MSc thesis in Water Management

Balance between water quality and quantity based on retention time in a biofilter

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By

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Abstract

Urbanization has led to increased impermeable surfaces, disrupting the natural hydrological cycle and resulting in more frequent urban flooding and pollution. There is an urgent need for cost-efficient and effective stormwater management solutions to improve stormwater quality and facilitate its reuse. FieldFactors' BlueBloqs system integrates stormwater collection, water treatment in a biofilter, and aquifer recharge. The BlueBloqs system's biofilters are soil-plant systems with a submerged zone. Before being used to recharge an aquifer, the effluent from a biofilter must meet specific water quality standards. Improvements in water quality within the biofilter are achieved mainly through static optimization (changing media materials, the depth of layers, and plant species) and dynamic optimization (controlling hydraulic behavior). Some research found that retention time plays a crucial role in the operation of a biofilter, influencing both the quality and quantity of the effluent. The central challenge lies in operating the biofilter's retention time to maximize water recharge while ensuring optimal water quality.

The objective of this research is to determine the optimal retention time for the biofilter to achieve the best water quality while maximizing the total amount of water to be recharged by controlling the pump. This thesis includes water quality measurement and water quantity simulation. In the water quality part, the performance of the biofilter at different retention time (2, 6, 16, and 24 hours) is evaluated in terms of the removal efficiency of turbidity, nutrients (nitrate and phosphorus), dissolved and particulate metals (Mn, Ca, Mg, Ba, Zn), UV254 and DOC with two different influent types (surface water and stormwater). In the water quantity part, Cromvliet Park, with an 8000 m^2 collection area, was modelled using Python and SWMM to operate the biofilter with various retention time under one year of rainfall data (total rainfall 731mm). This modelling was done to calculate the total water volume available for recharge. The sections on water quality and quantity were integrated by controlling and evaluating the biofilter based on the retention time.

The results indicate that the efficiency of the biofilter's pollutant removal is influenced by several factors. Turbidity (40-90%) is effectively removed by the filtration in the biofilter. Nitrate removal efficiency was 12-49% with short retention times (2-6 hours) but fluctuated with longer durations (16-24 hours), decreasing to -84-13% and then changing to -6-0%. Measurements of dissolved oxygen in the effluent indicated that an increase in nitrate removal efficiency due to nitrification happened with longer retention time. For dissolved zinc, removal efficiency ranged from 10-60% with stormwater influent and 0-100% with surface water because of the adsorption competition of metals. Combined with the water quantity calculations performed in SWMM, it is advisable to set the optimal retention time for the

biofilter at 4–6 hours. This duration allows for the maximization of water reuse while maintaining high nitrate removal efficiency.

Preface

The completion of this thesis wouldn't have been possible without the invaluable support of lots of people. Firstly, I'd like to express my great thanks to Joshua and my colleagues at FieldFactors for their unwavering support and assistance. I've asked numerous questions to Joshua throughout my thesis, and he consistently provided professional and insightful responses. Secondly, I would like to say a lot of thanks to Boris and Jeroen, my thesis supervisors. These professors have challenged me with unexpected questions, encouraging me to go deeper into the “why” and “how”. I'm truly appreciative of their guidance and advice throughout my thesis. Finally, my thanks to Jean-Paul from Green Village, the lab assistants from the water lab, Noman, and Merlien from IHE. Their help has been invaluable to the successful completion of my thesis.

Looking back on more than two years of my Delft time, there are stories of laughter and tears here. I have met a lot of friends who helped me during my two years in the Netherlands, and I have gained a lot of growth and happiness. The company and encouragement of my family are also important in these two years, no matter what happens, no matter when, my family will always be my strongest support.

I wonder what I will be like in ten years. Will I be a professional engineer? Will I be an engineer as good as Joshua? (Or even better than him :)) I wish I could fast-forward to the day I realize my dream of being an engineer. But no matter what, please continue to be brave, strong and enjoy the world.

Great thanks to all you guys!

Yuhan Mao

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1. Introduction

1.1 Background

As urbanization rapidly progresses, impermeable surfaces like pathways and roofs are increasing. With urbanization comes an expansion of impervious areas, which reduces infiltration and surface storage of precipitation. Consequently, the natural hydrological cycle is disrupted, leading to an increase in both the total volume and peak flow of runoff, resulting in more frequent urban flooding [1]. Rainwater is not contaminant free as it contacts impervious surfaces and becomes stormwater, but further mobilizes a broad range of pollutants including particulate matter, nutrients, oil and grease, toxic organic compounds, metals, and microorganisms [2]. As a result of increased human activity and changes in land use, urban runoff transports a large amount of pollutants into surface water, and this non-point pollution has resulted in water pollution and environmental harm [3]. One of the urgent challenges in urban construction and development is how to improve stormwater quality in a cost-efficient way and how to effectively reuse stormwater. To face the uncertainty of future climate change, different countries have proposed different solutions, with outstanding examples including low impact development, green infrastructure, and best management practices in the United States, water sensitive cities in Australia, and sponge cities in China [4]. As a component of stormwater management, bioretention (biofilter) has received significant attention for its effectiveness in improving water quality and reducing runoff volume. Biofilters offer on-site treatment that enhances the hydrological cycle through improved infiltration and stormwater reuse. They are not only effective in reducing stormwater runoff at the source and improving runoff water quality, but they also have the advantage of mitigating flood risks and recharging groundwater. Furthermore, biofilters can be flexibly integrated into urban landscapes.

However, it is crucial to explore effective biofilter design and optimize its operation. Field measurement data for extended periods of operational performance are often inadequate [5]. Due to the multiple factors that influence biofilter during practical operation, biofilter designers and urban planners lack familiarity with various design options, including the selection of appropriate vegetation and substrate for specific locations or purposes. Design flexibility is frequently constrained by local regulations. In addition, analyzing the factors that affect water quality treatment by biofilter and assessing its effectiveness on different pollutants is necessary.

1.2 BlueBloqs System

The BlueBloqs system is a stormwater collection, retention, treatment, storage and reuse system, which is designed and constructed by FieldFactors. This system collects stormwater

from roofs, pavement, or surface water through drainage pipes and transports it to a buffer tank for storage. The collected water is pumped to the biofilter for treatment, where the quality of the effluent is improved and continuously monitored. The effluent from the biofilter is recharged into the aquifer by activating and deactivating the infiltration pumps. The construction of the BlueBloqs presents a novel opportunity for mitigating urban flooding and facilitating the reuse of stormwater. This design improves the aesthetics of urban rain gardens while offering creative solutions for urban flood control and stormwater recycling by combining the natural cycle with engineering design.

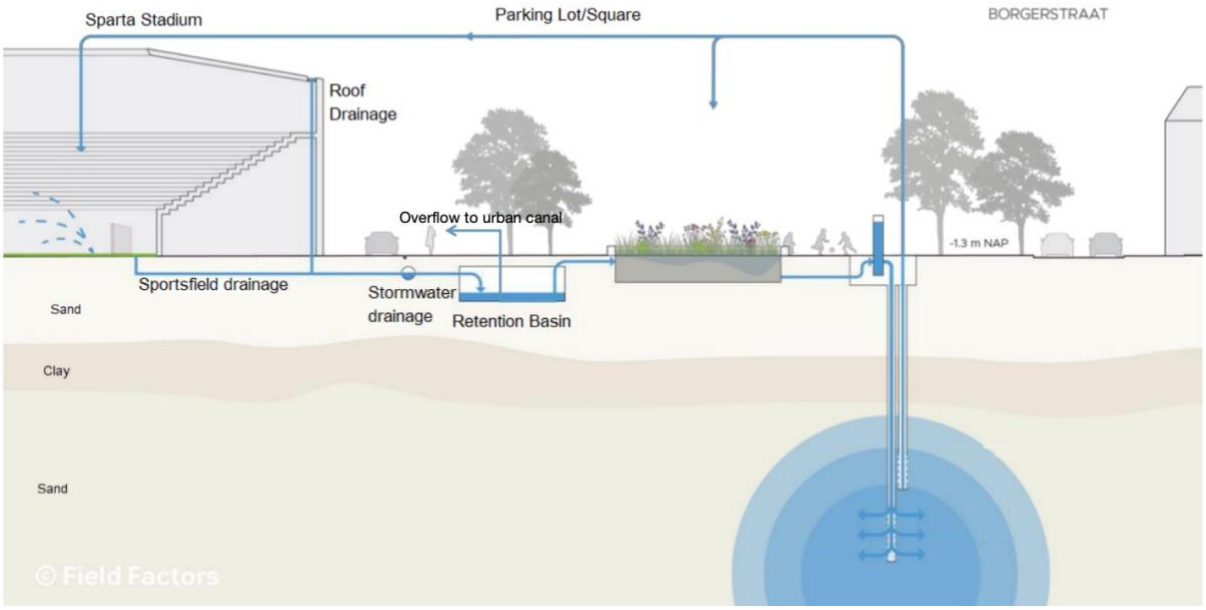

Figure 1.2.1.: Schematic Overview of BlueBloqs system

1.3 Biofilter 2.0

The standard biofilter (bioretention) includes plants, filtration medium, and water collection system at the bottom. The operation of the biofilter is that the influent passing through dense vegetation and then vertically through the soil filtration media. Through processes such as sedimentation, filtration, adsorption, and biological reactions, the treated water can be either discharged directly into natural water bodies or stored for potential reuse. The media varies from the upper to lower layers, consisting of sandy soils with different grain sizes or materials in the biofilter. The species of plants include short grasses, shrubs, and even small trees [6].

FieldFactors biofilter is a multilayer sand filter with a vegetated top surface. The biofilter is planted with wet and drought-tolerant plant species for both their functional and aesthetic qualities.

The biofilter is composed of layers of technical sand with varying grain sizes. The feed water is extracted from the buffer tank through a pumping system and uniformly distributed across the surface of the biofilter. Effluent is collected through a drainage pipe beneath the filter media and then flows over a raised outlet into a collection well. The overflow level is situated at a height of 0.55m from the bottom of the biofilter, creating an internal water storage (IWS) within the biofilter. The dimensions of IWS are 0.55 m in height and a surface area of $1m^2$. The existence of an internal water storage area is crucial for ensuring water quality improvement. The activation and deactivation of the pump to the biofilter can be managed either on-site or remotely through a programmed control system. Pump control conditions primarily include monitoring the flow rates of influent and effluent, as well as the timing of valve opening and closing. Additionally, there is the option of regulating the flow rate based on the conditions of the effluent water quality.

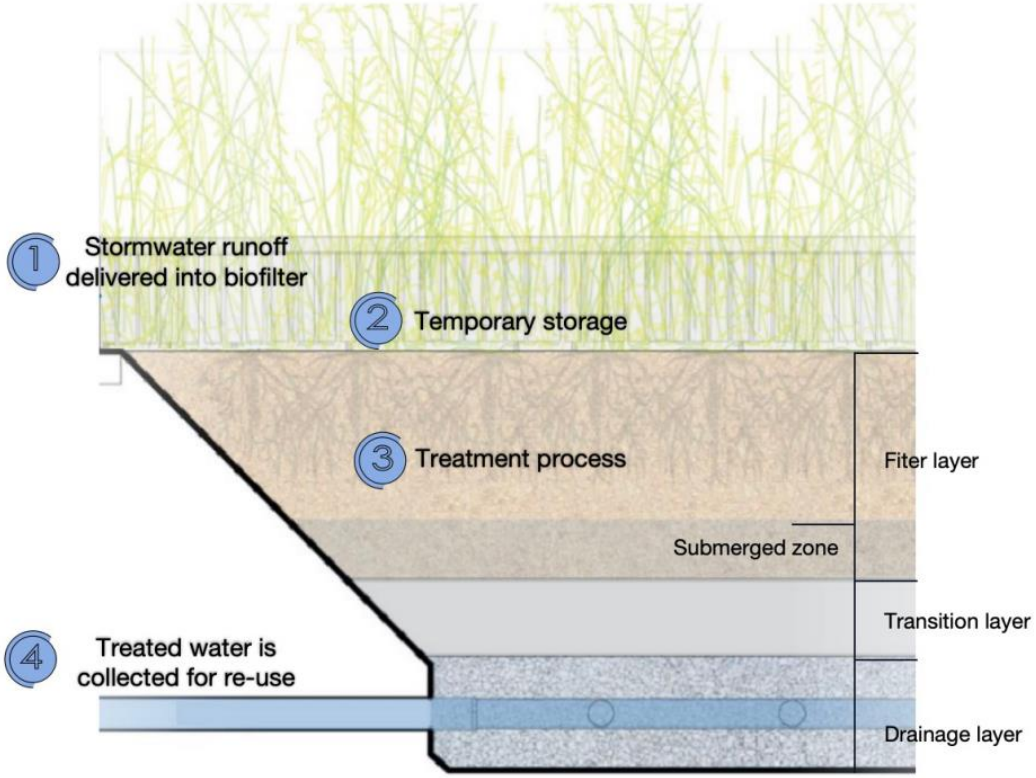

Figure 1.3.1.: Design of the BlueBloqs Biofilter

In comparison to the Biofilter 1.0, the Biofilter 2.0 system changes the biofilter's concrete edge. In the case of the 1.0 biofilter, it receives its influent from a diagonal position along the edge, but this feeding configuration is not optimal for efficiently utilizing the entire filter surface. The 2.0 system was improved with a cascade feed, which evenly distributes the influent across the biofilter. Meanwhile, this cascade configuration has the advantage of increasing the oxygen in the influent.

1.4 Problem statement

Biofilters are considered a popular component in urban landscapes for stormwater management and pollutant treatment. However, there are still unresolved questions in biofilter research. While some scholars have evaluated pollutant removal from biofilters using various materials and media depths under laboratory conditions [7][8], there have been limited studies focusing on established field systems to test the performance of biofilters. This is due to the challenges faced by biofilters in the field, which include a lack of regular maintenance, fluctuations in influent water quality, irregular wet and dry periods, variations in vegetation growth and turnover, and the influence of climate conditions. These practical factors often result in biofilters that deviate from the ideal conditions observed in laboratory conditions [9]. Therefore, it's necessary to perform field measurements and evaluations of biofilters to understand the performance of biofilter systems.

Rapid urbanization has led to an increase in heavy metals in stormwater, posing threats to the water environment and ecosystems. Evaluating the efficiency of biofilters in removing heavy metals has become a main topic. Some scholars have explored the removal mechanisms and efficiency of biofilters for total metals [10]. However, heavy metals in stormwater are classified as particulate or dissolved metals. Dissolved metals, while more challenging to remove than particulate ones, are often more available for biological processes and therefore pose a greater risk [11]. Scholars offer varied perspectives on the removal of dissolved metals by biofilters. Some suggest that biofilters can consistently and effectively remove dissolved metals [12]. Some scholars hold different views, with certain results indicating a leaching effect of dissolved metals in biofilters [13]. Therefore, assessing the efficacy of biofilters for heavy metal removal is a worthwhile direction of research.

Previous research indicates that a biofilter's effectiveness is closely dependent on design factors. In research aimed at enhancing biofilter performance, the primary methods for improving pollutant removal are categorized into static and dynamic optimization. Static optimization involves enhancing water quality by altering the filter media type and proportion, selecting different plant species, and adjusting the media depth [14]. Some scholars have made modifications to biofilter properties and evaluated water quality by varying factors such as media material type, proportion, particle size, and layer depth [7][8]. Furthermore, research has explored the impact of plants with different traits and root systems on water treatment, and these findings have considered biofilter design considerations [9]. Dynamic optimization is achieved by managing the system's hydraulic behavior, which facilitates pollutant removal. However, due to the unpredictability of rainfall, the biofilter experiences varying frequencies of wet and dry cycles. This leads to water being retained for different durations within the biofilter, which was often overlooked in most laboratory studies. These

irregularities result in varying retention times for the water within the biofilter before it is eventually flushed out. However, altering the retention time in the biofilter also results in a decrease in the total volume of effluent. Shen et al. implemented various real-time control strategies to assess the efficiency of biofilters and observed that longer retention times notably enhanced the removal of nutrient, sediment and E. coli. However, longer retention time reduced total water treatment volume in biofilter, which decreased from 28.4% to 5.4% [15]. Blecken et al. explored the impact of retention periods on the removal of heavy metals and found that the removal efficiency of Pb and Zn exceeded 95% when stormwater flowed regularly. However, a retention period of more than three weeks led to a deterioration in the metal removal performance of the biofilter [16]. There is a trade-off between water quantity and quality when controlling the retention time in stormwater reuse systems. Therefore, it is crucial to consider how to find an optimal balance between improving water quality and increasing water quantity.

In the BlueBloqs system, understanding the impact of the retention time on water quality is vital. Beyond its stormwater treatment process, the system includes two main components: rainwater harvesting and effluent recharge. The frequency of wet-dry cycles and the biofilter's retention time influence the size of buffer tank and the overall volume of water designated for recharge. A shorter retention period allows for smaller tanks and facilitates water quality recharges into the aquifer. This is directly related to the investment and cost-effectiveness of BlueBloqs. Therefore, evaluating the operation method and pump regimes of the biofilter can offer valuable instruction for system design optimization [17]. At the same time, a shorter retention time may mean that the removal of pollutants from the water in a biofilter is not sufficient. Longer retention times can enhance the quality of the effluent but lead to a reduced total volume of water. [15]. This needs to be considered a trade-off between water quality and quantity by controlling the retention time of the biofilter.

1.5 Research objective

In the problem statement, it is mentioned that the static and dynamic optimisation in biofilter can lead to changes in water quantity and quality. The cost-effectiveness of the BlueBloqs design process and the estimation of future water reuse are directly related to changes in water quantity and quality. It is essential to assesses static optimisation by analyzing water treatment in a biofilter with the addition of media, comparing it to using only technical sand with two different types of influent water. Additionally, it evaluates dynamic optimisation by assessing treatment performance with different retention times in the biofilter. Therefore, the following research questions are proposed:

- **How much water can be treated and recharged annually while maintaining water quality based on retention time of biofilter?**

The research question is divided into three sub-questions:

1. How much stormwater can be collected by BlueBloqs system in annual rainfall data if the system is operated with different pump regimes?

2. How is the removal efficiency performance of the biofilter with static optimization (different retention times (2, 6, 16, 24 hours), biofilter material, and influent water type)?

3. What's the best operation scenario for a biofilter to maintain both water quality and maximum infiltration volumes?

2. Literature research

2.1 Water quality

2.1.1 Removal Mechanisms

The main purpose of designing a biofilter is to replicate the physical, chemical, and biological processes observed in the natural environment to improve the quality of stormwater and water reuse. The pollutant removal mechanisms include physical filtration, absorption, and biological processes [18].

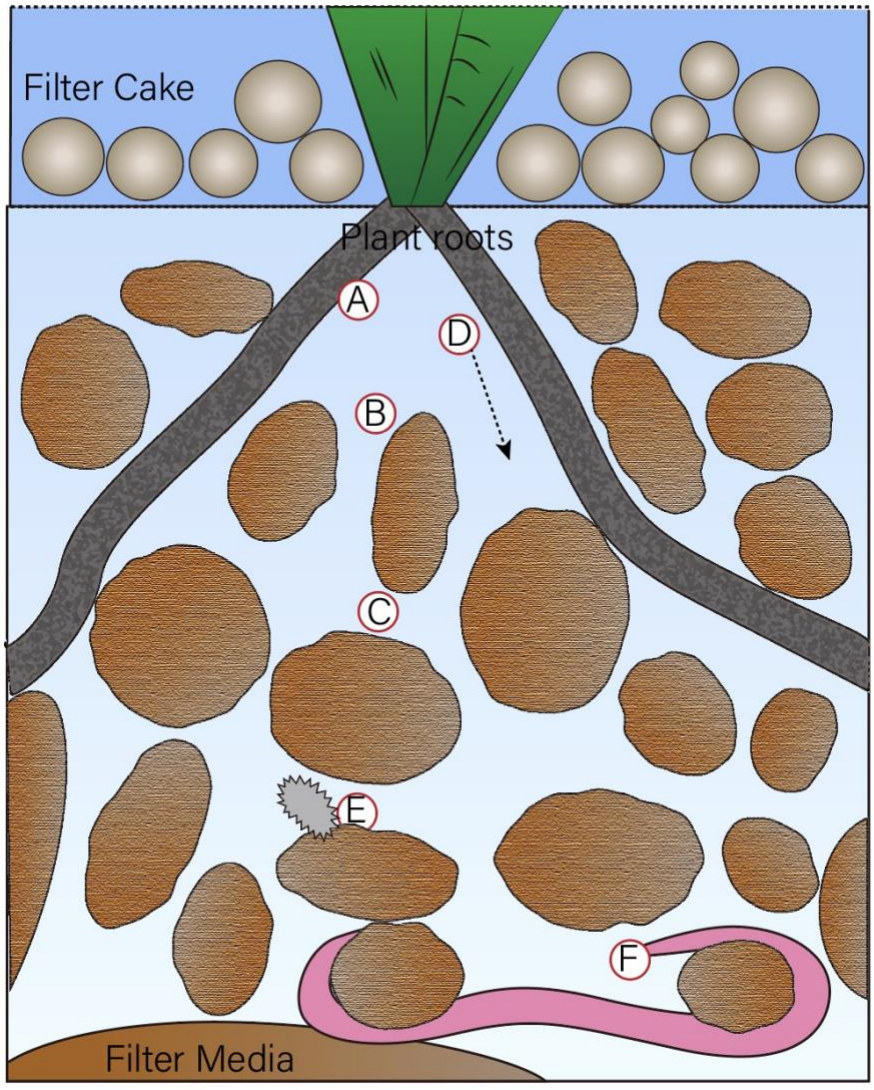

Figure 2.1.1.: Closeup of typical unsaturated biofilter media showing filter cake layer, media grains, pore water, plant roots, and infauna (figure not drawn to scale). Main removal processes removal in a biofilter are denoted by A-F : (A) shows the adsorption to plant roots, (B) shows captured by biofilter media grains, (C) shows thin film straining in a pendular ring of water between grains. (D) shows transport in a preferential flow path alongside plant roots, (E) shows grazing by protozoa, (F) shows ingestion by nematodes. Adjusted from[19][20].

