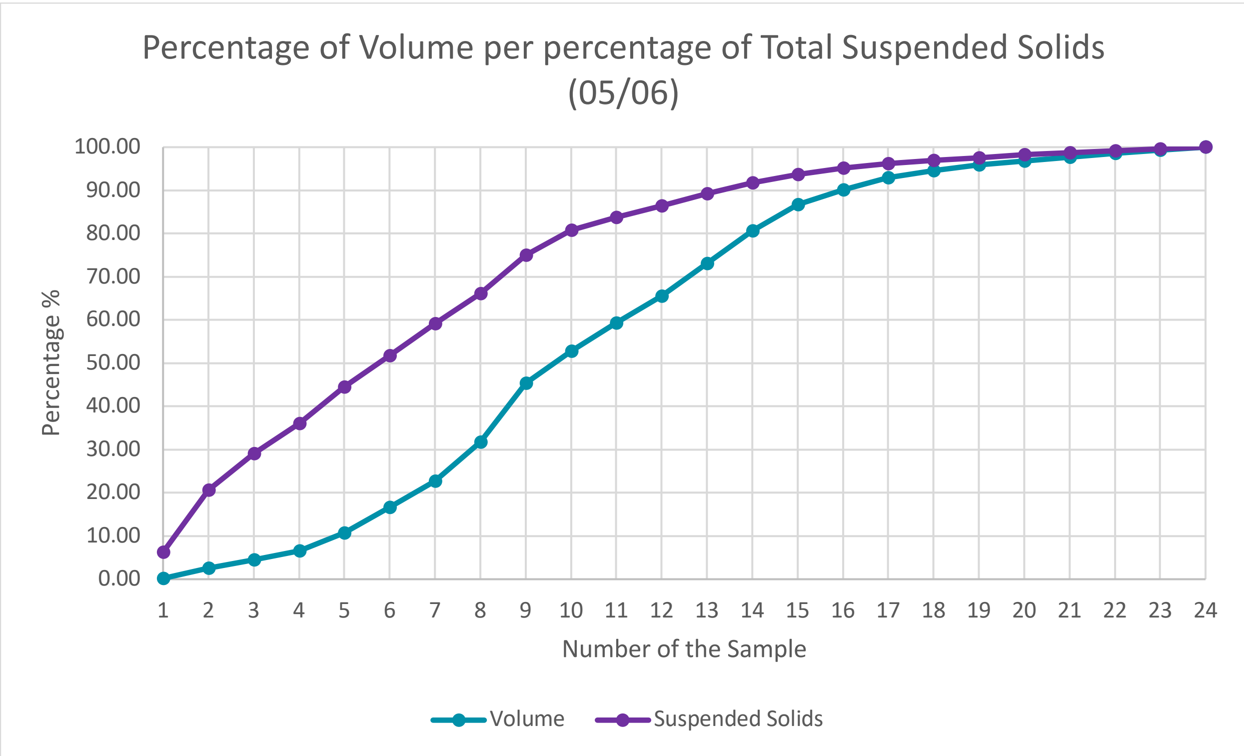

Figure 31: Proportion of Volume and Suspended Solids present in each sample out of the total sampled (05/06/2023)