(a) Physical filtration

In a biofilter, the presence of plant roots, mulch, and filler particles establishes a retention effect on the influent, enabling the upper layers of filter media to filter out particulate contaminants.

(b) Adsorption

The attraction between ions immobilizes liquid or dissolved substances on the surface of media with a large specific surface area, such as plant roots and filtration media. These surfaces have the capacity to adsorb pollutants, including NH4-N, phosphorus (P), heavy metals, and more. The decay and decomposition of plants result in the production of humus, which increases the organic matter in the soil. As the organic matter in the soil increases, the soil adsorbs more heavy metals and nitrates [21][22].

(c) Biological process

Biological processes in biofilters include nitrification, denitrification, and biological degradation which is breaking down of chemical compounds by microorganisms in the soil medium. Nitrification is the biological process where bacteria oxidize ammonium into nitrate, a highly soluble form that can be readily absorbed by plants. Denitrification is the process by which bacteria convert nitrate into nitrogen gas, which is then released into the atmosphere. This occurs when soil oxygen levels are low, temperatures are elevated, and there is sufficient organic matter.

2.1.2 Target pollutants

While the pollutants found in stormwater can vary depending on the region and level of urbanization, several key pollutants have been identified as important for analysis. These include particulate matter, nutrients, oil and grease, toxic organic compounds, metals, and microorganisms. Previous research has indicated that the effluent from a biofilter contains low concentrations of suspended solids, nutrients, and heavy metals. Some researchers have explored the efficiency of biofilters in removing pathogens and particulate pollutants. T. M. Jonker has assessed the performance of a biofilter in removing *E. coli* at Spangen Stadium in Rotterdam and modelled E. coli variations under different influent regimes using PHREEQC [23]. Due to limitations in experimental conditions and thesis time, the removal of E. coli and other pathogen in biofilter was not assessed in this study.

(a) Turbidity

Turbidity is a measure of water clarity how much the material suspended in water decreases the passage of light through the water. This metric accounts for light scattering caused by suspended particles and light absorption by solute molecules. The level of turbidity

is influenced by various factors, including the quantity, shape, size, and fraction coefficient of the suspended solids present in the water. Biofilters achieve turbidity reduction through sedimentation and filtration processes, with removal rates often exceeding 95%. However, some studies have indicated that failure happens in some situations. In field experiments, Hsieh et al. discovered that filtration in new established biofilters, or those with improperly graded media, was not as effective at particle removal as initially expected [24]. However, this problem was gradually mitigated as the system stabilized [25].

(b) Nitrogen

Nitrogen in stormwater runoff exists in both organic and inorganic forms. Organic nitrogen is further divided into particulate organic nitrogen (PON) and dissolved organic nitrogen (DON). Meanwhile, the inorganic nitrogen includes ammonium, nitrate, and nitrite. Bioretention systems remove nitrogen through both non-biotic and biotic processes. Non-biotic mechanisms mainly include adsorption, ion exchange, and complexation. On the other hand, biotic processes involve vegetative and microbial actions. As for the removal of organic nitrogen, particulate organic nitrogen (PON) is removed with other particulate materials in the runoff through filtration, adsorption, and retention within the biofilter media [26]. Dissolved organic nitrogen (DON) is transformed into ammonium and nitrate through the process of ammonification [27]. In the removal of inorganic nitrogen, positively charged ammonium readily adsorb onto the negatively charged particles in the biofilter media [28]. Ammonium nitrogen, as well as organic nitrogen that has been converted to ammonium in stormwater runoff, are further oxidized to nitrate by ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) [29]. This process also recreates the capacity of media to adsorb positively charged ions [30]. As a result, the ammonium present in the biofilter is ultimately removed in nitrate. Nitrate within the biofilter can be removed through the denitrification process, converting it to nitrous oxide (N_2O) or nitrogen gas (N_2) [31]. For efficient denitrification, several conditions must be met: the denitrifying microorganisms, an anoxic environment, enough reaction time, and a carbon source. Previous research has indicated that establishing internal water storage can significantly enhance the effectiveness of nitrate nitrogen removal [32]. Through appropriate design, internal water storage in a biofilter can ensure adequate reaction time for denitrification, thereby improving nitrogen removal efficiency. Moreover, numerous strategies have been researched to improve the biofilter's nitrogen removal efficiency. These include adding extra carbon sources, optimizing plant selection, and refining the filler media ratio [31].

(c) Phosphorus

Phosphorus in urban runoff is distributed between dissolved forms (generally organic P and phosphate species) and particulate forms. Phosphorus removal in the biofilter is similar to that of turbidity; particulate phosphorus is mainly removed through physical methods of retention and filtration [33]. In addition, phosphorus in runoff mainly exists in the form of particulate phosphorus [34]. Dissolved phosphorus is removed through processes like adsorption, precipitation, and biological utilization. While plant root uptake and microbial enrichment are commonly used methods for phosphorus removal, it's worth noting that phosphorus absorbed during plant growth could be reintroduced into the soil through plant decay [35]. Some research has indicated that the removal of dissolved phosphorus in biofilters is facilitated by the adsorption and chemical precipitation of metal salts, such as calcium, aluminum, and iron, present in the media material. These metal salts form granulated precipitates, which are then physically removed from the water [36][37][38]. The kinetics of the precipitation reaction are slower than those of the direct adsorption reaction, sometimes taking several days to complete [39]. Due to the limited adsorption capacity of dissolved phosphorus, traditional biofilters show wide fluctuations in phosphorus removal efficiency [40]. This efficiency can generally be improved by modifying the filter material.

(d) Metals

With urbanization on the rise, there's growing concern over the potential toxic effects of heavy metals on organisms and the increasing concentration of heavy metals in stormwater. The forms in which these heavy metals appear in stormwater runoff include particulate, colloidal, or dissolved, which can vary based on environmental conditions [41]. Heavy metals, both in dissolved and particulate forms, are removed from bioretention via interception by the surface media, adsorption within the internal media, and absorption by plant roots. The efficiency of this removal in bioretention is influenced by several factors [30][42]. These include stormwater characteristics, such as pollutant concentration and rainfall duration, as well as biofilter attributes like material type, layer depth, vegetation variety, and the size of the internal storage area.

Hatt et al. evaluated the pollutant removal efficiency of six different biofilter materials and discovered that all soil blends effectively removed over 90% of Cu, Pb, and Zn [43]. Based on field measurements in car parks, Glass et al. discussed how the removal mechanisms of biofilters varied for different heavy metals [44]. Hsieh's research indicates that 56% of Pb in stormwater runoff is removed through adsorption on TSS [45]. Roberson et al. observed that by increasing the organic matter in the soil, there was an increase in the biofilter's capacity to adsorb heavy metals [46]. Kim et al. discovered that submerged zones with organic carbon

sources enhanced the removal of nutrients and heavy metals, with notable removal efficiency for Cu [47].

Muthanna et al. found that biofilters trapped 81–99% of Cu, Pb, and Zn, with only 2–8% of these heavy metals being absorbed by plants [48]. Davis et al. conducted a similar study and discovered that plants absorbed 10% of the total heavy metals removed [49]. Read et al. determined that dissolved heavy metals were absorbed through the plant root system. Furthermore, they discovered that using a mix of plant species was more effective for this uptake than relying on a singular type of vegetation [50].

Furthermore, it's noteworthy that many design manuals related to biofilters primarily focus on pollutants such as TSS, total nitrogen, and total phosphorus, often neglecting the consideration of heavy metals in pollutant removal indicators. In future biofilter designs, there is a critical need to assess the biofilter's capacity to remove heavy metals to enhance and refine the overall design.

(e) UV254 and DOC

Natural organic matter (NOM) is a complex matrix of heterogeneous organic material present in all natural waters. It is derived from decaying terrestrial plants and as a by-product of bacteria, algae, and aquatic plants. NOM is introduced in water sources through interactions between the hydrologic cycle, biosphere and geosphere. Simple techniques such as dissolved organic carbon (DOC), and ultraviolet (UV254) absorbance are commonly employed in quality control. The presence of organic matter influences the removal of other pollutants, such as nutrients, nitrogen, and phosphorus, by impacting plant roots and microbial activity [51]. The performance of the biofilter in organic matter removal was analyzed by measuring the UV254 and DOC concentrations in both the influent and effluent [52].

2.1.3 Key design factors of biofilter

Most stormwater biofilters are passive and experience unsteady conditions, receiving water from rain events. The treatment process includes a combination of filtration, adsorption, and biological processes. The effluent is collected via a pipe located at the biofilter's bottom, and the water is released into a local water body or reserved for future reuse. The influents for biofilters include surface runoff, drainage from parking areas, and stormwater from rooftops in urban areas. As described in section 1.4, optimizing water quality in biofilters involves both static and dynamic optimization. Static optimization includes modifying the filter media, plant species, and depth of internal water storage to enhance pollutant removal. Dynamic optimization focuses on managing the biofilter's retention time. Key design factors for biofilters include:

(**a**) Type of plants

The role of plants in biofilters is essential for several reasons. First, plant roots can directly absorb pollutants like nitrogen and phosphorus to improve water quality [53]. Second, the secretions from plant roots and their large surface area offer both energy and attachment points for microorganisms. This facilitates the growth of microbial communities that further contribute to the uptake and transformation of pollutants within the biofilter [54][55]. Third, the complex root systems of plants serve to reduce the flow and velocity of influent to facilitate its filtration and infiltration [56]. At the same time, the growth and replacement of the root system prevent soil pore clogging and crusting. This maintains the media's porous and permeable structure in the biofilter, ensuring optimal porosity and drainage [57]. Lastly, plants play a crucial role in landscaping, adding aesthetic value to the engineered system.

(**b**) Internal water storage (submerged zone)

The biofilter is efficient at removing ammonium and Kjeldahl nitrogen. Under aerobic conditions, ammonium is converted to nitrate by nitrification. However, nitrate is less easily removed by soil media, resulting in higher nitrate levels in effluent. The internal water storage is built to create an anaerobic zone within the biofilter. This design optimizes conditions for the denitrification process, thereby enhancing the removal of nitrates [58][59]. In addition, internal water storage provides the biofilter with greater resilience against the adverse effects of drought periods. Overall, biofilters with internal water storage exhibited better total nitrogen removal efficiency. During extended droughts, these biofilters recover their nitrogen removal capabilities more quickly compared to those without internal water storage [60].

(**c**) Filtration media

For biofilter media materials, the requirement is that the media be capable of filtering pollutants and have adsorption properties [61]. Second, the media in biofilter serves a dual purpose: it acts as a substrate for plant growth and offers attachment sites for microorganisms. Both the type and depth of the media influence the biofilter's hydrological performance and its efficiency in pollutant removal [62]. To maintain hydraulic conductivity in a biofilter, it is crucial to maintain the infiltration rate of the media within a specific range. On one hand, this ensures rapid drainage of influent, while on the other hand, it provides sufficient retention time to enhance treatment effectiveness and support plant growth [63]. Pollutants like particulates and particle metals are typically removed through filtration in the upper layer, leading to their accumulation on the surface [64]. As a result, the media in the upper part of the biofilter should be regularly maintained and replaced every few years.

(**d**) Retention time

Stormwater events are variable in frequency, quantity, and duration, exposing biofilters to intermittent wetting and drying conditions of varying length. This variability has been ignored by most laboratory studies, which have been based on regular or constant dosing. The varying intervals of stormwater lead to different retention times for water within the biofilter. The efficiency of a biofilter in removing pollutants can be influenced by the retention time [15]. However, research by Hatt et al. indicated that the removal efficiency for TSS, heavy metals, and phosphorus was independent of the retention time. Extended retention time cause soil within the biofilter to dry out and crack. These cracks can lead to preferential flow, where runoff quickly bypasses the media and root system, limiting the contact needed for pollutant removal. While the increased soil oxygen from these dry periods can enhance nitrification (converting ammonium to nitrate), it can hamper denitrification, which requires anaerobic conditions. As a result, the effluent may have higher nitrate concentrations. Moreover, prolonged retention time can cause cell death, releasing nitrogen from the deceased cells and potentially elevating the nitrogen concentration in the outflow, sometimes even surpassing influent [65]. Manganka et al. conducted research on the influence of hydraulic and hydrological factors on the pollutant removal efficiency of a biofilter. Their findings revealed that an extended retention time not only enhances nitrification and improves ammonium removal but also promotes the retention of particulate phosphorus. However, it's important to mention that a longer retention time may lead to an increase in nitrate (NO_3) levels in the effluent [66].

Variations in retention time resulting from fluctuations in rainfall frequency, duration, and total rainfall have been observed to change the redox conditions and microbial growth within the biofilter. These changes impact the biofilter's effectiveness in pollutant removal. However, Blecken's study revealed that retention time lasting three weeks led to a reduction in metal removal. This phenomenon is attributed to factors such as the oxidation of pre-existing heavy metal accumulations and sediment deposition, which subsequently decrease the biofilter's capacity to uptake heavy metals [16].

2.2 Water quantity

2.2.1 Stormwater Management Model (SWMM)

Rapid urbanization has led to a series of challenges, making it necessary to focus on the effectiveness of stormwater drainage and the development of optimal stormwater management solutions. In recent years, several models have emerged for stormwater management based on the fundamental principle of simulating the hydrological process of surface runoff during precipitation using algorithms.

In this study, the SWMM (Storm Water Management Model) was utilized. SWMM is an urban stormwater quantity and quality prediction and management model developed by the U.S. Environmental Protection Agency (EPA). This model performs better at simulating both the quantity and quality of water resulting from single or long-term rainfall events within urban areas. SWMM's simulations include surface runoff, variations in water levels within the drainage network, and changes in volume within storage units. In recent years, the SWMM model has garnered significant attention, with a growing number of scholars conducting case studies with SWMM. [67][68].

2.2.2 Python & SWMM

PySWMM is a Python package designed to interface with the Storm Water Management Model (SWMM). This package enables users to define components, input data, and establish control rules all within Python and show more detailed simulation progress. PySWMM offers functionalities for running simulations and retrieving results, including flow rates, water levels, and pollutant concentrations [69].

In the case study of Cromvliet park from FieldFactors' project, PySWMM was applied to analyze SWMM results. The estimation of water quantity under long-term rainfall events was calculated through various pump regimes and the buffer tank's effective volume. To achieve cost-effectiveness, these water quantity calculations served as critical support for both system design and storage volume determination.

3. System description

3.1 Research area

3.1.1 The Green Village

The Green Village serves as a field laboratory situated to the south of the TU Delft campus. There is an office building for administrative staff, several buildings designated for experiments and equipment storage, and a few residences where individuals live full-time. Within the Green Village, FieldFactors' BlueBloqs demo system is located at the Heat Square. The BlueBloqs collected stormwater from a combined surface area of 1600 m^2, consisting of both pavement and rooftops within the Green Village. The collected water is delivered via drainage pipes to a 10 m^3 retention tank.

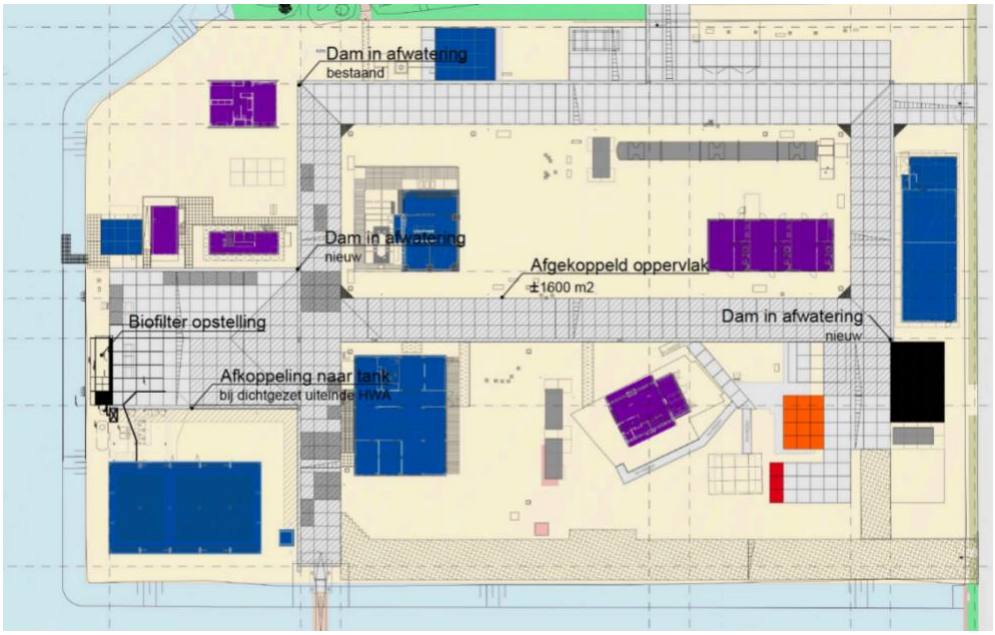

Figure 3.1.1.: The Green Village: Building layout and impermeable surface area for rainwater collection (1600 m^2)

3.1.2 Biofilter in the Green Village

Figure 3.1.2.: Biofilter in the Green Village: From Left to Right - Storage tank, Influent sump, Effluent sump and PLC, 4 biofilters, and Plant test bed.

The collected water is stored in a buffer tank before being pumped at a fixed flow rate of 0.3 m^3/h to four biofilters (A, B, C, and D), each with an area of 1 m^2 and a depth of 1 m. The water from the buffer tank enters the biofilter through an inlet situated centrally above the biofilter and is evenly distributed over the surface via a cascade feed. This influent then sequentially passes through the filtration layer, the transition layer, and finally the drainage layer. A drainage pipe was buried at the bottom of the biofilter to collect the treated water. Effluent was overflowing through an outlet that was 550 mm from the tank's base.

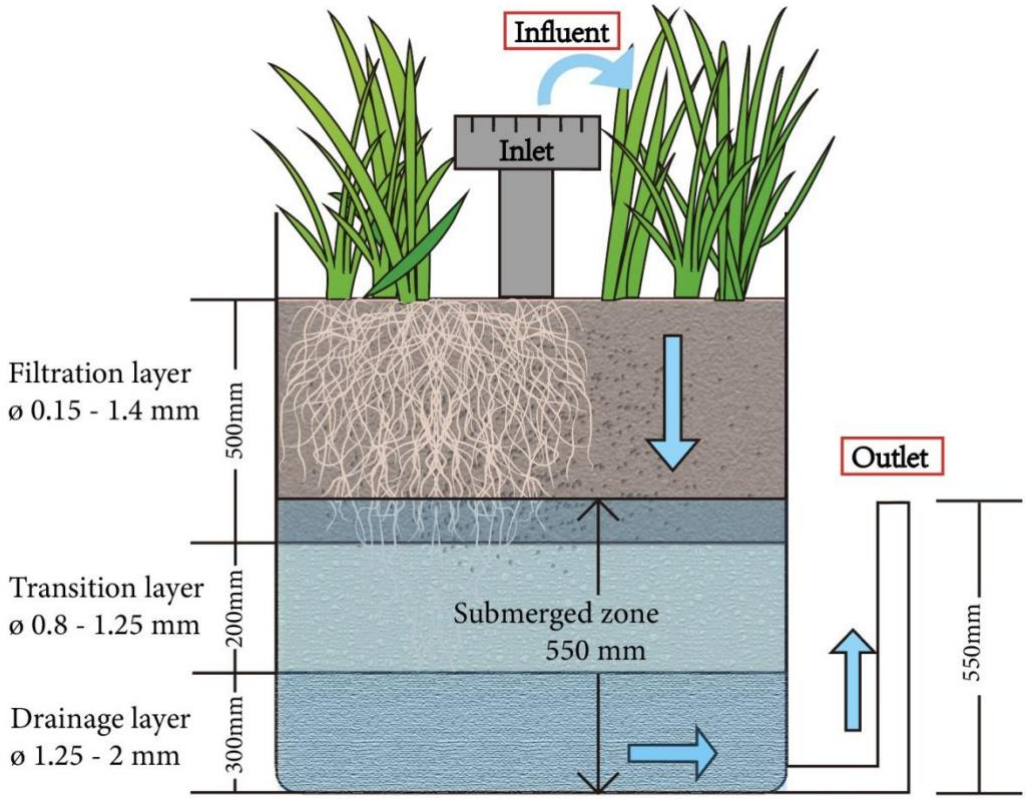

Figure 3.1.3.: Biofilter cross-section: Top to bottom - Vegetation, Central inlet, Filtration layer(depth: 500mm), Transition layer(depth: 200mm), Drainage layer(depth: 300mm), Submerged zone(depth: 550mm), Outlet connecting to the bottom of drainage layer.