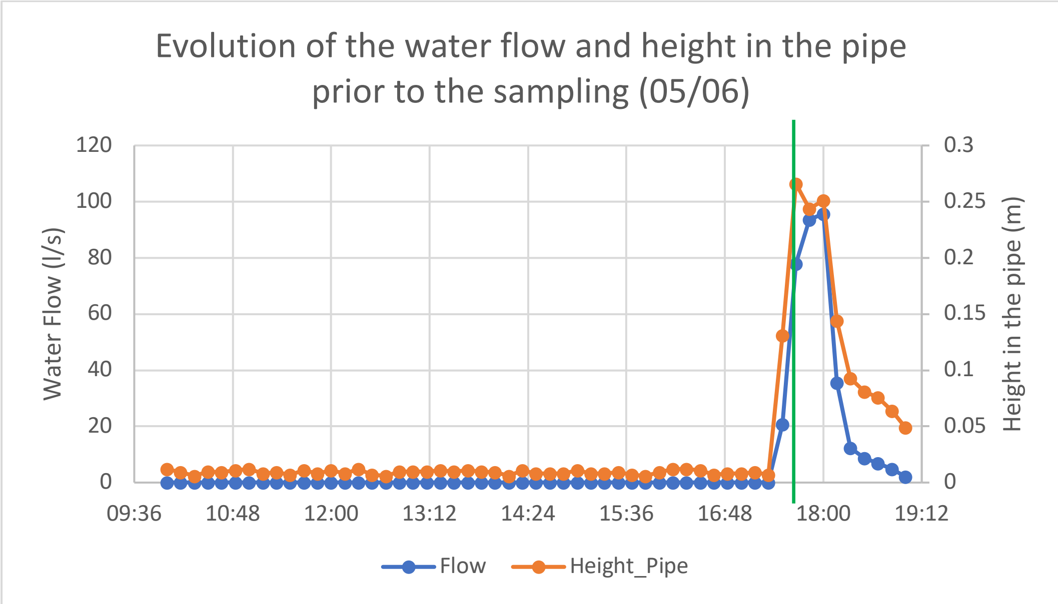

Figure 32: Variations in Water Flow and Height in the Pipe the hours preceeding the sampling (05/06/2023).

As we have seen in the results section, our ability to sample was not always effective. Regarding the automatic sampler, we were able to capture the first flush for two instances while we did not manage to sample appropriately for the 12/05. Indeed, another runoff event that we were not able to capture with the automatic sampler seemed to have influenced the lack of first flush effect observed in the samples that were taken. For the total sampler, results were less conclusive, as it seems that it was harder to calibrate it, especially due to the influence that the shaft area has on the sample taking process. This is not the case for the automatic sampler as it takes the samples at the first entry point. Overall, the results exacerbate the difficulty of being able to sample effectively over time, thereby highlighting the importance of sampling a large number of runoff events to obtain comprehensive data on the system.

6. Interpretation and Limitations

In line with the results that have been presented in the previous section, the interpretation part of this master's thesis aims to provide an overview of the different findings, how they can be compared with the literature, and the main limitations of the research that has been carried out.

This critical perspective will give us the opportunity to synthesise, analyse, and contextualize the results within the broader landscape of existing knowledge in the literature. We will particularly discuss the sampling process and the first flush phenomenon. Following this chapter, we will look at the conclusions of the work and propose an outlook regarding what has been found.

6.1 Interpretation

The observance of the first flush phenomenon was well captured by the automatic sampler for the 2nd February and then 5th June events. Indeed, there was a larger proportion of the TSS that were carried in the first samples compared to the middle and the end ones (Figure 27 and Figure 31). The maginitude of the first flush that we captured was very smiliar to the definition of Wanielista and Youssef (1993) of 50/25, although it did not reach the significant first flush definition described in Bertrand-Krajesky et al. (1998). On the other hand, we were not able to observe the same for the 12th May (Figure 29), either suggesting a different distribution of the pollutants throughout the recorded events or our inability to capture the event at the good timing (Figure 30).

We could emit two main hypotheses regarding the potential explanations behind it:

- It could be due to a different rainfall pattern such as a difference in the length of the precipitation event or a variation in intensity.

- It could also be the case that there was a difference in the way that the event was sampled like the inability of the automatic sampler to capture the beginning of the event and therefore, the time at which there was the highest concentration in sediments in the runoff.

As it has been highlighted in the literature, there is the need to have a certain amount of time where there is no precipitation, in order to consider it as a new rainfall event. Different time periods have been discussed by other researchers such as 10 hours by Barret et al. (1998) down to one hour according to Molina-Sanchis et al. (2016). This defined time period leaves the time for sediments and other pollutants to accumulate on the road surface before being flushed away by the next event.