Table 3.1.1.: Dimension of BlueBloqs and Biofilter in the Green Village

Dimension of Bluebloqs and Biofilter in the Green Village		
Catchment area	1600	m^2
Buffer tank volume	10	m^3
Number of biofilter	4	-
Pump flow rate to biofilter	4×0.3	m^3/h
Surface area of biofilter	4×1	m^2
Biofilter depth	1	m
Biofilter volume	1	m^3
Depth of filter layer	0.5	m
Depth of transition layer	0.2	m
Depth of drainage layer	0.3	m
Depth of submerged zone	0.55	m
Porosity of biofilter	0.39	-

The materials used in these biofilters are different:

- In biofilter A, 20% of the material consists of MnO, which is mixed with technical sand and placed on the top 30 cm of the filtration layer. The remaining 80% of the material is composed of technical sand.

- In Biofilter C, 20% of the material is MnO mixed with technical sand and is in the top 30 cm of the filtration layer. Additionally, 10% of lime mixed with technical sand is situated 20 cm from the bottom of the filtration layer. The remaining material in the biofilter is technical sand.
- Biofilters B and D are full of technical quartz sand.

Each biofilter overflows its effluent through individual outlets that flow into a single collection well. The collected effluent is used for irrigating vegetation and domestic water within the Green Village.

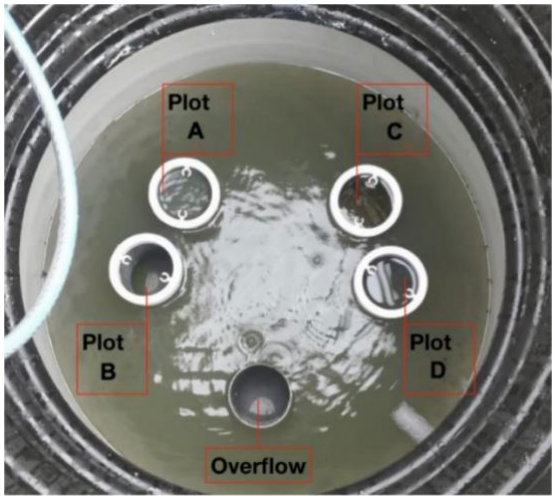

Figure 3.1.4.: Top view of biofilter outlets in effluent sump (Top left: biofilter A; Bottom left: biofilter B; Top right: biofilter C; Bottom right: biofilter D; Centre bottom: Overflow)

3.1.3 Cromvliet Park

Figure 3.1.5.: The Impermeable surface area for rainwater collection at Cromvliet Park (8000 m^2)

Cromvliet Park in The Hague is surrounded by residential buildings and pathways. FieldFactors' BlueBloqs system collects rainwater from both rooftops and road surfaces, covering an area of 8,000 m^2. Furthermore, this system is linked to a nearby urban canal, connecting surface water into a buffer tank via a valve for subsequent treatment and reuse.

The stormwater was collected through a drainage pipe network to a storage tank with a capacity of 75 m^3. This tank is linked to a pump sump. The influent for the biofilter is pumped from this sump via a variable pump. After the water treatment progresses through the biofilter, the effluent is directed to an infiltration well by gravity for both aquifer recharge and reuse.

The biofilter in this system covers an area of 30 m^2 and has a depth of 1 m, filled with technical sand. The effluent is gathered in an outlet well and repurposed for irrigating a local urban garden. In addition, the BlueBloqs system features remote control capabilities, allowing for the manipulation of pump settings and data monitoring remotely.

Table 3.1.2.: Dimension of BlueBloqs and Biofilter in Cromvliet Park

Dimension of Bluebloqs and Biofilter in Cromvliet Park		
Catchment area	8000	m^2
Buffer tank volume	75	m^3
Number of biofilter	1	-
Pump flow rate to biofilter	0-10	m^3/h
Surface area of biofilter	30	m^2
Biofilter depth	1	m
Biofilter volume	30	m^3
Depth of filter layer	0.5	m
Depth of transition layer	0.2	m
Depth of drainage layer	0.3	m
Depth of submerged zone	0.55	m
Porosity of biofilter	0.39	-

4. Materials and Methods

4.1 Pore volume

To determine the time required to flush out water from the internal storage, it's essential to calculate the pore volume of the biofilter. This was established as the duration needed to empty the internal storage. Combining this calculated time with actual tracer experiment measurements can indicate if preferential flow is present within the biofilter and if the biofilter operates as an ideal plug flow. These calculations are based on the biofilter's depth, porosity, and pump flow rate.

$$1 \text{ Pore volume } = \frac{\text{Area}(m^2) \times \text{Depth}(m)}{\text{Flow rate of pump}(m^3/h)} \times \text{Porosity } = \text{X hour(s)}$$

4.2 Tracer test

To test if the biofilter had an ideal plug flow and the water in the internal storage could be fully flushed out through the outlet, two tracer tests were performed on the biofilter before water sample collection. Electrical conductivity (EC) was measured for stormwater, tap water, and surface water, yielding values of 105 µS/cm, 315 µS/cm, and 735 µS/cm, respectively. Because of the considerable differences in EC values, tracer tests were carried out to determine whether the biofilter was a plug flow. This was done to ensure that the water in the internal storage was completely drained out of the biofilter during the next influent event. If there is preferential flow in the biofilter, the water in the internal storage area will mix with the influent, lowering the effluent quality and influencing the experiment results. Tracer testing was performed to verify if the effects of preferential flow are present in the biofilter.

4.2.1 Field tracer measurements

First of all, the biofilter was filled with low-conductivity stormwater. Once the EC in the outlet stabilizes, medium conductivity tap water was introduced to the biofilter's surface via a pump system. At the same time, both the outlet's EC and time were continuously monitored using a sensor at the outlet. The time required for the influent to reach the biofilter's outlet was determined through the calculation of pore volume. To check if there is preferential flow within the biofilter, the time it takes for the EC to change is experimentally measured and compared to the calculated flow time. In the second tracer experiment, the same procedure was performed: high-conductivity surface water was used to flush the biofilter after it has been filled with tap water. The time at which the EC value changes was continuously monitored at the outlet.

The calculations based on the biofilter's dimensions and pump flow rate indicate that the time required to flush out 1 pore volume in an ideal plug flow is 78 minutes ($\frac{1m^2 \times 1m}{0.3m^3/h} \times 0.39 = 1.3h = 78\ mins$). The internal storage water was flushed out in 43 minutes ($\frac{1m^2 \times 0.55m}{0.3m^3/h} \times 0.39 = 0.715h = 43\ mins$) after switching on the pump in case of ideal plug flow. The results about tracer test are shown in chapter 5.2.

4.2.2 Tracer test simulation

The Convection-Dispersion Equation (CDE) is a fundamental equation in groundwater hydrology and environmental engineering, particularly in the context of solute transport in porous media. It describes the transport of solutes by advection, dispersion, and diffusion. The one-dimensional form of the CDE is given by:

$$\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2}$$

where C is the concentration (kg/m^3), t is time (s), v is velocity(m/s), x is length(m), D diffusion/dispersion coefficient (m^2/s).

CXTFIT2.0 is to fit analytical solutions of the one-dimensional convection-dispersion equation (CDE) to tracer breakthrough curves. This allows for the estimation of parameters such as the dispersion coefficient and the pore water velocity. The program CXTFIT2.0 was used to estimate parameters in several models for transport during steady one-dimensional flow by fitting the parameters to observed laboratory or field data obtained from solute displacement experiments. In this research, the curve was adjusted by setting the relevant parameters of the biofilter.

4.2.3 Electrical Balance

In the analysis of water samples, the fundamental principle is that water solutions must be electrically neutral. This means that in real solutions, the total sum of all the positive charges (cations) must equal the total sum of all negative charges (anions) in meq/L.

$$\Sigma\ cations = \Sigma\ anions$$

However, several factors can contribute to electrical imbalances in water analysis, including the presence of unanalyzed species and analytical errors. To quantify and assess these potential errors and the overall quality of water analysis, the Charge Balance Error (CBE) is performed. The CBE represents a relative error in percentage:

$$Electrical\ Balance(E.B.,\%) = \frac{\Sigma\ cations - |\Sigma\ anions|}{\Sigma\ cations + |\Sigma\ anions|} \times 100$$

Another method is estimating the EC from the sum of the anions and the cations separately, using a rule of thumb. Both the anion and cation sums should be 1/100 of the measured EC value [70].

$$\Sigma\ cations\ (meq/L) = \Sigma\ anions\ (meq/L) = EC/100$$

4.3 Retention time measurements

4.3.1 Before measurement

Before the experiment began, the pH, DO (dissolved oxygen), and EC (electric conductivity) meters were calibrated in the water lab. Following the calibration, the influent water was thoroughly mixed, and its physical parameters were measured. The measuring equipment should be securely positioned before monitoring starts. Finally, connected the peristaltic pump to both the battery and the tube.

4.3.2 During measurement

(a) Influent water

Before initiating the experiment at the Green Village, a buffer tank was filled with 4,000L of stormwater. For each retention time (2, 6, 16, or 24 hours), a volume of 250 L (which is 0.55 Pore volume) from this buffer tank was pumped to per biofilter. For each retention time measurement, an influent water sample was taken from the buffer tank 10 minutes before switching on the pump.

Once the measurements were finished and the stormwater was depleted, the buffer tank was emptied. Subsequently, a pump, boasting a flow rate of 2.4 m^3/h, was connected to the nearby surface water at the Green Village. This pump was used to transfer 4,000L of surface water into the buffer tank. The subsequent steps were repeated as stormwater measurements, but this measurement used surface water as the influent.

(b) Sample schedule

This experiment was based on the biofilter located within the Green Village, which had been constructed and operated for two years. The purpose was to analyze the impact of various retention time on the removal of nutrients, metals, and other physicochemical parameters. Four different retention time were established: 2, 6, 16, and 24 hours.

All four biofilters operated at the same flow rate of 0.3 m^3/h at same time. Calculations based on pore volume indicated that the water within the internal storage area would be

flushed out within 43 minutes after there was overflow from the outlet. The effluent will be sampled three times at ten-minute intervals following the overflow. The first flushing process took place between 8 and 9 a.m. Subsequently, after a complete flushing and retention period of 2/6/16/24 hours, the pump was reactivated to flush the water out of the internal storage and collected the effluent samples at the outlet. The influent water was stormwater and surface water.

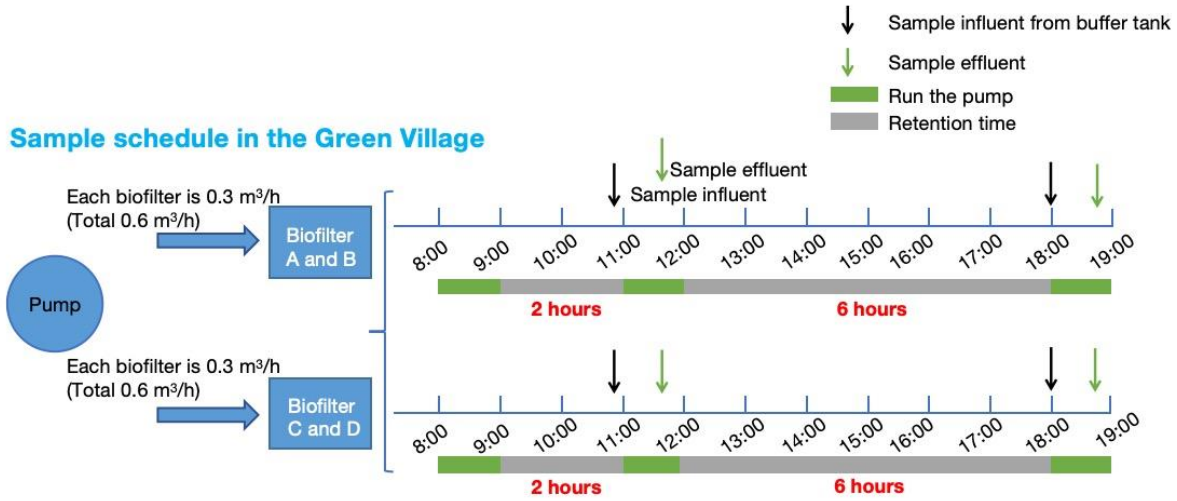

Figure 4.3.1.: Schedule for single sampling day (2 and 6 hours retention time as examples)

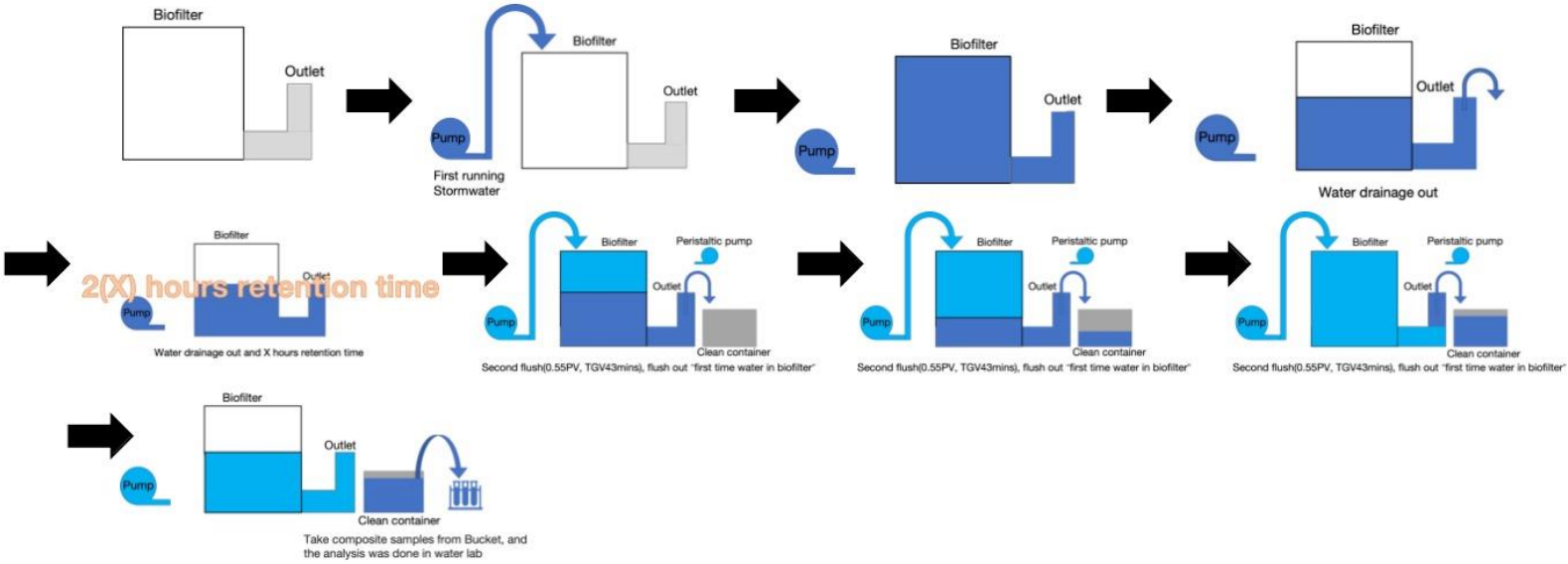

Figure 4.3.2.: Internal water level changes in the biofilter during sampling

(c) Sample process

Following the preparation, influent samples from the buffer tank were gathered using tubes and telescopic rods. Once collected, the water samples were categorized and labelled. The experiment sampled at Green Village. At Green Village, the influent were surface water

and stormwater. During the water sampling in the Green Village, the water samples were stored in a cooler with ice packs. Previous calculations showed that the pore volume in submerged zone was 0.2145 m^3 with a total pore volume for each biofilter was 0.39 m^3. The water in the internal storage was completely drained out of the outlet in 43 minutes. Hence, grab sampling was performed at the biofilter outlets A, C, and D at the same time every 10 minutes. Meanwhile, peristaltic pumping was used to do composite sampling at biofilter outlet B.

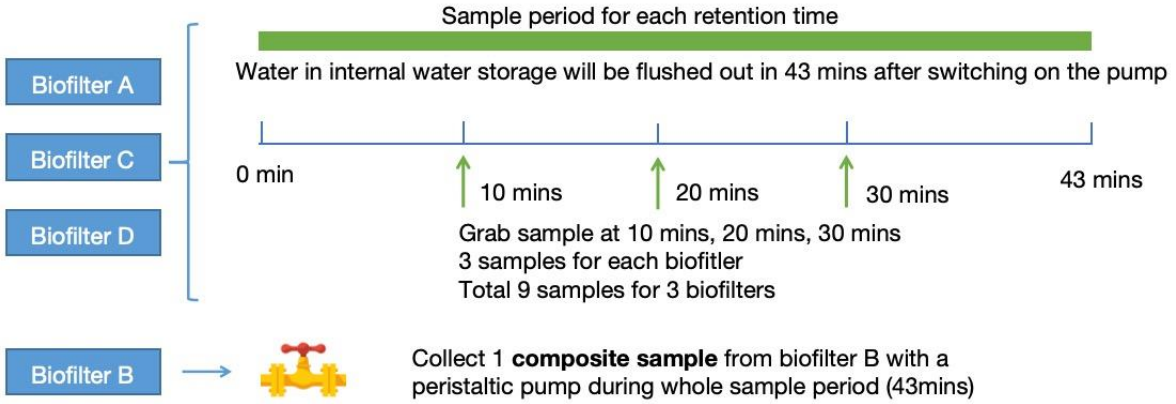

Figure 4.3.3.: Three samples were taken in the A, C, and D biofilters for each retention time at 10-minute intervals. Composite sampling was performed in biofilter B.

4.3.3 After measurement

Water samples were delivered to the water lab within two hours after collection and were subsequently stored under refrigeration. The samples were prepared based on various analytical methods within 48 hours. Water quality analyses for the experiment were performed in the water lab located on the TU Delft and IHE Delft. The parameters analyzed including turbidity, nutrients and select metals, UV254 absorbance, dissolved organic carbon (DOC), and physical water quality parameters such as dissolved oxygen (DO), electrical conductivity (EC), and pH, which were monitored in the field.

4.4 Water quality analysis method

ICP-OES Analysis: The analysis for both dissolved and particulate metals using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was performed at IHE Delft. The filtration threshold for classifying metals between dissolved and particulate is set at 0.45 microns. Dissolved metal samples were obtained by laboratory filtration of water samples. All samples were acidified using 69% nitric acid within a 48-hour window. To prevent any clogging of the ICP-OES equipment, all samples—both for dissolved and total metals— undergo final filtration through a 0.2-micron membrane. Each sample tube was filled with 14.9 ml of the sample, to which an additional 0.1 ml of nitric acid was added. The detection limits for ICP-OES at IHE Delft are specified at the concentrations shown in the Table **4.4.1**.

Table 4.4.1.: Detection limits and upper range of ICP-OES in IHE Delft

Elements/Analytes	Detection Limit (µg/L)
Ca	20 - 200,000
Mg	2 - 100,000
Na	20 - 200,000
K	60 - 500,000
Fe	2 - 10,000
Mn	2 - 10,000
As	10 - 10,000
Al	2 - 1,000
Ba	2 - 10,000
Cu	2 - 50,000
Pb	10 - 10,000
Zn	2 - 1,000
Cd	2 - 5,000
Cr	2 - 25,000
Co	2 - 10,000
Ni	120 - 1,000
Sr	2 - 800

IC Analysis: The ion chromatography analyses were carried out in the Yellow Lab within the water lab on the TU Delft campus. A volume of 5 ml from each sample was filtered through a 0.45 µm membrane filter. Prior to the analysis, blank samples and standards for both anions and cations were prepared.

DOC Analysis: Dissolved Organic Carbon (DOC) analyses was conducted in the Yellow Lab at the Water Laboratory. Samples were passed through a 0.45-micron membrane filter and subsequently acidified with 2 ml of 1% hydrochloric acid within 48h after sampling. Following filtration and acidification, aluminum foil was placed flatly over the top of the bottle, which was sealed with a cap. DOC standards and blanks were prepared using the same way.

UV254 Spectrophotometry: UV254 spectrophotometry was operated in the water lab. 5 ml of the water sample was shaken evenly and added to the quartz cuvette, and then the cuvette was placed into the ultraviolet spectrophotometer to measure the absorbance at the wavelength of 254nm to get the UV254 value of the water sample.

Table 4.4.1.: Equipment and measurement parameters for water quality analyses at the water lab

Water quality analysis	
Equipment	**Parameters**
TOC analyzer	DOC
Turbidimeter	Turbidity
Spectrophotometers	UV254
Aqua Sound	EC, DO, Temperature
ICP-OES	Heavy metals: As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn
IC	Main cations: Ca, K, Mg, Na, Ammonium
	Cl,Br,SO4,NO3,NO2,F,PO4

5. Results & Discussion

5.1 Influent water quality

To assess the pollutant removal performance of the biofilter in BlueBloqs systems, it is crucial to begin with an evaluation of influent water quality. This section will specifically address the pollutant characteristic values for the two types of influents (surface water and stormwater).

The influent water of the biofilter included both stormwater and surface water. Stormwater collection began two months before the experiment started. The surface water was obtained from a river near Green Village. For both the stormwater and surface water trials, eight influent water samples were collected: four from stormwater and four from surface water. All stormwater samples were collected from the same buffer tank, which includes 4000L of stormwater, with all four samples being gathered within the span of a week. Similarly, the surface water samples were also sampled from the same tank, and the sampling was finished within a week. This table below provides an overview of the water quality and its respective ranges for both stormwater and surface water.

Table 5.1.1.: Influent water quality range, N=4 (Left: Surface Water; Right: Stormwater)

Influent: **Surface water**					
		Min	Max	Mean	Unit
Temperature		12.90	21.00	17.80	˚C
Turbidity		1.24	1.52	1.36	NTU
EC		840.00	895.00	875.00	µS/cm
DO		6.69	8.92	7.12	mg/L
PH		6.96	7.20	7.00	-
Cl^-		79.29	93.89	90.97	mg/L
NO_3^-		0.74	1.62	1.08	mg/L
PO_4^{3-}		0.85	2.10	1.63	mg/L
SO_4^{2-}		77.10	80.27	78.48	mg/L
F^-		0.22	0.27	0.25	mg/L
Br^-		0.69	0.76	0.72	mg/L
NH_4^+		0.91	1.02	0.97	mg/L
Na^+		41.49	59.50	55.80	mg/L
K^+		6.51	12.43	9.54	mg/L
UV254		0.40	0.45	0.42	-
DOC		12.34	13.55	12.94	mg/L
Total	Ca^{2+}	100.30	146.85	109.91	mg/L
Dissolved	Ca^{2+}	90.10	128.84	98.15	mg/L
Total	Mg^{2+}	15.50	22.37	18.02	mg/L
Dissolved	Mg^{2+}	12.60	20.27	15.06	mg/L
Total	Al^{3+}	63.79	78.70	71.15	µg/L
Dissolved	Al^{3+}	62.45	68.70	65.41	µg/L
Total	Cu^{2+}	< 2	< 2	< 2	µg/L
Dissolved	Cu^{2+}	< 2	< 2	< 2	µg/L
Total	Mn^{2+}	106.37	80.06	93.67	µg/L
Dissolved	Mn^{2+}	61.95	105.82	82.77	µg/L
Total	Fe^{3+}	34.02	72.20	59.70	µg/L
Dissolved	Fe^{3+}	0.00	12.90	8.43	µg/L
Total	Ba^{2+}	8.47	11.40	10.10	µg/L
Dissolved	Ba^{2+}	8.22	10.30	9.55	µg/L
Total	Co^{2+}	< 2	< 2	< 2	µg/L
Dissolved	Co	< 2	< 2	< 2	µg/L
Total	Ni^{2+}	< 120	< 120	< 120	µg/L
Dissolved	Ni^{2+}	< 120	< 120	< 120	µg/L
Total	Pb^{2+}	< 10	< 10	< 10	µg/L
Dissolved	Pb^{2+}	< 10	< 10	< 10	µg/L
Total	Zn^{2+}	8.50	14.75	11.24	µg/L
Dissolved	Zn^{2+}	7.10	12.54	9.17	µg/L
Total	As^{3+}	< 10	< 10	< 10	µg/L
Dissolved	As^{3+}	< 10	< 10	< 10	µg/L
Total	Sr^{2+}	533.10	589.62	556.50	µg/L
Dissolved	Sr^{2+}	460.48	567.69	511.00	µg/L

Influent: **Stormwater**					
		Min	Max	Mean	Unit
Temperature		12.20	13.50	12.50	˚C
Turbidity		1.12	3.79	2.70	NTU
EC		83.20	85.00	84.50	µS/cm
DO		7.69	9.10	8.60	mg/L
PH		6.50	7.20	6.90	-
Cl^-		2.28	2.49	2.38	mg/L
NO_3^-		< 0.1	< 0.1	< 0.1	mg/L
PO_4^{3-}		< 0.1	< 0.1	< 0.1	mg/L
SO_4^{2-}		2.25	2.82	2.45	mg/L
F^-		0.05	0.07	0.06	mg/L
Br^-		< 0.1	< 0.1	< 0.1	mg/L
NH_4^+		-	-	-	mg/L
Na^+		2.38	4.07	3.31	mg/L
K^+		1.92	4.55	2.85	mg/L
UV254		0.17	0.28	0.20	-
DOC		8.25	12.34	10.65	mg/L
Total	Ca^{2+}	9.44	13.85	12.42	mg/L
Dissolved	Ca^{2+}	6.73	11.08	9.50	mg/L
Total	Mg^{2+}	0.62	1.10	0.88	mg/L
Dissolved	Mg^{2+}	0.35	0.89	0.72	mg/L
Total	Al^{3+}	41.04	50.70	44.52	µg/L
Dissolved	Al^{3+}	27.39	51.40	40.71	µg/L
Total	Cu^{2+}	< 2	< 2	< 2	µg/L
Dissolved	Cu^{2+}	< 2	< 2	< 2	µg/L
Total	Mn^{2+}	18.04	33.70	25.41	µg/L
Dissolved	Mn^{2+}	16.76	25.38	22.72	µg/L
Total	Fe^{3+}	1.84	4.65	2.79	µg/L
Dissolved	Fe^{3+}	1.20	1.70	1.48	µg/L
Total	Ba^{2+}	4.49	5.00	4.69	µg/L
Dissolved	Ba^{2+}	3.07	5.00	4.26	µg/L
Total	Co^{2+}	< 2	< 2	< 2	µg/L
Dissolved	Co	< 2	< 2	< 2	µg/L
Total	Ni^{2+}	< 120	< 120	< 120	µg/L
Dissolved	Ni^{2+}	< 120	< 120	< 120	µg/L
Total	Pb^{2+}	< 10	< 10	< 10	µg/L
Dissolved	Pb^{2+}	< 10	< 10	< 10	µg/L
Total	Zn^{2+}	23.28	60.69	37.22	µg/L
Dissolved	Zn^{2+}	20.17	34.10	25.55	µg/L
Total	As^{3+}	< 10	< 10	< 10	µg/L
Dissolved	As^{3+}	< 10	< 10	< 10	µg/L
Total	Sr^{2+}	37.75	43.90	41.79	µg/L
Dissolved	Sr^{2+}	26.91	43.49	38.31	µg/L

The two tables presented above outline a range of water quality parameters for both stormwater and surface water, including maximum, minimum, and average values (N=4). These water quality parameters are physical parameters, nutrients, and concentrations of both total and dissolved metals.

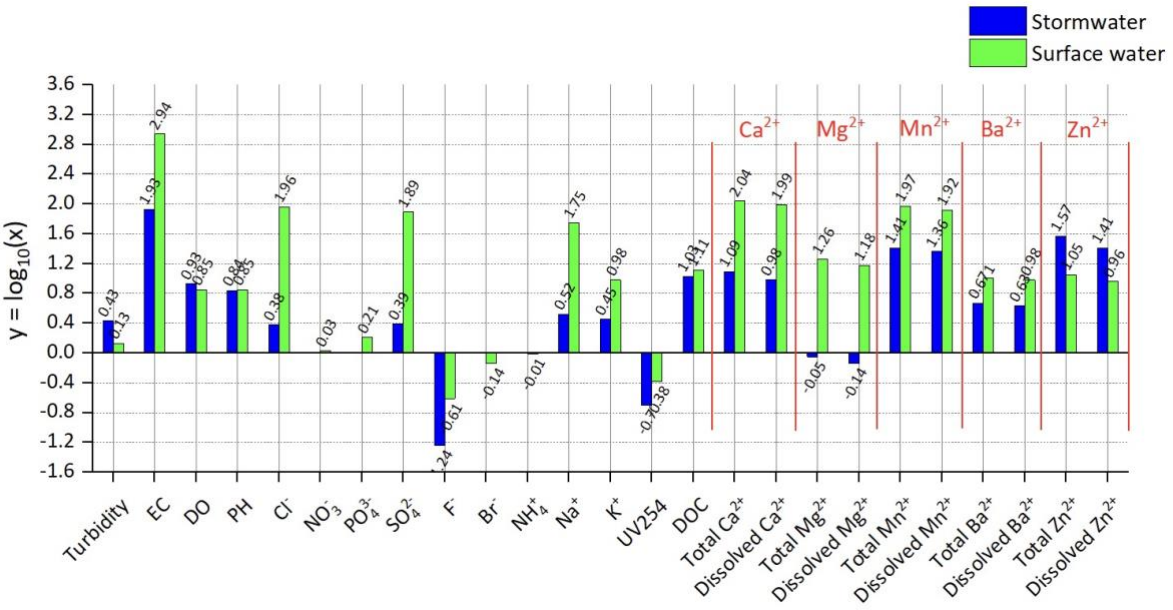

Figure 5.1.1.: Concentration on the $\log_{10}$ scale of stormwater and surface water as influent

In the figure above, the x-axis represents water quality parameters, and the y-axis shows the average concentrations of each parameter on a $\log_{10}$ scale. Stormwater is indicated by blue, while surface water is represented by green.

5.1.1 Stormwater influent water quality

Stormwater was gathered during intermittent rainfall between April and May 2023. It was collected from the pavements and roofs of the Green Village, flowing into the buffer tanks. A total of 4000 liters of stormwater were collected before the measurements commenced. Influent samples were collected from May 8th to May 10th, four times, with varying retention time. These samples were stored in the water lab's refrigerator for cold storage and were analyzed within three days.

Typically, conductivity in stormwater is relatively low. An Australian study assessing stormwater quality found that the median electrical conductivity in stormwater was 183 µS/cm, which is comparable to many drinking water sources [73]. In the Green Village measurements, the average electrical conductivity of stormwater was even lower, at 84.5 µS/cm. The lower conductivity indicates better water quality with lower total dissolved solids and salinity. The lower EC is not surprising, given that the Green Village primarily consists of residential and office areas, and there are no large industrial areas in the neighborhood. Stormwater is mainly collected from pavements and rooftops.

Dissolved oxygen in the measurements exhibited variation, ranging from 7.69 mg/L to 9.1 mg/L, with a mean value of 8.6 mg/L. Stormwater stored in the tank undergoes two primary processes of oxygen consumption. First, oxygen is consumed through microbial aerobic respiration when a sufficient carbon source is available. Secondly, nitrification consumes

oxygen, leading to increased nitrate levels in the stormwater. However, the change in dissolved oxygen in the stormwater was not significant due to the open nature of the rainwater harvesting system, which allowed for ample air contact with the stormwater.

The pH of stormwater exhibited variation, ranging from 6.5 to 7.2, with an average value of 6.9. It's worth noting that stormwater is often characterized as slightly acidic due to its interaction with carbon dioxide in the atmosphere. In general, the pH range of stormwater typically falls between 6 and 9 [74].

The main source of metals in stormwater comes from pollution during the run-off process when stormwater encounters hard surfaces. These typically include roofs, walls, and roads. Dust, animal faeces, plant debris, and metals and carbonates from roofs end up in the collected stormwater. Generally, the quality of stormwater collected by roofs is poorer than the quality of the stormwater itself. The type of roof surface, its smoothness and roughness, and the angle and orientation of the roof all affect stormwater quality. According to a recent study [75], the presence of cadmium (Cd), chromium (Cr), lead (Pb), manganese (Mn), aluminum (Al), and iron (Fe) in stormwater has been identified as a potential risk to human health, even at relatively low concentrations. In the stormwater collected at Green Village, these metals originate from sources such as the ground and roofing materials. It's noteworthy that metals like Cu, Co, Ni, Pb, and Zn were measured below the detection limit. The concentrations of both total and dissolved metals are illustrated in the figure. Among the metals detected, it's evident that dissolved forms were dominant for Ca, Mg, Al, Mn, Ba, and Sr. Specifically, dissolved Fe constituted 53.1% of the total Fe, and dissolved Al accounted for 91.4% of the total Al. This finding contrasts with the study conducted by Sansalone et al. [76], which revealed that in urban stormwater runoff from roadways, Fe and Al were primarily present in particulate form. Pitt and Maestre [77], in their research, reported that the proportion of dissolved zinc (Zn) in stormwater was approximately 45%. The Green Village experiment indicated a higher percentage of dissolved zinc, with its accounting for 68.6% of the total zinc.

The main sources of nitrogen and phosphorus, the primary nutrients found in urban stormwater, include fertilizers, cleaning agents, plant residues, atmospheric deposition, and animal waste. In the Green Village measurements, the concentrations of nitrate and phosphate were found to be below the detection limit of ICP-OES.

Table 5.1.2 shows the average concentrations of metals and nutrients in Dutch stormwater [71][72] and the stormwater results from the Green Village. The results show that the metal and nutrient concentrations in the Green Village are lower than the average concentration for Dutch stormwater, which suggests that the quality of the collected

stormwater in the Green Village is better. Lower concentrations in the stormwater influent could lead to fluctuations in effluent removal efficiency.

Table 5.1 2.: Metal and nutrient concentrations in stormwater runoff in the Netherlands

	Stormwater mean concentration (Dutch data) [71]	Stormwater quality from Dutch residential areas roofs and roads [72]	Measurement results in the Green Village
Cd (µg/L)	-	0.27	<2
Cr (µg/L)	-	6.2	<2
Cu (µg/L)	26	19	<2
Pb (µg/L)	33	18	<10
Ni (µg/L)	-	5.6	<120
Zn (µg/L)	194	102	37.22
Cl (mg/L)	-	18.3	2.38
Ptot (mg/L)	0.42	0.4	<0.1 (PO_4^{3-})
TKN (mg/L)	2.8	1.9	<0.1 (NO_3^-)
SS (mg/L)	49	29.9	-

5.1.2 Surface water influent water quality

Surface water was sourced from the river near the Green Village area. Following the emptying of the stormwater buffer tank on June 4th, 2023, surface water was pumped to the buffer tank on June 5th, 2023, with a 2.4 m^3/h pump. A total volume of 4000 L of surface water was pumped into the buffer tank before the start of the experiment. During the experiment, influent water samples were collected four times between June 5th and June 7th, 2023. Following collection, these samples were delivered to the water lab for storage and subsequent water quality analysis, all of which took place within three days.

The conductivity of surface water is influenced by the area through which the water flows, and groundwater inflows can have a similar effect depending on the bedrock. Typically, surface waters have conductivities ranging from 200 to 1500 µS/cm. In the surface waters of Green Village, the electrical conductivity (EC) varied between 840 and 895 µS/cm across the four measurements, with an average EC of 875 µS/cm.

The dissolved oxygen (DO) concentration in surface water fluctuated between 6.69 mg/L and 8.92 mg/L, with an average value of 7.12 mg/L. Notably, the DO concentration in the surface water held in the buffer tank was slightly lower than that in stormwater. Two potential reasons may explain this difference. First, surface water tends to have a higher microbial population compared to stormwater, and the aerobic respiration of these microorganisms can consume dissolved oxygen. Second, the average temperature of the surface water was higher than that of the stormwater due to the experiment being conducted during the

summer. An increase in temperature can lead to a reduction in the amount of dissolved oxygen in the water.

The pH of surface water ranged from 6.69 to 8.92, with an average value of 7.12. Surface water pH tends to be more variable than stormwater pH. The fluctuations in surface water pH can be influenced by various factors, including soil types, the activity of plants and animals in the vicinity, and the presence of carbon dioxide in the air. It's important to recognize that pH variations in water can have an impact on the removal of metals through adsorption in the biofilter.

In surface water, both the total and dissolved concentrations of metals were notably higher compared to stormwater. Notably, concentrations of copper, cobalt, nickel, lead, and arsenic in surface water were below the detection limits. For all other metals except zinc, the concentrations in surface water were nearly ten times higher than in stormwater. The lower zinc concentrations in surface water can be attributed to its primary source, which is typically the flushing of zinc from roof or wall materials [78]. Unlike stormwater, where dissolved iron constituted 14.1% of the total iron concentration, surface water mainly contained iron in the form of particulates. In surface water, most of the other metals were in dissolved forms.

The nitrogen and phosphorus levels in surface water were higher than those in rainwater. The average nitrate concentration in surface water was 1.08 mg/L, and the average phosphate concentration was 1.6 mg/L. The elevated phosphate concentrations observed may result from several factors. The elevated phosphorus concentrations could be attributed to seepage between groundwater and surface water [79]. Increased algal growth was noted in the sampled water body. The absence of rainfall in the two to three weeks before sampling could have led to nutrient accumulation [80]. Additionally, frequent bird and swan activity in the water body, along with human use of chemical fertilizers, might have also contributed to the high phosphorus levels [81]. The increase in nitrogen in the water can be attributed to factors such as animal activity in the nearby river and the density of plant cover in the area. These factors contributed to the elevated nutrient levels observed in surface water.

5.2 Accuracy of sum of cations

To assess the accuracy of the analysis, the accuracy of sum cations was calculated based on the cation concentrations measured in the influent water. As titration experiments for alkalinity were not conducted, it was determined to utilize 1/100 of EC equals the total sum of cations in meq/L to check the accuracy of sum of cations.

The table 5.2.1 presents the calculations of accuracy based on the sum of cations in the influent water. When the influent water was stormwater, the sum of cations measured 8.856

meq/L, resulting in an error of 1.353%. This small error falls within a reasonable range, which can be attributed to the low concentration of ions in stormwater and its relatively low salinity. For surface water influent, the sum of cations was 9.731 meq/L, yielding a higher error of 11.212%. This increase in error could be due to the higher ion concentration in surface water. The error may be influenced by the higher sodium concentration in the influent water, which could lead to an overestimation of calcium levels as measured by ICP-OES. In addition, the four sampling times were spread across different days of the week, resulting in variations in ion concentrations in the influent samples.

Table 5.2.1.: Sum of cations and accuracy results for two different types of influent water

Influent type	Sum of cations(meq/L)	Accuracy(%)
Stormwater	0.856	1.353
Surface water	9.731	11.212

5.3 Tracer test results

The simulation of tracers requires the setting of specific parameters in the biofilter to simulate the change in influent and effluent electrical conductivity over time. This was done by setting the influent and effluent conductivities and porosity of the biofilter. Due to the uncertainty of the longitudinal diffusion coefficient of the biofilter, the longitudinal diffusion coefficient of the biofilter and the influent pump flow velocity were changed by the trial-and-error method to obtain the minimum standard deviation. The simulation curves were made to fit the measured results as perfectly as possible. The deviations between the fitted and measured results account for measurement errors and short-circuiting in the biofilter.

The simulation analysis revealed that the simulated results were close to the measured data. The effluent EC began to change approximately 43 minutes after there was an effluent overflow from the outlet, stabilizing around 75 minutes. The porosity of the biofilter in the equation is 0.38, deviating from the original design value of 0.39. As the biofilter has been in operation for two years, it's reasonable that the biofilter's porosity has slightly changed due to frequent operations, accounting for the difference between the simulation and the field measurements.

Table 5.3.1.: Parameters for tracer test simulation using CXTFIT 2.0.