Another indicator that we could look at is the rainfall intensity which has been described as being an important parameter influencing the strength and the maginitude of the first flush effect (Taebi and Droste, 2004; (Zhang et al., 2013)). If we look at the rainfall just before the sampling, we can see that the 02/02 had a higher rainfall intensity than the 12/05 but on the other hand the 05/06 saw a very small precipitation occurrence prior to the sampling. As a result, we could emit the hypothesis that in the case of the recorded event on the 12th May, we did not manage to capture the beginning of a rainfall event but only the continuation of one that started a little bit before we sampled (Figure 17). It could also even be the case that because of the constant rain in the hours preceding the sampling, the pollutants had already been washed out therefore in not present in a high concentration in the samples that were taken.

Regarding the low number of samples taken during the 02/02, it would be rather ambitious to draw a definite conclusion regarding the observance of the first flush phenomenon for this event. Indeed, although these 6 samples seem to have captured the highest proportion of pollutants for this runoff event, there was still quite a high water flow circulating when the last sample was taken (Figure 15). This is especially not enough when considering that many researchers mentioned that it was necessary to sample the whole event to do a proper characterisation (Huber et al., 2016)

On the other hand, the 02/02 was our first properly recorded runoff event, and we can highlight that the interval chosen (3 minutes) was already relevant according to our objectives. For instance, if we had followed the approach of Han et al. (2006) to sample every 15 minutes, we would have sampled at 00:50 and at 1:05. This means that we would have been able to capture the peak in TSS, but not the different variations that take place within this 15-minute timeframe.

However, these changes at 3 minutes intervals are very important to investigate as it can give us an indication of the real length of the first flush, especially the percentage of pollutants carried during the first few minutes of the runoff event. Moreover, thanks to this way of sampling we were able to notice a sharp decrease between 00:56 and 00:59 before going back to almost the same level at 01:02. Although the sedimentation and filtration processes will take a lot of time and knowing the data at this precise interval range will not really be important for that matter, it is crucial to know it to characterise the first flush to then be able to understand how our system is affected by this phenomenon. This has also been the argument advanced by Tiefenhalther et al. (2001) to motivate their choice of using a highly reduced interval to sample (respectively 2 and 3 minutes intervals). For instance, Tiefenhalther et al. (2001) found that 75% of the total suspended solids was washed off in the first fifteen minutes. In that context, if they had used the approach of Han et al. (2006), they would not have been able to see this important concentration of pollutants contained in the first minutes of the runoff event.

Considering these perspectives, we can say that our choice to sample at a short interval was relevant as we had the objective to sample the first flush. Moreover by having 24 samples taken within a 3 minutes interval between each other (for the 12/05 and 05/06), we were able to cover more than one hour of the event, which can be deemed as being enough considering that the first flush usually takes place between the first 30 and 60 minutes of the runoff event (Huber et al., 2016).

In this master's thesis, the analysis of the first flush phenomenon can serve as a good basis to identify our ability to sample with accuracy, as we were especially targeting the first flush effect. On the other hand, the number of events sampled is extremely low to make any kind of general conclusions regarding the observance of the first flush effect at this stormwater collector system. According to Thomson et al. (1997), it would have been necessary to have a minimum of 17 sampled events to be able to derive representative conclusions. In additional to the number of events, it is also necessary to have a study that encompasses a wide range of climatic conditions that takes into account the seasonality of rainfall events and of the distribution of pollutants. Covering all the seasons is also critical due to the seasonal variations also affecting heavy metals, as many of them have a higher mass concentration in summer and some metals like aluminium or Cadmium have a higher dissolved part in winter (Hallberg et al., 2006). In addition to this, these seasonal variations also have a considerable impact on the particle settling in the sedimentation tank, as mentioned by Rommel and Helmreich, (2018).

In that context, this master's thesis further highlights the difficulty of sampling consistently over time. For instance, (Zhang et al., 2021) had to exclude many events due to equipment failure while Terzaquis et al. (2008) managed to sample 70% of the rain event over a one year period. It is almost inevitable that there will be some events that are not possible to record or that the failure of some equipments will make it difficult to characterise the runoff or the first flush. In our case, we were often limited in the number of workers being able to collect the samples, and recharge the batteries of the devices, thereby affecting our ability to sample more. Hubert et al. (2016), further mentioned holidays as being another element impacting the number of events that can be sampled.

Investigating the relevance of using total samplers instead of automatic samplers was also one of the outlined objective. Regarding this matter, we can say that we have obtained mixed results and that it was often hard to sample at the right point to have a comprehensive assessment of the runoff event as it was conveyed by the automatic sampler/

We had some difficulties measuring the turbidty with our total sampler. Firstly, as it has been highlighted on Figure 23 and Figure 24, we measured a turbidity value that was way lower compared to the one that was found throughout the runoff events from the turbidity measurement device located in the pipe. One element that could have caused this issue would be the influence of the sedimentation tank that is connected to the shaft. Kasting et al. (2003) mentioned that it was critical to avoid the settling of particles in a sedimentation area, to ensure that it does not influence the accuracy of the values measured. In our case, the pipe was independent from the whole sedimentation system while it was not the case for the shaft, thereby being a potential explanation to our inability to capture a similar turbidity value in the shaft (total sampler) compared to the one measured by the device located in the pipe. This can be further highlighted by the comparison of total suspended solids between both samplers. Indeed, the value of total suspended solids was considerably higher compared to the peak value derived from the analysis of the automatic samples (for the 12/05). The cause can be linked to the remobilisation of suspended solids that accumulated in the shaft when the total sampler got filled. On the other hand, we found that by looking at the average concentration of TSS in the automatic samples and the one taken by the total sampler for the 05/06, we could have a decent estimation of the TSS concentration during the event, although the total sampler did not measure the peak reached.

Being able to accurately sample the runoff event with the total samplers would have proven to be a good solution to the cost-demanding and labour-instensive issues related to automatic sampling. Unfortunately the use of this kind of device has not really been documented in the road runoff literature, making a relevant comparison quite difficult. Even in the study of Huber et al (2016) which looked at 294 sites, there was not a sampling strategy that was close to the one we carried out (or it was not detailed as some studies did not give enough details about their procedure).

In the light of the various instruments we had at our disposal to measure the concentration of pollutants, it's critical to have a look at how their results might have varied. Indeed, laboratory analysis are more costly, take more time, and it is needed to prepare them shortly after collection.

On the other hand, online measurements are easier to obtain but calibration difficulties are sometimes a challenge to obtain reliable results over time.

As highlighted in the literature, we managed to observe a correlation between the TSS and the Turbidity (NTU) curves (Figure 21 and Figure 22). Wakida et al. (2013) mentioned the increase of turbidity in the runoff following an augmentation of suspended particles. By looking at these figures, we can clearly see that their curve follows a similar pathway, going down throughout the rainfall event.

One element we can notice from the graphics is that the TSS curve tends to have stronger fluctuations than the turbidity one. Although it could just be the case that the values were a little bit different, there are also possibilities that it could be related to the handling and the preparation of the samples prior to the analysis. However, we made sure to observe a short handling time, which was definitely lower than the maximum duration prescribed by Kayhanian et al. (2012).

6.2 Limitations

This thesis project had a timespan of around 7 months and was predominantly based on fieldwork and data obtained during the Spring and Summer of 2023. There was also some data that had been collected in the previous Winter season, but being very limited, it was not usable. It is essential to mention that monitoring and investigating the system over a longer period of time would have been able to showcase more accurate and precise results. For instance, it would have been possible to identify seasonal trends and even how climatic variations could impact the results over a few years or even a decade (Thomson et al., 1997).