CXTFIT2.0 Parameters			
EC of Stormwater	105	[µS/cm]	Electrical Conductivity of Stormwater (Measured)
EC of Tap water (First tracer test	315	[µS/cm]	Electrical Conductivity of Tap water (Measured)
EC of Tap water (Second tracer t	435	[µS/cm]	Electrical Conductivity of Tap water (Measured)
EC of Surface water	725	[µS/cm]	Electrical Conductivity of Surface water (Measured)
Porosity	0.38	[-]	Porosity (Fixed)
v	0.83	[m/h]	Velocity (Optimise)
α(Stormwater/Tap water)	0.32	[cm]	Longitudinal Dispersivity (Optimise)
α(Tap water/Surface wayer)	0.94	[cm]	Longitudinal Dispersivity (Optimise)
R	1	[-]	Retardation Factor (Fixed)
k	0	[1/h]	Decay coefficient

(a) Stormwater flushed with tap water

The figure 5.3.1 presents measured data from the first tracer experiment (depicted as dots) and simulation results using the CDE equation (illustrated as a line). The experiment was performed by filling the submerged zone with low-conductivity stormwater (EC: 105 µS/cm), followed by flushing it with tap water (EC: 315 µS/cm), while monitoring the changes in conductivity at the outlet. Based on the simulation results, the dispersivity is calculated to be 0.32 cm. Considering the depth of the biofilter is 1 m, the dispersivity accounts for less than 1% of the depth. This small value could be attributed to the initial run of the biofilter. With subsequent wetting processes, there might be a gradual increase in dispersivity over time [82].

Based on previous calculations, the water within the submerged zone was expected to be flushed in 43 minutes, with a total flushing time of 78 minutes for the entire biofilter. The measured results indicate that the water in the submerged zone was flushed out in 46 minutes, and the complete flushing of the biofilter was achieved in 76 minutes. Although there is a minor error between the measured and simulated results, it falls within an acceptable range. The CDE-simulated conductivity results for the middle conductivity value (EC: 210 µS/cm) corresponded to a time of 54 minutes after switching on the pump, whereas the measured value at this conductivity corresponded to a time of 55 minutes. When the change in EC at the outlet reaches a middle value (210 µS/cm) there is a 1 minute discrepancy between the simulated and measured results corresponding to this middle change point of EC. Potential sources of error include measurement inaccuracies in the EC meter and the mixing of stormwater and tap water at the outlet's corner. Despite these errors, the experiment with the tracer demonstrated the plug-flow of the biofilter.

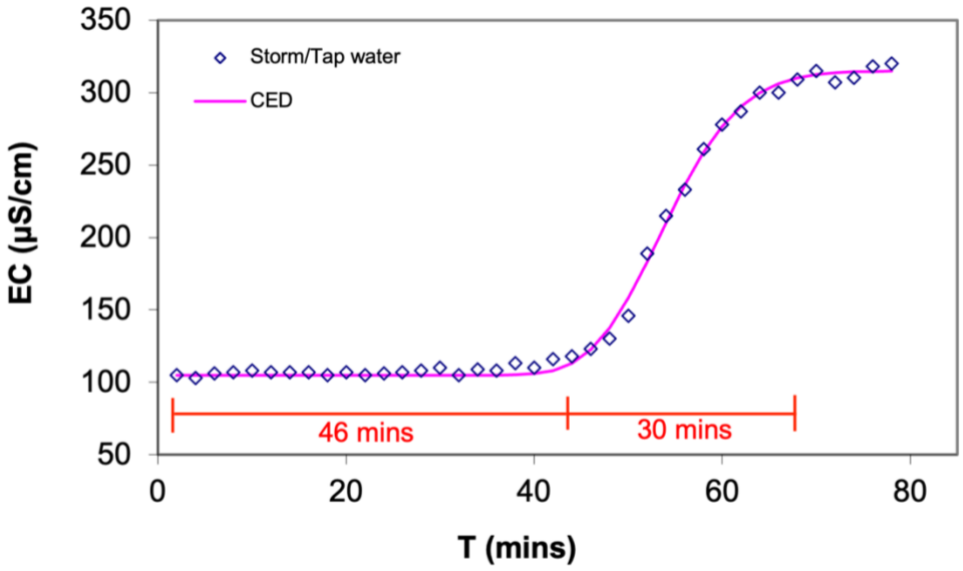

Figure 5.3.1.: First tracer test: submerged zone filled with stormwater and flushed with tap water (measured data and simulated results)

(b) Tap water flushed with surface water

In the figure 5.3.2, both the measured and simulated results of the second tracer experiment are displayed. The experimental procedure was the same as the first tracer experiment. The biofilter was flushed with surface water (EC: 725 µS/cm) after the submerged zone was filled with tap water (EC: 435 µS/cm). According to the simulation results, the dispersivity of the biofilter is 0.94 cm, which is approximately 1% of the depth of the biofilter. This indicates a slight increase in dispersivity compared to the first run. Perfect et al. conducted an evaluation of 69 soil columns across six soil types, finding dispersivity estimates ranging from 1 to 192 mm [83]. Notably, the dispersivity for sandy clay in their study was around 1 cm, which aligns with the results simulated in the biofilter, which is predominantly composed of technical sand.

The measured results showed that the water in the submerged zone was flushed within 42 minutes, and the entire biofilter was completely flushed in 75 minutes. It's worth mentioning that the time corresponding to the middle value of conductivity (EC: 580 µS/cm) in the simulation results was 53 minutes, while the measured results for this conductivity level corresponded to 51 minutes. When the change in EC at the outlet reaches a middle point (580 µS/cm) there is a 2 minute discrepancy between the simulated and measured results corresponding to this middle point of EC. In contrast to the first measurement, there was an error between the measured and simulated results in this second experiment. The reason for this error is that the second tracer experiment was performed after the first one. The biofilter

could not have been completely dry after the initial wetting, leading to a faster rate of change in electrical conductivity.

In summary, the results of the two tracer tests indicate that the biofilters at Green Village are not perfect plug-flow biofilters but closed to the plug-flow. In the two tracer experiments, the time discrepancy between the simulated and measured results was 1 minute and 2 minutes, respectively, when the electrical conductivity reached the middle change point. But the errors are still within the acceptable range for a system that has been built for over two years, and biofilters can be reasonably approximated as plug-flow.

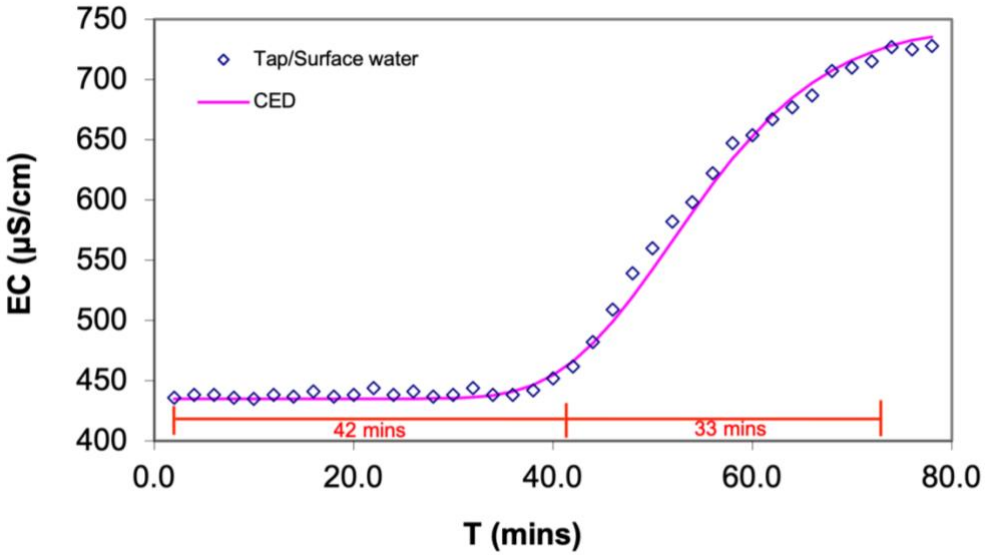

Figure 5.3.2.: Second tracer test: submerged zone filled with tap water and flushed with surface water (measured data and simulated results)

5.4 Turbidity removal

In the experiment, the turbidity removal efficiency of four different material biofilters (A, B, C, and D) is depicted in the following graphs: These biofilters were tested under two different influent conditions (surface water and stormwater) while also considering varying retention time (2 hours, 6 hours, 16 hours, and 24 hours).

Influent was stormwater:

The influent had an average turbidity of 2.7 NTU, while the turbidity in the effluent ranged from 0.44 to 1 NTU when the influent was stormwater. The average removal efficiencies for retention time of 2–16 hours were concentrated in the range of 40–90%. Biofilter D exhibited the highest removal efficiency at 93% at 16 hours retention time, while the lowest removal efficiency of 33% was observed at 24 hours retention time for biofilter C. However, the overall removal efficiency at 24 hours was slightly lower due to the frequent operation of biofilter, resulting in a decrease in the turbidity of the influent. In the field measurements by Huang and Allen [82], it was found that continuous inflow led to a slight increase in total suspended solids in the effluent compared to intermittent inflow.

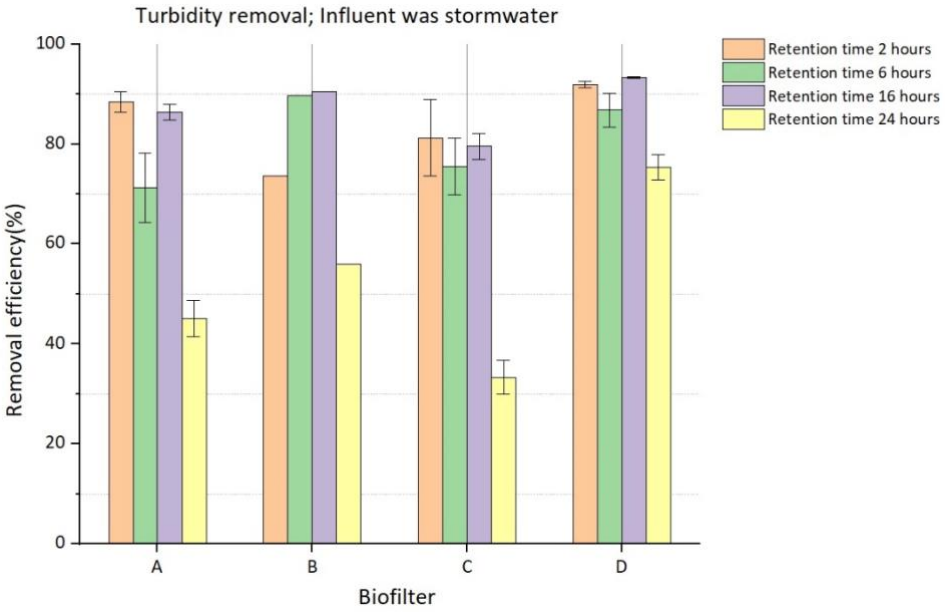

Figure 5.4.1.: Turbidity removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

Influent was surface water:

When the influent was surface water, the turbidity removal efficiency exhibited a range of variations, with an average removal efficiency primarily falling within 40–70%. Biofilter A achieved the highest removal efficiency at 73% at 16 hours retention time, while the lowest removal efficiency of 44% was observed for biofilter B at 6 hours retention time. The removal

efficiency of the biofilters for turbidity experienced a slight decrease during the extended retention time of 24 hours. The influent average turbidity was 1.36 NTU. The turbidity in the effluent ranges from 0.42 to 0.72 NTU. This longer time resulted in the settling of suspended solids in the buffer tank.

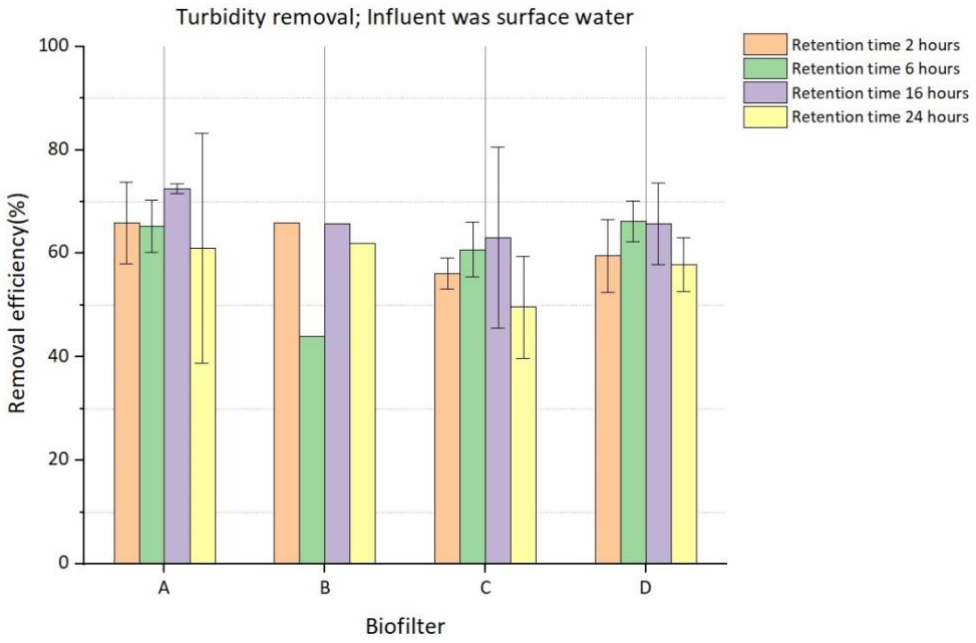

Figure 5.4.2.: Turbidity removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

Based on the measured results, the biofilter demonstrated effective removal capabilities in both stormwater and surface water, even when the turbidity in surface water was higher than that of stormwater. Turbidity removal in the biofilter occurs through interception, as larger suspended particulate matter is captured by soil particles and retained within the filtration media. Muha et al. discovered that in biofilters, the removal of turbidity and total suspended solids demonstrated a significant correlation, with an R^2 value of 0.89 [85]. Various factors, including different retention time, influent water types, and the type of biofilter material, showed no significant impact on turbidity removal. The experiment results indicate that the biofilter was effective in removing turbidity from the influent water, consistent with findings from previous studies by other scholars [86][87].

5.5 Nitrate and ammonium removal

This section discusses the variations in NO_3^- and ammonium removal efficiency of the biofilter under different retention time when surface water is used as the influent. In addition,

NO_3^- and ammonium was not detected in stormwater. This section focuses on surface water as the influent.

Influent was surface water:

When the influent consisted of surface water, the ammonium concentration was detected at 0.97 mg/L. However, in the effluent from all four biofilters across four different retention times, no ammonium concentration was detected. This suggests complete removal of ammonium in the biofilter. Nitrogen transformation in the biofilter is complex, including processes like assimilation, nitrification, and denitrification [88], each occurring at varying rates [89]. The mutual effects of plants, soil, and microorganisms in biofilters create favorable conditions for nitrogen removal. Moreover, plants can absorb and assimilate inorganic nitrogen, primarily NH_4^+ and NO_3^-. Assimilation is a process where microorganisms transform NH_4^+ or NO_x^- into microbial cell mass or plant biomass, temporarily storing it as organic nitrogen. Another way of removing NH_4^+ from the biofilter involves nitrification, a process where NH_4^+ is first converted to NO_2^- and then to NO_3^- under aerobic conditions [90].

The influent's nitrate concentration varied from 0.74 to 1.62 mg/L, while in the effluent, it varied from 0.6 to 1.2 mg/L. The figure 5.5.1 illustrates the NO_3^- removal efficiencies of the four biofilters at varying retention time when using surface water as the influent. The results highlight the significant impact of retention time on nitrate removal efficiency. Nitrate removal ranged from 12% to 49% during short retention time of 2 and 6 hours. However, at longer retention time of 16 and 24 hours, the removal efficiency exhibited a declining trend, with effluent NO_3^- concentrations surpassing influent levels (-84-13% in 16 hours retention time and -6-0% in 24 hours retention time.)

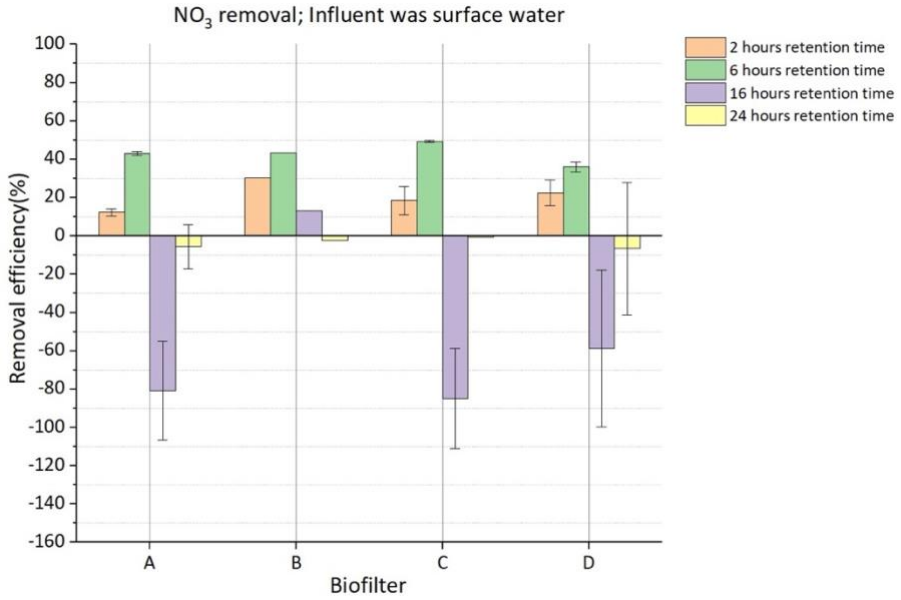

Figure 5.5.1.: Nitrate removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

This change can be attributed to the initial removal of NO_3^- by plant roots and microbial assimilation, causing a reduction in NO_3^- concentration in the effluent. As microbial assimilation and plant root uptake reached their maximum capacity, nitrification reactions under aerobic conditions became more active, resulting in an increase in NO_3^- concentration [29]. NO_3 is negatively charged and cannot be absorbed by soil particles, so it has high mobility in biofilter system and is easy to leach out along with next influent feed cycles [91]. This leaching phenomenon accounts for the increase in effluent NO_3^- concentrations observed at the 16 and 24-hour retention time. The table below presents the dissolved oxygen concentration in the influent and effluent water, with the dissolved oxygen sensor placed in biofilter B. As the retention time increases, there is a rise in the consumption of dissolved oxygen from 1.02 to 5.01 mg/L. Microbial respiration and nitrification contribute to the consumption of DO. The nitrification by which the ammonium was oxidized to nitrate led to nitrate leaching over longer retention times. The slower rate of denitrification led to a longer retention time for the denitrification reaction. The slight increase in removal efficiency at the 24-hour retention time, compared to the 16-hour retention time, could be attributed to the occurrence of the denitrification reaction at the longer retention time.

Table 5.5.1.: Dissolved oxygen in influent and effluent at 2 to 24 hours retention time, influent is surface water

Influent: Surface water				
Retention time (h)	2	6	16	24
DO in buffer tank (mg/L)	7.48	9.21	7.14	8.23
DO in submerged zone (mg/L)	6.46	7.85	4.27	3.22
Changes in DO (ΔDO)	1.02	1.36	2.87	5.01

In previous studies, the efficiency of biofilters in removing nitrate (NO_3^-) varied widely, ranging from -766% to 99%, depending on the materials used [92]. However, this study did not observe a significant correlation between NO_3^- removal and biofilter material (biofilters B and D: technical sand. A: MnO and technical sand. C: MnO, lime and technical sand). Nevertheless, there are several potential methods for enhancing NO_3^- removal, such as optimizing the biofilter material, increasing the outlet height, introducing organic carbon sources, and reducing the influent load [88].

5.6 Phosphorus removal

Influent was surface water:

The influent had an average phosphate concentration of 1.6 mg/L, with the effluent's concentration ranging from 0.5 to 1 mg/L. The figure 5.5.2 displays the phosphorus removal efficiencies of the four biofilters at varying retention time when surface water served as the influent. As previously mentioned in Section 2.1.2(c), phosphorus exists in the form of particulate phosphorus, and its removal is achieved through interception. It's worth noting that some effluent phosphorus concentrations analyzed by IC in the experiment measurements were missing.

During retention time ranging from 2 to 16 hours, the biofilters demonstrated high phosphorus removal efficiency, ranging within the 60–70% range. However, at 24-hour retention time, the phosphorus removal efficiency in the biofilters decreased. Biofilter A and D removal efficiencies are 35% and 14%, respectively, while Biofilter B showed negative removal (-22%). Previous studies suggest that the “rapid-reversible” sorption reactions predominate when water flows through the media, while “slow-irreversible” adsorption interactions continue to occur between events [33]. Through these reactions, part of the P rapidly bound to reversible sites will be relocated to more irreversible sites, which frees rapid reversible sites for uptake during the next rainfall event. According to Hsieh and colleagues [93], who observed that as the loading of phosphorus increases, the removal efficiency gradually decreases. field evaluations have shown that P becomes tightly bonded to the media over time and is mostly present near the top of the media layer [94].

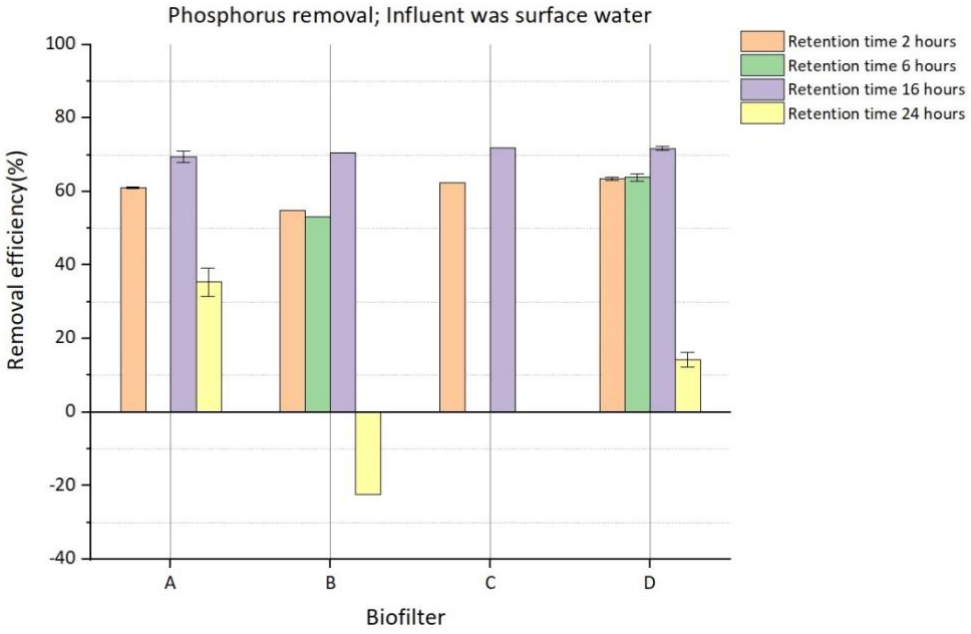

Figure 5.6.1.: Phosphorus removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

5.7 Metals removal

5.7.1 Mn removal

This section discusses the performance of four biofilters (mixed-material biofilters A: MnO + technical sand and C: MnO + lime + technical sand; single-material biofilters B and D: only technical sand.) in removing dissolved and particulate manganese under two different influent types (surface water and stormwater) with various retention time (2 hours, 6 hours, 16 hours, and 24 hours).

Influent was stormwater:

When stormwater served as the influent, the mean concentration of dissolved Mn in the influent water was 22.5 µg/L, with the concentration of dissolved Mn in the effluent ranging from 0 to 4.9 µg/L. All four biofilters consistently exhibited high removal rates for dissolved manganese, with removal efficiencies ranging from 84% to 100%. In contrast, the removal efficiency for particulate manganese was more variable in stormwater. In the influent, the average concentration of particulate Mn was 1 µg/L, while the concentration of particulate Mn in the effluent varied between 0 and 1.2 µg/L. The lowest removal was observed in the 24-hour biofilter C, reaching only 11%. The variability in particulate manganese removal efficiency in stormwater could be that the influent concentration of manganese in stormwater is approximately one-fourth that in surface water. The lower influent concentration leads to a wider range of manganese removal efficiencies.

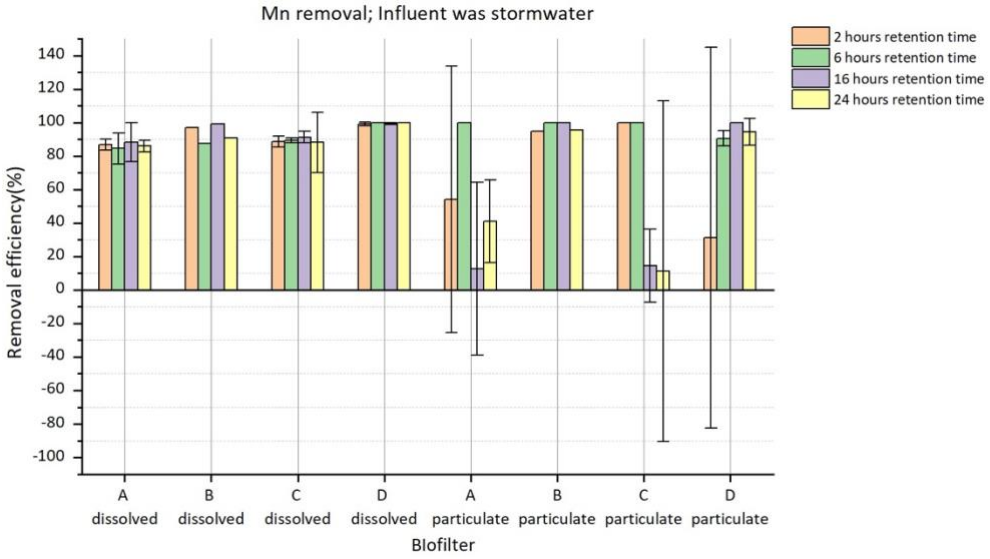

Figure 5.7.1.: Mn removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

The results showed that the biofilter exhibited efficient adsorption of manganese. Idrees et al. found that manganese removal efficiency exceeded 80% when biochar was introduced, particularly at a pH level of 6 [95]. Due to the low concentration of H^+, there is less competition for the adsorption of manganese on negatively charged adsorption surfaces. However, at lower pH levels, manganese adsorption efficiency decreases. This decline is attributed to excess H^+ in acidic influent, which surrounds sorption sites, thereby reducing the adsorption capacity. Ali et al. found that the optimal pH for manganese removal was 7 [96]. Similarly, an increase in pH to 8 led to a reduction in manganese adsorption, primarily due to the precipitation of $Mn(OH)_2$ complexes. The higher removal efficiency of manganese can be attributed to the fact that the influent pH of both stormwater and surface water during the experiment was approximately 7.

Influent was surface water:

When the influent was surface water, all four biofilters consistently demonstrated high removal efficiency for dissolved manganese over four different time periods, with removal efficiencies nearing 100%. This indicates that biofilters are effective in removing dissolved manganese. The average concentration of dissolved Mn in the influent was 82.8 µg/L and the concentration of dissolved Mn in the effluent varied between 0-1.2 µg/L in the four biofilters.

The average concentration of particulate Mn in the influent was 10.9 µg/L, and the concentration of particulate Mn in the effluent varied between 0-0.4 µg/L in the four biofilters. As for particulate manganese, the biofilters initially displayed high removal efficiency with shorter time intervals. However, during the 16-hour retention time, biofilters C and D

exhibited a slight reduction in particulate manganese removal efficiency, 85% and 80%, respectively.

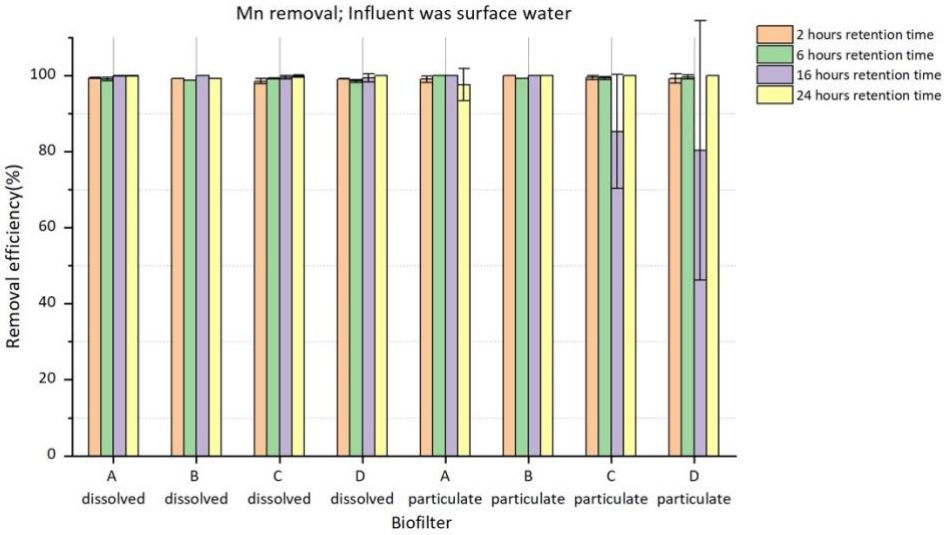

Figure 5.7.2.: Mn removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

5.7.2 Ca removal

This section discusses the removal efficiencies of the biofilters for dissolved and particulate calcium with varying retention time when the influents were both surface water and stormwater.

Influent was stormwater:

The influent had an average dissolved calcium concentration of 9.5 mg/L when the influent was stormwater, while in the four biofilters, the effluent's dissolved calcium concentration ranged from 8.5 to 25.1 mg/L. The removal efficiency of dissolved calcium consistently showed negative values with different biofilters and retention time (except a 22% removal efficiency observed in the 2-hour retention time for biofilter B). This suggests that biofilters are generally ineffective in removing dissolved calcium from stormwater. For particulate Ca, the influent's average concentration was 2.9 mg/L, and in the effluent, it varied between 0 and 5 mg/L. The changes for the removal of particulate Ca in removal efficiency were more variable. While effective removal of particulate Ca was observed, there were still two times that the removal efficiency was negative (the 2-hour and 24-hour retention time for biofilter B, -13% and -100%). The reason for the variance in removal efficiency is the significantly lower calcium concentration in stormwater compared to surface water, leading to a wide range of removal efficiencies.

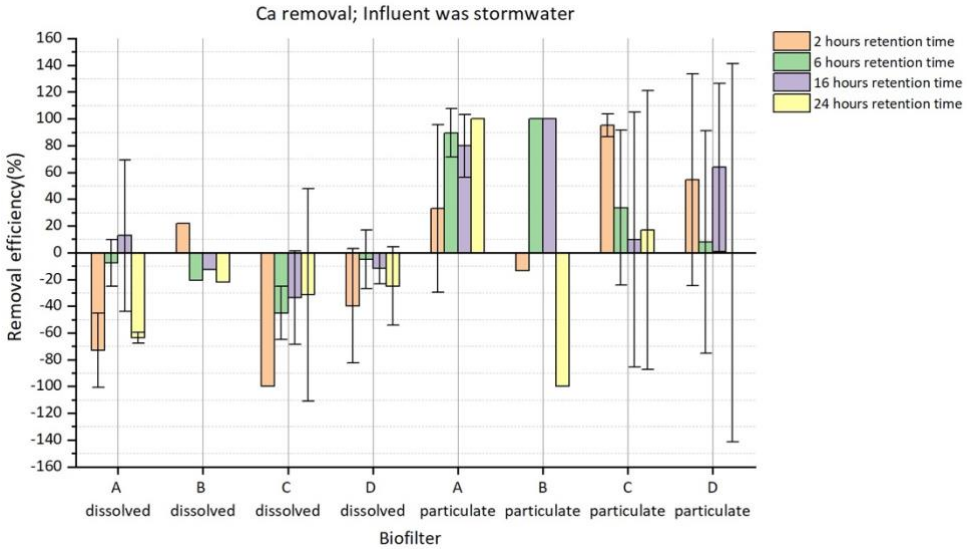

Figure 5.7.3.: Ca removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

Influent was surface water:

The average concentration of dissolved Ca in the influent was 98.2 mg/L, with the effluent showing a range of 60.4 to 120.0 mg/L when influent was surface water. The removal efficiency of dissolved calcium exhibited a wide range between 4% and 32%. Negative removal was observed four times, specifically at the 2-hour retention time in biofilter B (-2%), the 16-hour retention time in biofilter B (-17%), the 16-hour in biofilter C (-8%), and the 16-hour in biofilter D (-4%).

The average concentration of particulate Ca was 23.9 mg/L in the influent and varied between 0.08 and 27.4 mg/L in the effluent. In comparison, biofilters showed slightly better removal of particulate calcium than dissolved calcium. The removal of particulate calcium varied from 77% to 90% within the 2–16-hour retention time in biofilters A, B, and D, but negative removal efficiency was observed at 24 hours (-30% in A, -100 in B, -5 in D). Mixed-material biofilters A (MnO + technical sand) and C (MnO + lime + technical sand) demonstrated higher removal efficiencies in surface water compared to single-material biofilters B and D (technical sand). MnO's high specific surface area and crystal structure enhance its adsorption capabilities [97]. Lime is commonly used as a method for water softening and hardness reduction in water treatment processes, and its presence in the biofilter contributed to the enhanced removal of particulate calcium. A study conducted by Luo et al. analyzed the adsorption mechanism of lime using X-ray spectroscopy (EDS) and found that the primary elements adsorbed on the surface of lime were calcium, iron, aluminum, and silica [98].

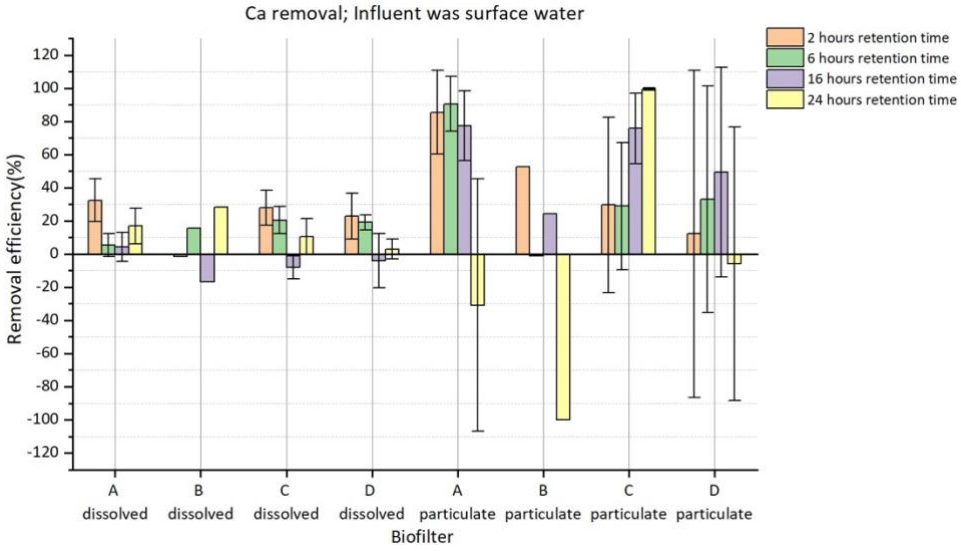

Figure 5.7.4.: Ca removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

Overall, the biofilters demonstrated effectiveness in removing particulate calcium, while the removal of dissolved calcium was not significant and fluctuated (-17% to 32%). The removal of particulate calcium in the biofilter occurs through adsorption by the surface of the

filtration media. The addition of MnO and lime enhanced the adsorption of particulate calcium within the biofilter, resulting in improved removal efficiency. It's important to note that metals adsorbed on organic matter within the biofilter media are not permanently bound. Processes like the leaching of organic matter, which includes dissolution or biotransformation, can lead to the release of adsorbed metals [99].

5.7.3 Mg removal

In this section, the efficiency of the biofilters in removing both dissolved and particulate magnesium with varying different retention time is discussed.

Influent was stormwater:

When the influent was stormwater, the influent's average concentration of dissolved Mg was 0.7 mg/L, with the effluent ranging from 0.6 to 2 mg/L. The removal efficiency of dissolved magnesium showed negative values with different biofilters and retention time. As for particulate Mg, the influent averaged 0.16 mg/L while the effluent varied from 0 to 0.5 mg/L The removal efficiency of particulate magnesium showed fluctuating changes, ranging from -33% to 100%. These variations in removal efficiency did not appear to be significantly correlated with the material of the biofilter. The reason for the large standard deviation and uncertainty in removal efficiency was the low concentration of magnesium in the influent stormwater. This lower concentration contributes to the fluctuating changes in removal efficiency.

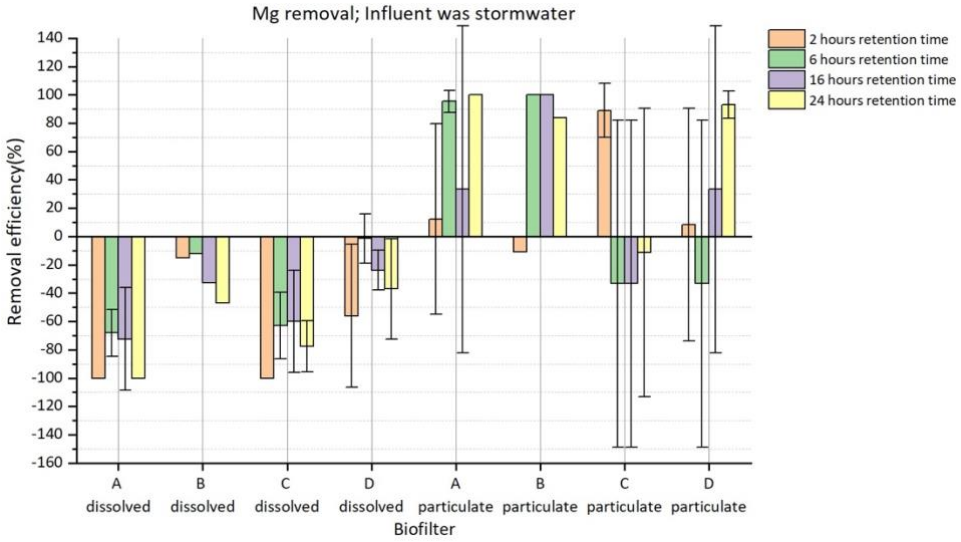

Figure 5.7.5.: Mg removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

Influent was surface water:

When the influent was surface water, average dissolved Mg concentration in the influent was 15.06 mg/L, with the effluent ranging from 6.1 to 17.8 mg/L The removal efficiency of dissolved magnesium showed a range from 12% to 52%, with only one time of negative removal occurring at the 2-hour retention time in biofilter B (-6%). For particulate Mg, the influent's average was 3.8 mg/L, while in the effluent, it varied between 0.02 and 7.2 mg/L. The mixed material biofilters (A: MnO and technical sand and C: MnO, lime and technical sand) performed better than the single material biofilters (B and D, only technical sand) at the 2, 6, and 16-hour retention time. However, negative removals were observed at the 24-hour in biofilters A (-44%), B(-100%), and D(-12%).

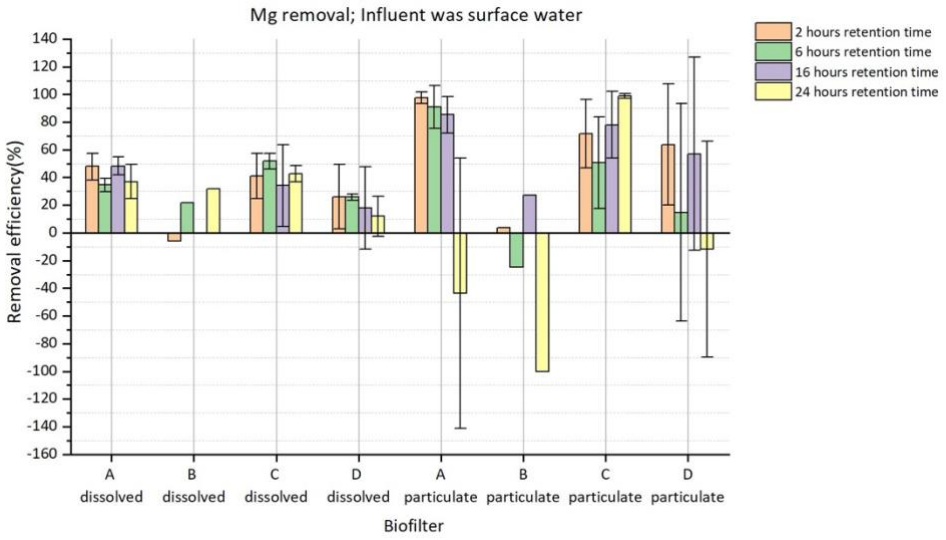

Figure 5.7.6.: Mg removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

5.7.4 Ba removal

This section discusses the removal efficiencies of dissolved barium and particulate barium by the biofilter with different retention time when the influents are both surface water and stormwater.