Indeed, there has been an increase in extreme precipitation events, especially during the spring and the summer seasons compared to the last decade (IEA, 2021) Sometimes, the system can receive the amount of precipitation – in a single rainfall event – that it should receive in a whole week, or even two weeks. An overloading of the system considerably impacts the ability of the sedimentation and filtration processes to take place as designed in the project. In addition to this, with the drastic changes that climate change entails, we can expect to have a considerable change in precipitation patterns and intensity in the future. These will inevitably impact the system's purification ability and therefore, the toxicity of the effluent. In that context, this master's thesis evaluated the efficiency of this urban runoff stormwater collector system, 10 years after its initial construction.

In that regard, we could also emit some hypotheses regarding the performance of the system overtime. Firstly, as with every type of system, ageing is something that needs to be taken into consideration. While good maintenance can successfully extend its lifespan, there are still some technical limitations that need to be evaluated, coupled with the changes in climate that we have discussed. Indeed, we could evaluate that the diameter of the pipe would not be able to handle the amount of water during extreme events or that the sedimentation tank is not effective anymore to settle a sufficient number of particles prior to the loading on the filter bed.

The data analysis that has been carried out in this project has further highlighted the difficulty of finding and getting a representative sample. It was sometimes due to the varying climatic conditions but mainly to sampling issues. Indeed, as the sample taking was triggered by the water height in the pipe, it was needed to know how the targeted rainfall event would translate into the height. This also depended on another array of parameters, which combined together, make it quite difficult to always have a precise and calibrated water sample taking process.

A problem that has often been observed was that an annex event was sampled instead of the bigger one that occurred before or afterwards. During the data analysis process, it was essential to have a look at the discharge measurements from the Nivus device in combination with the precipitation data in order to understand whether we had sampled an important rainfall event or whether it was just a secondary one that had been captured. This issue directly affected our ability to define the first flush with the highest accuracy possible.

Overall, the analysis has also been undermined by the lack of data regarding one or more parameters. In some cases, we had the turbidity and the conductivity data but not the suspended solids. This is also true for other parameters, and we would have benefitted highly from having every parameter for every event and every individual sample. However, the reality of working in the field means that we observed inaccuracies very frequently and it’s important to acknowledge them and deal with them in an adequate manner.

Another point that needs to be thoroughly discussed, is the reliability and accuracy of the data that have been collected and then used for this master’s thesis. Firstly, we have mentioned that due to the varying ways of sampling, it could undermine the accuracy of the analysis. In addition to that, we have also noticed that there were a lot of data values that were inaccurately high. For instance, the online turbidity measurements often showed a 999 turbidity error value. It was often displayed when there was no water coming into the system and sometimes in the middle of a rainfall event where it lacked logical coherence that the turbidity would spike to this level. Moreover, this error value was always the same and never a bit above or a bit below.

This can be further highlighted by the lack of conformity between the measurement devices that were installed in the influent and those installed in the effluent part of the system. For instance, the total samplers were different in both shafts while the online measurement turbidity device was only set up in the influent part. Indeed, having on-site turbidity measurements for the effluent could have provided us with a helpful source of data in addition to the one in the influent. Indeed, while this master’s thesis focused essentially on the system from the influent point of view, it would be highly relevant to compare the results from this paper with similarly sampled data from the effluent. This would give us an indication on the overall efficiency of the system to purify the polluted runoff.

Most of these limitations are closely related to the fact that this sampling project was above all an experimental one and although the system definitely served its purification purpose, it was in constant improvement. From the sampling processes to the analysis processes, many changes were implemented along with the findings that were found and sampled. These changes will still occur as the project is still ongoing for at least one more year. Indeed, this master’s thesis was only one part of this project covering the whole stormwater treatment plants. In that context, the recommendations proposed in this thesis will be an addition to the findings found by the other researchers and workers on the projet. Overall, the entirety of the system, the sampling strategies that have been chosen, as well as the effiency of the purification process will be analysed to give a well-rounded picture of the stormawater treatment plant.

7. Conclusion and outlook

This master's thesis has pursued a comprehensive investigation of the highway runoff stormwater collector system and its associated dynamics. By thoroughly analysing and comparing different sampling methods, we have gained valuable insights into their efficacy in capturing relevant rainfall events and detecting the first flush phenomenon.