Influent was stormwater:

The mean concentration of dissolved Ba in the influent was 4.3 µg/L when influent was stormwater, and in the four biofilters, the concentration of dissolved Ba in the effluent varied from 1.3 to 6.3 µg/L. Effective removal of dissolved barium from stormwater was observed in all four biofilters, with only two times the negative removal efficiencies (specifically, the 2-hour biofilters B and D). Additionally, the average concentration of particulate Ba in the influent was 0.43 µg/L, with the effluent exhibiting a variable concentration of particulate Ba

ranging from 0 to 1.6 µg/L. For particulate barium, the biofilters showed effective removal, but there was three times negative removal (6-hour biofilter D: -18%, 24-hour biofilter A: -8%, and B: -100%). The wide range of standard deviation in removal efficiency for particulate barium suggests that when the influent was stormwater, there was a fluctuation in removal efficiency. The lower concentration of particulate barium in stormwater leads to fluctuating changes in removal efficiency.

Barium tends to form insoluble salts with common environmental components like carbonates and sulphates, making it relatively immobile [100]. Like manganese, the concentration of H^+ affects the adsorption sites of metals and soil particles. Higher pH levels cause barium to precipitate. The optimal adsorption of barium occurs at a pH range between 6 and 7. Additionally, the duration of contact time also plays a role in barium removal. Ghaemi et al. discovered that the uptake of barium by dolomite is rapid during the first 60 minutes [101].

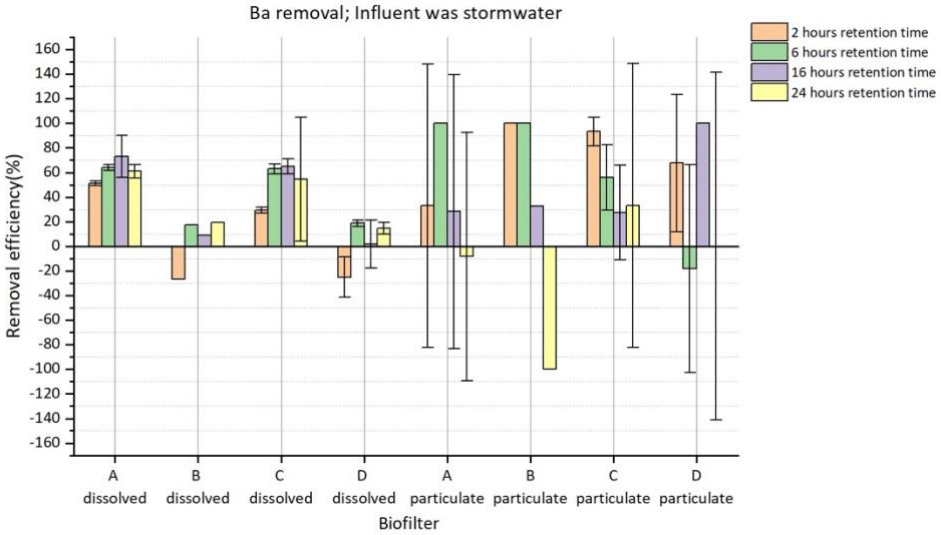

Figure 5.7.7.: Ba removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

Influent was surface water:

When the influent was surface water, the mean concentration of dissolved Ba in the influent was 9.5 µg/L. While in the four biofilters, the concentration of dissolved Ba in the effluent varied from 5.3 to 30 µg/L. Biofilter B and D consistently showed negative removal (-58% to -100%) of dissolved barium over four time periods. As for biofilters A and C, biofilter A achieved only 34%, 30%, and 19% removal at 2, 6, and 16 hours, respectively. These results

showed that the biofilter has limited efficiency in removing dissolved barium when the influent was surface water, and the removal efficiency fluctuated.

Additionally, the average concentration of particulate Ba in the influent was 0.6 µg/L, with the effluent showing an average particulate Ba concentration ranging from 0 to 0.88 µg/L. As for the removal of particulate barium, four biofilters showed effective removal of barium with different retention time. Negative removal efficiency was not observed, and the removal efficiency showed fluctuations, varying between 20% and 100%. The removal efficiency of particulate barium was independent of retention time and materials, indicating that the biofilter is capable of efficiently removing particulate barium.

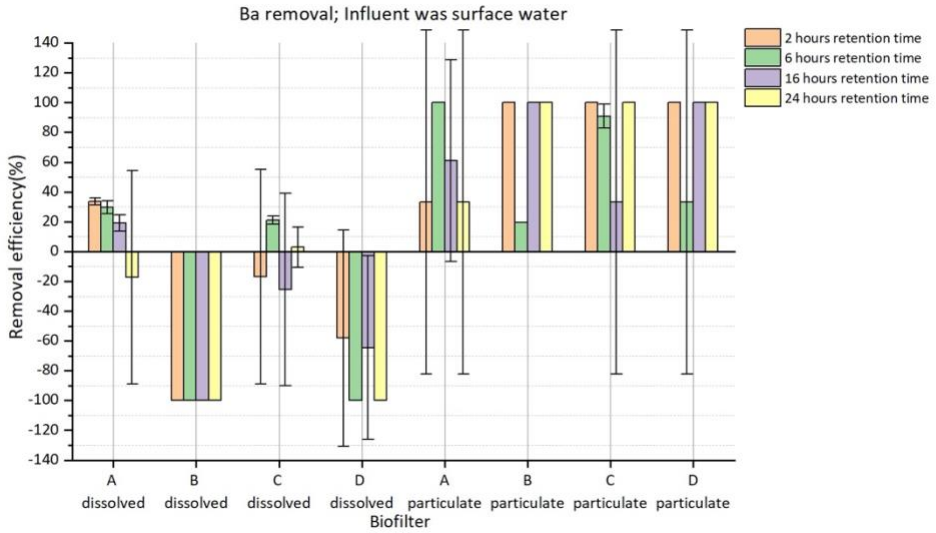

Figure 5.7.8.: Ba removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

5.7.5 Zn removal

This section discusses the removal efficiencies of dissolved and particulate zinc in four biofilters with different retention time when the influent was surface water and stormwater.

Influent was stormwater:

The influent's average dissolved Zn concentration was 25.5 µg/L, with the effluent's concentration ranging from 8.7 to 20.8 µg/L. All four biofilters consistently demonstrated effective removal of dissolved Zn across all four time periods without negative removal efficiencies. However, the removal efficiencies for dissolved zinc are higher at 2–16 hours compared to 24 hours for all biofilters. For particulate Zn, the influent averaged 3.5 µg/L, while the effluent varied from 0.02 to 5 µg/L. Negative removal efficiencies for particulate zinc are observed three times: the 2-hour biofilter B (-36%) and the 24-hour biofilters A (-16%) and C (-1%). The range of effective removal efficiencies for particulate Zn varied from 29% to 100%.

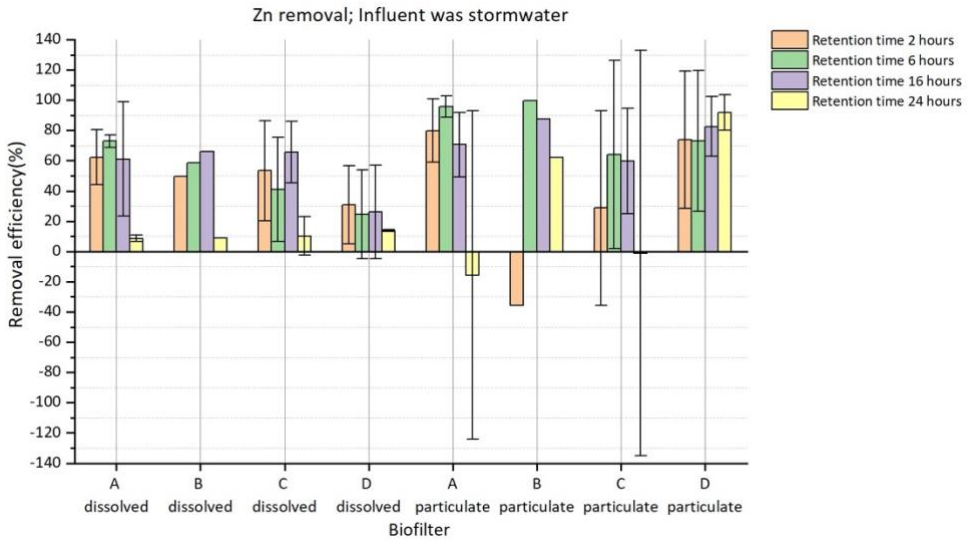

Figure 5.7.9.: Zn removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

Influent was surface water:

The influent's average concentration of dissolved Zn was 9.2 µg/L, while the effluent's ranged from 9 to 15.7 µg/L. The removal efficiency of dissolved zinc by the biofilters resulted in negative values (-15% to -87%) for the retention time ranging from 2 to 16 hours. Only biofilters A and D showed effective removals at 24 hours, with efficiency of 26% and 19%, respectively. For particulate Zn, the influent averaged 2.1 µg/L, and the effluent's average concentration varied between 0 and 4.1 µg/L. All four biofilters consistently achieved

effective removal over all four time periods. The lowest removal efficiency observed was 7%, which occurred in biofilter A at 24 hours.

Zinc primarily exists in a dissolved form in stormwater [77]. Katharina et al. found that although biofilter did not have a significant removal pattern for most dissolved metals, it was able to achieve 65% removal efficiency for dissolved zinc [102]. The higher removal efficiency of dissolved Zn in stormwater than surface water is due to the higher concentration of other metals in surface water, which compete for adsorption sites. Abd-Elfattah and Wada studied the competitive adsorption of heavy metals in soil. Their analysis identified the specific order of adsorption preferences for heavy metals in soil as follows: Cr > Pb > Cu > Cd > Zn, and Pb > Cr > Cu > Cd > Ni > Zn [103]. The adsorption of Zn in soil ranked lower among the metals, which also illustrates the competition between the metals for adsorption. Esfandiar et al. evaluated the removal of metals by adsorbents in a stormwater system and found that the adsorption removal efficiency (from highest to lowest) was single-metal > multi-metal > multi-contaminant solutions, and the removal efficiency ranking among metals was Cr≈Cu≈Pb > Ni > Cd > Zn [104].In addition, Esfandiar found the removal efficiency of loamy sand in biofilter for Zn decreased significantly in the multi-metal condition compared to the single solute tests [30].

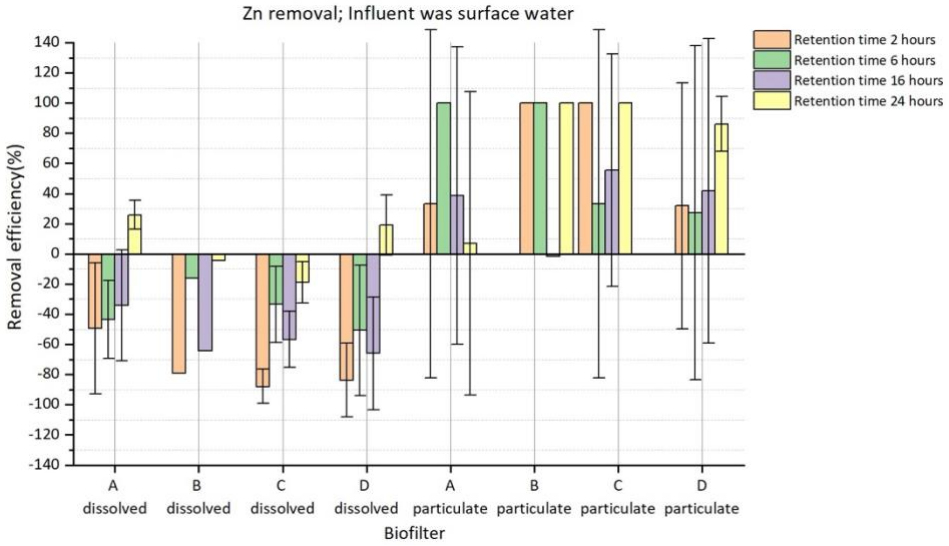

Figure 5.7.10.: Zn removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

5.8 UV254 & DOC removal

This section addresses variations in the removal efficiency of UV254 and DOC when both surface water and stormwater are used as influents. UV254 and DOC are sensitive indicators of changes in organic matter within the water.

5.8.1 Stormwater as influent for UV254 & DOC

Influent was stormwater:

In the influent, the average UV254 value was 0.2 and the mean DOC concentration was 10.6 mg/L. In the effluent, UV254 values ranged from 0.04 to 0.2, and DOC concentrations varied between 4.4 and 11.5 mg/L. In the results for UV254 with stormwater as the influent, it's evident that the removal efficiencies for single material biofilters B and D (technical sand) remained close to zero or even turned negative between 2 and 16 hours. Only the removal efficiency increased at 24 hours of retention time in biofilters B and D. In contrast, mixed material biofilters A (MnO and technical sand) and C (MnO, lime and technical sand) consistently demonstrated effective removal at all four time periods, with biofilter A ranging from 68% to 83% and biofilter C from 24% to 85%. However, it is important to note that there were some errors in the DOC and UV254 stormwater samples. Storing water samples in the refrigerator for more than one week may have influenced the accuracy of the results. In a study of biofilters made of biochar-pyrite and biochar-woodchip, the results showed a correlation between the removal of organic matter and the biofilter material [105]. Many scholars have also identified the effective removal of organic matter by biofilters in experiments with various materials [106][107][108]. Moreover, the removal efficiency slightly increased with the longer retention time.

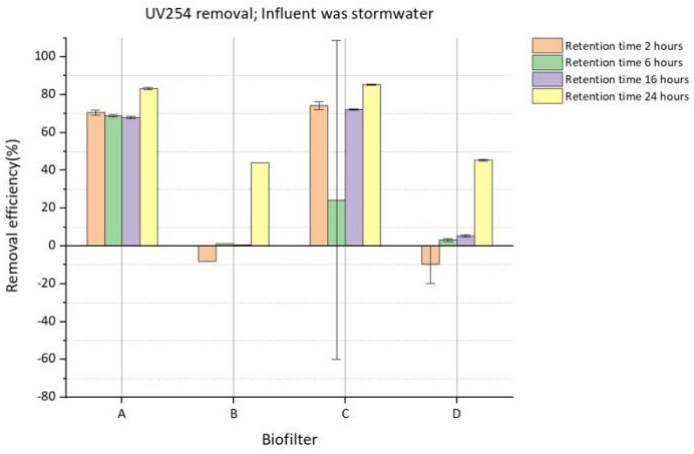

Figure 5.8.2.: UV254 removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

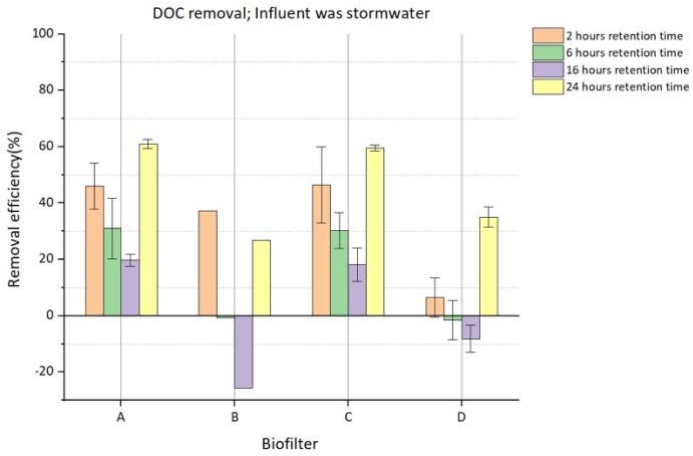

Figure 5.8.1.: DOC removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was stormwater.

5.8.2 Surface water as influent for UV254 & DOC

Influent was surface water:

The influent had a mean UV254 value of 0.4 and a mean DOC concentration of 12.9 mg/L. In the effluent, the UV254 values ranged from 0.06 to 0.41, and the DOC concentrations varied between 2.8 and 12.3 mg/L. The figure 5.7.1 and 5.7.2 illustrates the variations in removal efficiency of UV254 and DOC when surface water was used as the influent. In UV254 measurements, the highest removal efficiency of 87% was observed in biofilter A at 16-hour retention time. There is no observable change in UV254 with an increase in retention time. In DOC measurements, the removal efficiency of DOC showed a slight increase with the longer retention time in biofilters A and C. The highest removal efficiency, reaching 81%, was observed in biofilter C at a 24-hour.

In the UV254 and DOC results, the removal efficiencies of single-material biofilters B and D (technical sand) are notably lower than those of mixed-material biofilters A (MnO and technical sand) and C (MnO, lime and technical sand), except for DOC at 2-hour. This indicates that mixed-material biofilters are more efficient in removing organic matter compared to their single-material biofilters.

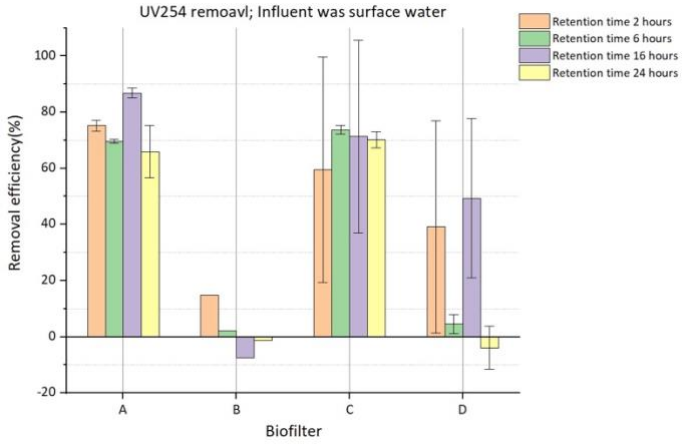

Figure 5.8.4.: UV254 removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

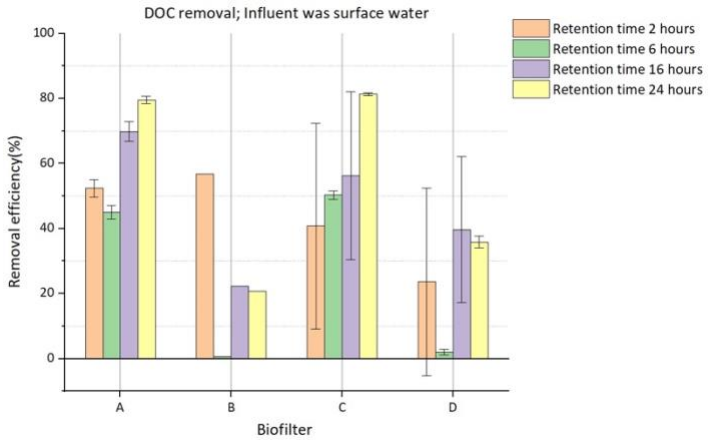

Figure 5.8.3.: DOC removal in four biofilters with retention time (2, 6, 16 and 24 hours), influent was surface water.

5.9 Ground water infiltration law

"Infiltratiebesluit bodembescherming" refers to the Infiltration Decision for Soil Protection established by the National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu, RIVM) in the Netherlands. These regulations are designed to ensure the protection of soil and groundwater from contamination. This law

offers a set of measures and standards aimed at preventing harmful substances from infiltrating the soil and groundwater, thus safeguarding the environment and public health. The categories of pollutants specified in the regulations include heavy metals, nutrients, physical parameters, chemical wastes, organic pollutants and pesticides.

The specific regulations and standards may vary over time and can also be location-specific. While not all heavy metals, such as Mo, Sn, and Sr, are subject to current regulations, it is essential that their concentrations remain below levels that pose risks to the environment and human health. Standards should be adapted or updated to align with local conditions. It's worth mentioning that regulated pollutants can vary depending on the location and the number of breakthrough days. For example, NO_3^- concentration may be allowed to exceed 5.6 mg/L for up to 70 days but should not exceed 11.2 mg/L.

Comparing the results of effluent quality with surface water and stormwater as the influent, when surface water is the influent, the phosphorus concentration in the effluent exceeds the groundwater recharge standard, whereas other water quality parameters, except for phosphorus, are below the standard. The reasons for the high concentration of PO_4^{3-} in the surface water influent are discussed in Section 5.1.2. The initially higher PO_4^{3-} concentration in the influent contributed to PO_4^{3-} concentrations in the effluent. It is essential to highlight that one of the crucial factors influencing effluent water quality is the quality of the influent water. In this experiment, the Green Village was situated in residential and office areas, resulting in good-quality stormwater. However, it should be noted that if the testing area is in a heavy industrial area or an area with a high level of pollution, a more comprehensive evaluation and analysis of effluent water quality would be necessary.