Regarding the automatic sampling process, we have found that according to three rainfall events sampled, we have been able to start sampling at the desired point in time for two of them (for the 02/02 and the 05/06). In other words, we were able to sample at the time when there was the first proper increase in water flow, suggesting the beginning of the incoming runoff coming into the system. The increase in water flow was closely correlated to the elevation of the height in the pipe, triggering the automatic sampler sensor to start the sampling process.

Concerning the total sampler sampling process, results are a bit more mitigated. Firstly, it appeared that the filling of the total samplers occurred at a later phase of the runoff event, which for the 12th May was more than one hour after the automatic sampler finished sampling. The turbidity from the total samplers was also significantly lower than the turbidity monitored by the dive in the pipe. It suggests that the total samplers were not able to capture a turbidity value that could be representative of the one from the associated runoff. Regarding TSS, the total sampler captured a value around twice higher than the peak measured in the automatic samples while for the 05/06, the value TSS could be qualified as being representative of the runoff event.

One of the central objectives of this master's thesis was also to investigate the first flush phenomenon. Although it would have been better to have a larger number of events, we were able to observe the occurrence of the first flush in two out of the three cases. Even though it was noticeable, we cannot qualify it as being "significant" if we use the terms that have been used in the literature. Thanks to the widely available data regarding the water flow in the pipe and the height in the pipe, we have been able to determine the reason that could explain our inability to observe the first flush for the 12/05. As far as it is indicated by the data, it seems to be linked to the fact that the automatic sampler should have been triggered earlier, at a time when there was already a noticeable increase in water flow and height in the pipe. Indeed, it seems that most of the sediments and pollutants were already washed out when we started sampling, thereby our inability to capture the first flush effect.

According to the results that have been obtained throughout the thesis, some recommendations can be made, whether for similar stormwater treatment plants or more generally for different studies on the topic:

- It is important to have a large amount of sampled rainfall events as it is sometimes complicated to ensure that the event is sampled appropriately. Thus, they should ideally be sampled at the beginning of the precipitation occurrence, as it is also the moment at which the runoff contains a high concentration of sediments and pollutants

- It is needed to further extend the monitoring and recalibration of our sampling devices and the one measuring the pollutants parameters. This includes the water samplers (especially the total sampler) but also the instruments measuring on-site parameters such as the turbidity.

8. Summary

This final chapter marks the completion of this master's thesis. This is the time to reflect on the motivation driving the thesis project and its purpose. We will also look at the different research questions that have been addressed as well as concisely outlining the principal results. These will be further discussed into the broader perspective.

The research that has been undertaken took place in the wider context of finding ways to address environmental pollution, particularly regarding the contamination of water bodies. Highway runoff is a very interesting topic and encompasses a wide range of fields such as environmental science, urban planning, water chemistry, hydrology, civil engineering but also includes important elements of policy and environmental law. The issues related to road runoff are important to tackle for governments, road infrastructure entities as well as environmental agencies and the people involved at the local level for the protection of their aquatic habitats.

Considering this wide perspective, our research focused on multiple aspects related to the collection of runoff from a highway surrounding Vienna and the sampling strategies that can be implemented to characterise the influent. Among these objectives, a particular attention was directed to the calibration of the sensor to sample at the right timing to capture the initial part of the runoff, with the aim to identify whether a potential first flush effect was noticeable.

To guide our analysis, we investigated potential answers related to the effectiveness of our sampling methods to capture relevant rainfall events, while also looking at whether the automatic sampler was able to identify the first flush effect. Furthermore, we also wanted to evaluate the relevance of using total samplers to give us indications related to the concentration of pollutants from the runoff.

The study employed different methods ranging from calculating hydraulic elements to using on-site and laboratory data to create comprehensive graphics. Firstly, a design rainfall event reflecting a strong precipitation occurrence has been used as a reference point to identify its impact on the runoff coming into the influent. With that objective in mind, the discharge of this event has been calculated, as well as the water level in the pipe that is reached throughout the precipitation occurrence. These calculations have also enabled us to know the amount of discharge when the pipe is full.

- According to the meteorological data of last year, the 1-year - 15 minutes event has not been reached, with the large majority of rainfall events generating a rainfall depth (mm) way below it. Due to climate change, it would be possible to record rainfall events of this magnitude in the future, although it is uncertain when.

- The automatic sampler was able to start sampling at an appropriate time for two events out of three while the total sampler was always delayed. For the 12/05 the total sampler started getting filled more than one hour after the end of the automatic sampling.

- There were significant differences between the online turbidity measurements and the turbidity measured by the total sampler. For the TSS, the value obtained by the total sampler for the 12/05 was too high compared to the ones obtained from the automatic sampler, while it was more comparable for the 05/06.

- We were able to observe the first flush phenomenon for two runoff events. The events for which we we were able to capture the first flush effect were the events that we sampled at the right time.

A comprehensive table has been created to provide a general overview of the runoff events sampled by the automatic sampler showcasing the number of samples taken, our ability to sample at the desired time, and the observation of the first flush phenomenon (Table 5).

Table 5: Summary table of the automatic sampling and first flush observation

DATE	02-Feb	12-May	05-Jun
TIMEPERIOD	00:50 to 01:05	08:25 to 09:34	17:22 to 18:31
INTERVAL	3 minutes	3 minutes	3 minutes
NUMBER OF SAMPLES	6	24	24
SAMPLING AT THE RIGHT TIME	YES	NO	YES
FIRST FLUSH OBSERVED	YES	NO	YES

This master's thesis can give good indications related to how we can monitor and sample using the real-life conditions of a stormwater treatment plant. Often, studies have been elaborated using laboratory or specifically designed environmental and sampling conditions. This is particularly helpful in providing advancing knowledge in the field of road runoff sampling, analysis and treatment but does not take enough into consideration the reality of the field.

Thus, this project shed light on the difficulties of calibrating water sampling in line with the environmental conditions and technical specificities. As more and more data is being collected at this stormwater treatment plant, the possibility to optimise the sampling process will be increasingly feasible. This would also enhance our capacity to capture and characterise the first flush phenomenon, essential to further evaluate the efficiency of the whole system.

The implementation of total samplers can be relevant in the future to overcome the fact that automatic samplings are very labour-intensive and not cost-effective. However, there is still the need to optimise the height and the filling of these total samplers in order for them to display an accurate portray of the content of the targeted road runoff.

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10. List of abbreviations

AS = Automatic Samples
Cd = Cadmium
Cr = Chromium
Cu = Copper
EEA = European Environmental Agency
Ni = Nickel
NTU = Nephelometric Turbidity Unit
Pb = Lead
TS = Total Samples
TSS = Total Suspended Solids
ZAMG = Zentralanstalt für Meteorologie und Geodynamik
Zn = Zinc

11. List of tables / figures

12. Appendix

Appendix 1: Information on the Automatic Samples: date, time, name

DATE	TIME	NAME
02/02/2023	00:50	AS1
02/02/2023	00:53	AS2
02/02/2023	00:56	AS3
02/02/2023	00:59	AS4
02/02/2023	01:02	AS5
02/02/2023	01:05	AS6
12/05/2023	08:25	AS7
12/05/2023	08:28	AS8
12/05/2023	08:31	AS9
12/05/2023	08:34	AS10
12/05/2023	08:37	AS11
12/05/2023	08:40	AS12
12/05/2023	08:43	AS13
12/05/2023	08:46	AS14
12/05/2023	08:49	AS15
12/05/2023	08:52	AS16
12/05/2023	08:55	AS17
12/05/2023	08:58	AS18
12/05/2023	09:01	AS19

12/05/2023	09:04	AS20
12/05/2023	09:07	AS21
12/05/2023	09:10	AS22
12/05/2023	09:13	AS23
12/05/2023	09:16	AS24
12/05/2023	09:19	AS25
12/05/2023	09:22	AS26
12/05/2023	09:25	AS27
12/05/2023	09:28	AS28
12/05/2023	09:31	AS29
12/05/2023	09:34	AS30
05/06/2023	17:22	AS31
05/06/2023	17:25	AS32
05/06/2023	17:28	AS33
05/06/2023	17:31	AS34
05/06/2023	17:34	AS35
05/06/2023	17:37	AS36
05/06/2023	17:40	AS37
05/06/2023	17:43	AS38
05/06/2023	17:46	AS39
05/06/2023	17:49	AS40
05/06/2023	17:52	AS41
05/06/2023	17:55	AS42
05/06/2023	17:58	AS43

05/06/2023	18:01	AS44
05/06/2023	18:04	AS45
05/06/2023	18:07	AS46
05/06/2023	18:10	AS47
05/06/2023	18:13	AS48
05/06/2023	18:16	AS49
05/06/2023	18:19	AS50
05/06/2023	18:22	AS51
05/06/2023	18:25	AS52
05/06/2023	18:28	AS53
05/06/2023	18:31	AS54

Appendix 2: Information on the Total Samples: date, time, name

DATE	TIME	NAME
02/02/2023	00:54	TS1
12/05/2023	11:14	TS2
05/06/2023	18:34	TS3

13. Curriculum Vitae

PERSONAL DETAILS:

Name: Eliott Gabriel

Place of residence: 17 Rue de Lattre de Tassigny, 67300, Schiltigheim, France

Telephone: +33770743135

Email: eliott.gabriel67@gmail.com

TRAINING

2021 - present: Master's degree in Environmental Sciences – Soil, Water, and Biodiversity at the

University of Natural Resources and Life Sciences, Vienna and the University of Copenhagen ; degree sought:

Master of Science, MSc

2018 - 2021: Bachelor in Environmental Sciences and International Development at the

University of East Anglia, Norwich; Degree

Bachelor of Science, BSc

2015 - 2018: French Scientific Baccalaureate obtained at Institution La Doctrine Chrétienne, Strasbourg

WORK EXPERIENCE AND INTERNSHIP:

February 2021 – Present: *French Teacher* on iTalki Language Learning Platform

July 2021 – July 2022: *Waiter* at the Restaurant “Le Basilic”, Copenhagen

October 2019 – June 2021: *Team Leader* at the University of East Anglia Student Union’s Supermarket

April 2019 and December 2019: *Intern* at the Centre for Interdisciplinary Studies, Kolkata, India.

LANGUAGES:

French: Mother tongue

English: Level C2

Italian: Level C1

Portuguese: Level B2

Spanish: Level B1

German: Level B1

Danish, Hindi and Indonesian: Level A1

EXAMINATIONS TAKEN DURING THE PROGRAM

At the University of Natural Resources and Life Sciences (2nd Year):

- Decision support system (3 ECTS)
- Ecological River Landscape Management (2 ECTS)
- Ecology of Aquatic System (3 ECTS)
- Human Impacts in Riverine Landscapes (2 ECTS)
- Human Nutrition (3 ECTS)
- Integrated Flood Risk Management (3 ECTS)
- Master's Thesis Seminar (2 ECTS)
- On-site Solutions for Water Supply and Sanitation (3 ECTS)
- Technology assessment (3 ECTS)
- Water resources planning and management (3 ECTS)
- Water Supply and Wastewater Treatment (3 ECTS)

At the University of Copenhagen (1st Year):

- Conflict Management (7.5 ECTS)
- Energy Systems and Climate Mitigation (7.5 ECTS)
- Entrepreneurship and Innovation (7.5 ECTS)
- Environmental Management in Europe (15 ECTS)
- Land Use and Environmental Modelling (7.5 ECTS)
- Plants in Populations and Communities (7.5 ECTS)
- Project Outside of Course Scope (7.5 ECTS)

INTERESTS

- Language Learning
- Sports (Water Polo, Swimming, Badminton)
- Hiking
- Backpacking
- Reading
- Online Freelancing