Table 5.9.1.: Infiltration water quality standard of “Infiltratiebesluit bodembescherming” in RIVM

Parameter	Standards in RIVM	Influent (surface water)	Effluent (surface water)	Influent (stormwater)	Effluent (stormwater)
pH(-)	Of interest for permit	6.69—7.2	6.8—7.3	6.5—7.2	6.3—7.1
Total Suspended Solids (mg/l)	0,5 (excludes dissolved fraction) (allowed to be higher 70 days a year, but no higher than 2)	-	-	-	-
Chloride (Cl) (mg/l)	200 (Of interest for permit)(allowed to be higher 70 days a year, but no higher than 300)	79.29—93.89	69.9—93.8	2.28—2.49	2.3—3.3
Sodium (Na) (mg/l)	120 (Of interest for permit) (allowed to be higher 70 days a year, but no higher than 180)	41.49—59.5	43—59.7	2.38—4.07	3.3—5.6
Fluoride (F) (mg/l)	1.00	0.22—0.27	0.01—0.3	0.05—0.07	0.05—0.08
Calcium (Ca) (mg/l)	Of interest for permit	100.3—146.85	47.6—141	9.44—12.34	8.5—16.4
NO_3-N (mg N/l)	5,6 (Of interest for permit) (allowed to be higher 70 days a year, but no higher than 11,2)	0.74—1.62	0.557—2.38	-	-
Total PO_4- P (mg P/l)	0.40	0.85—2.1	0.51—1.03	-	-
Sulphate(SO_4) (mg/l)	150 (Of interest for permit)	77.1—80.27	67.44—79.24	2.25—2.82	2.2—3.7
As (µg/l)	10.00	< 10	< 10	< 10	< 10
Ba (µg/l)	200 (allowed to be higher 70 days a year, but no higher than 300)	8.47—11.4	5.8—36.82	4.49—5	1.8—5.4
Co (µg/l)	20.00	<2	<2	<2	<2
Cr (µg/l)	2.00	<2	<2	<2	<2
Cu (µg/l)	15.00	<2	<2	<2	<2
Pb (µg/l)	15.00	<10	<10	<10	<10
Zn (µg/l)	65.00	8.5—14.75	8.3—16.41	23.28—60.69	6.4—44.7

5.10 Water quantity calculation

5.10.1 SWMM calibration

The research focuses on Cromvliet Park in The Hague, which will be simulated and modelled using the Storm Water Management Model (SWMM). Various pump operation regimes will be used in the model to calculate how much water can be recharged into the aquifer. The calibration will be based on water level changes and flow data in the buffer tank during a real stormwater event.

The calibration was performed through a real-time control system on-site at Cromvliet Park, with the depth sensor situated in the pump sump. Before starting the calibration work, the system was drained until it was empty, and the minimum water level was documented. The surface water was leaking into the system due to the connection of the pipework to the urban canal. The water level in the system was stable at 0.88 m after leaking, and the water level in the pump sump remained steady. The system was not operated, and pumps were closed for the subsequent week (from March 7th to March 10th, 2023). After one week, rainfall was recorded through radar data, water quality collections were performed in SWMM, and the changes in water levels were compared between SWMM and sensor data. The model was calibrated by adjusting parameters such as the impervious rate, infiltration rate, and depression within the subcatchment to align the simulated results closely with the observed data. The graph below illustrates the hourly cumulative rainfall data from March 7th to March 10th.

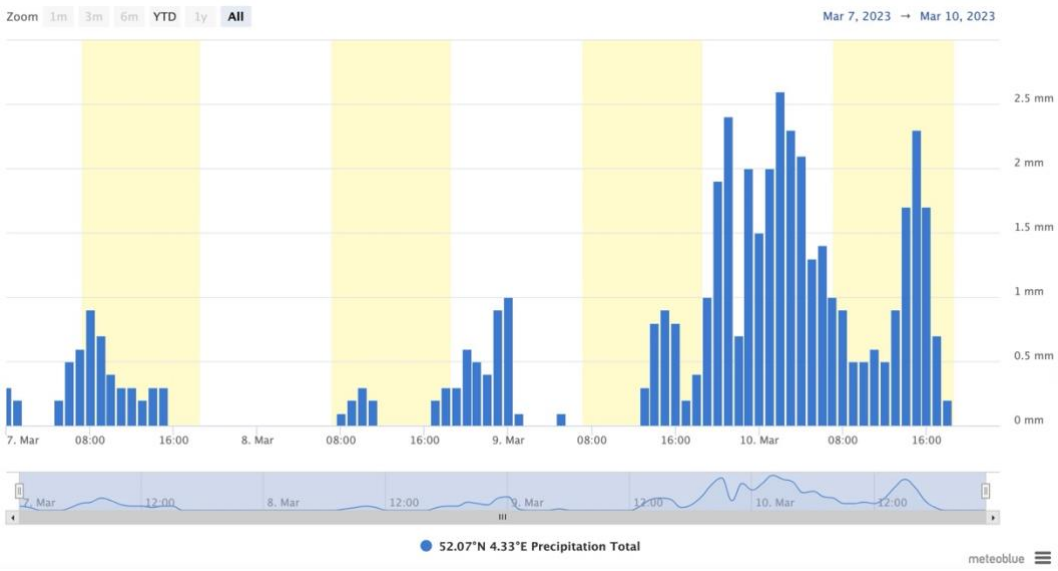

Figure 5.10.1.: Accumulate rainfall in hourly during calibration period (7 March, 2023 — 10 March, 2023)

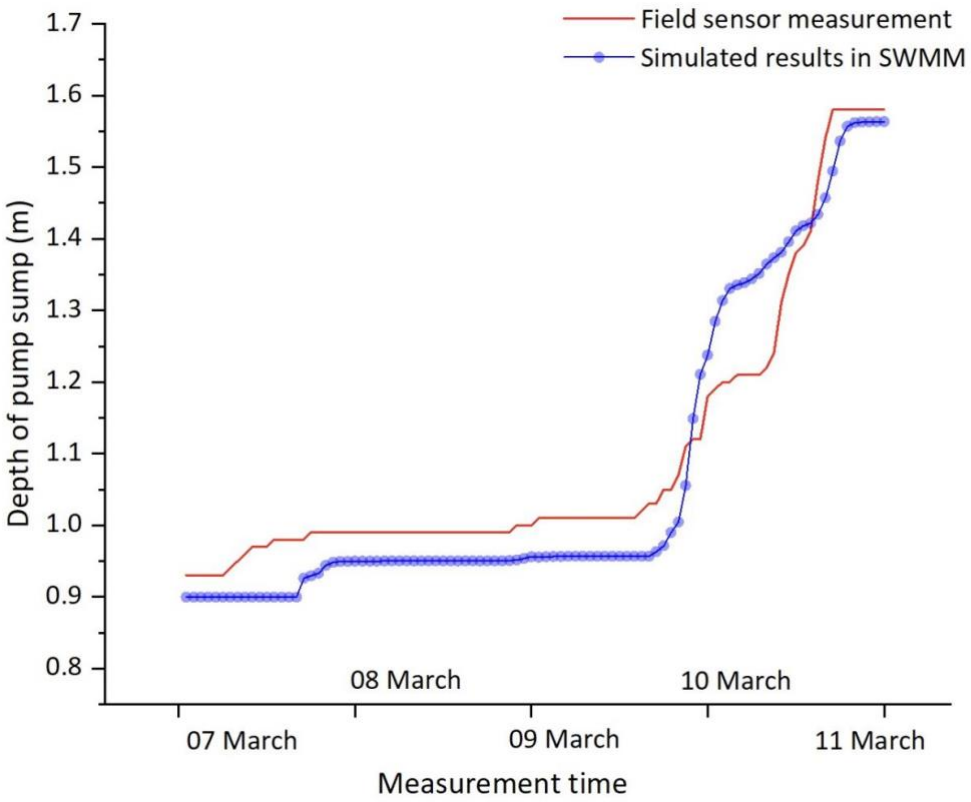

Figure 5.10.2.: SWMM calibration results (7 March, 2023 — 10 March, 2023)

This figure shows final calibration results: the red line represents the measured water depth changes in field within the pump sump, while the blue line depicts the modelled water level changes in the pump sump by SWMM. Initially, during the beginning of rainfall, the model indicates minor losses because of depression and infiltration. However, as the rainfall period goes on, both modelled and observed data follow a consistent trend. Moreover, the shifts in time in both curves are the same.

Residuals are defined as deviations between the observed and fitted values. To conduct a deeper analysis of the calibration results, residual analysis on the measured data of pump sump depth and the SWMM results was performed. The following results are shown below.

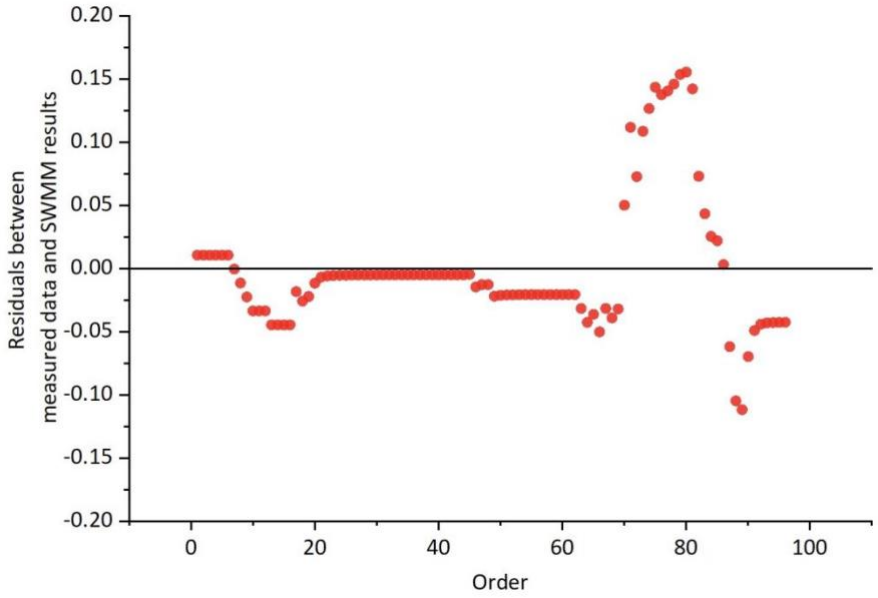

Figure 5.10.3.: Residuals between measured depth in pump sump and SWMM results

The residuals range from 0.156 to -0.111m. Fluctuations in the residuals were observed in the rainfall on March 10. The sources of error may include errors in the radar rainfall data, the real system not being completely dry, measurement errors in the sensors in the pump sump, and errors in the simulation of the SWMM. However, overall, the errors are still within acceptable limits, and the parameter settings of the model are a good representation of the real situation.

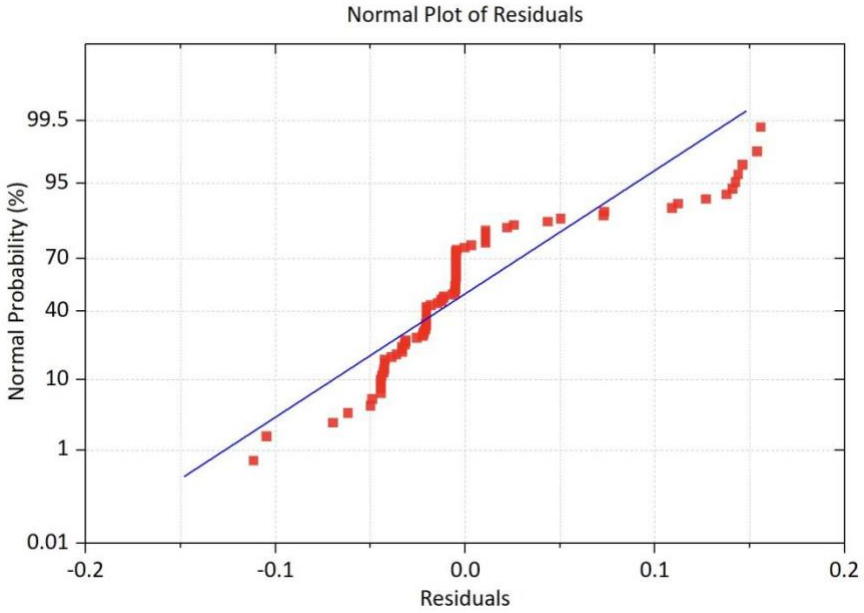

Figure 5.10.4.: Normal plot of residuals from calibration results

In the normal plot of the residuals graph, the scattered data points generally align along a straight line. Approximately 85% of the residuals fall within the range of ±0.05, indicating a distribution that closely approximates a normal distribution. Furthermore, the R^2 value between the measured data and SWMM simulation data was 0.9386. This high R^2 value suggests that the model accurately represents the real situation, making it suitable for subsequent analysis and calculations.

5.10.2 SWMM simulation setup

The simulation utilizes high-resolution hourly cumulative rainfall data derived from the Meteoblue NEMS radar. This data set covers the period from January 1, 2019 to January 1, 2020. The highest hourly cumulative rainfall reached 42mm on June 4, 2019. The total precipitation recorded for the whole year was 731mm.

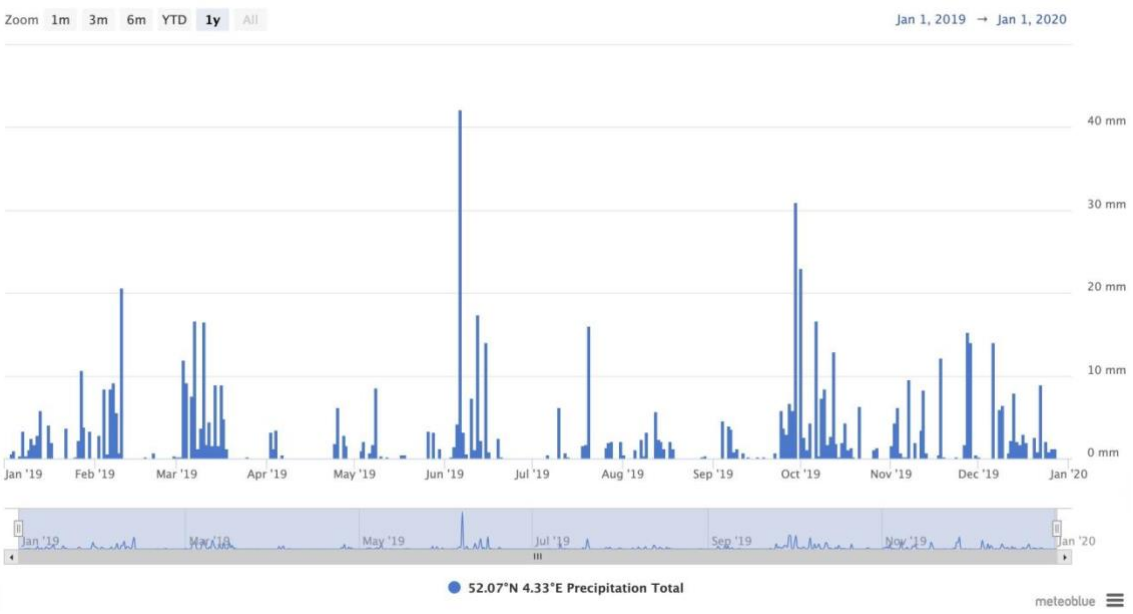

Figure 5.10.5.: Hourly rainfall data from meteoblue for SWMM simulation: January 1, 2019 to January 1, 2020.

The area of Cromvliet Park is approximately 25,000 m^2, including the BlueBloqs, which were designed by FieldFactors in 2021. The BlueBloqs system was designed to collect stormwater runoff from 8,000 m^2 of impermeable surfaces within the park.

Table 5.10.1.: Collection area of stormwater in Cromvliet park

Landuse type	Area (m2)
Concrete pathway	1800
Road	4200
Roof	2000
Total	8000

In the SWMM simulation, the study area was subdivided into 24 subcatchments, with sizes ranging from 200 m^2 to 800 m^2. Stormwater is collected from three different land uses: roofs, pedestrian pathways, and vehicle roads. These subcatchments are assigned 14 access junctions and linked by 19 PVC stormwater pipes, each with a diameter of 0.25 m. Effluent from the biofilter is recharged through gravity. In the simulations, surface water inflow is not considered, under the assumption that there is no leakage from the valve connecting the system to the surface water.

Figure 5.10.6.: Collection area layout in Cromvliet park

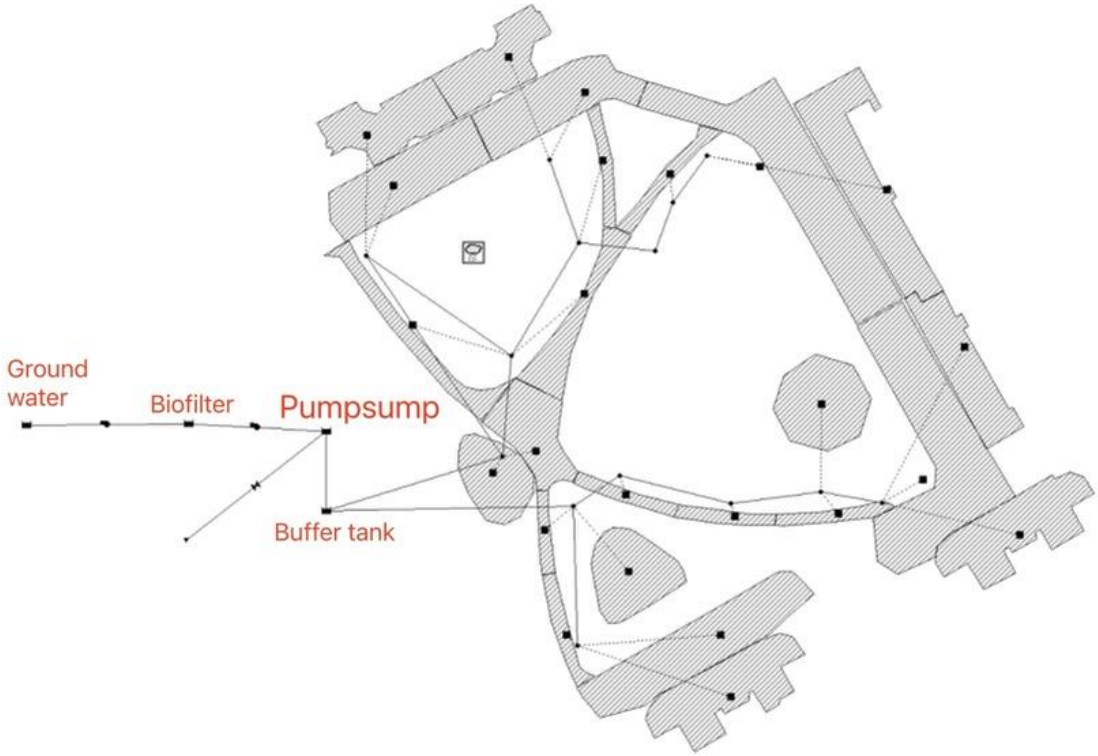

Figure 5.10.7.: SWMM layout of Cromvliet park

5.10.3 Physical characteristics in SWMM

For the infiltration model, the Horton method was selected—an empirical approach that is suitable for small-scale research areas and long periods of rainfall. For dynamic wave simulations, the Darcy-Weisbach method was used in the simulation because of the rainwater harvesting system.

The parameters set in SWMM can be categorized into two types. Firstly, there are parameters that are directly derived from geographic information and pipe network data, such as catchment area, slope, pipe shape, pipe diameter, pipe length, node bottom elevation, and their respective locations. These parameters are sourced from FieldFactors' design manuals. The second category includes parameters determined from the recommended ranges provided in the SWMM manual and the outcomes of calibrations. These parameters include impervious rates, depression, manning's coefficients (both for permeable and impermeable surfaces), pipe manning's coefficients, and infiltration rates.

Table 5.10.2.: Detailed parameters of Cromvliet park in SWMM

Parameters	Value
Roads impervious surface (%)	75
Roof impervious surface (%)	100
Pathway impervious surface (%)	80
Manning's coefficient of pipeline	0.01
Diameter of pipe	0.25
Average mannning's coefficient overland	0.015
Slope of study area	0.1 — 0.5
Impervious surfaces depression depth (mm)	1.5
Pervious surfaces depression depth (mm)	2
Maximum infiltration rate (mm/h)	15 — 55
Minimum infiltration rate (mm/h)	10 — 15
Decay constant (1/h)	5
Drying time (days)	4

5.10.4 Pump regimes

The research area was simulated in SWMM, and various pump operation regimes were implemented to determine the amount of water that can be recharged and the total loss. Rainfall was the only input, and surface water leakage was not considered in the simulation. The pump operation strategy was to run the pump continuously for two hours (for biofilter in Cromvliet park, 2 hours = 1 pore volume) every time it was activated. Following this two-hour period, a retention time was initiated, lasting from 2 to 24 hours. If the water level remains above the pump's start level at the end of this retention period, the pump will be reactivated for another two hours, after which another retention period will continue. This cycle continues throughout the year's rainfall duration to gather water for the rechargeable groundwater.

The water loss in the simulation can be attributed to two scenarios. The first scenario occurred when the pump was active and frequent, heavy rainfall led to the system reaching its maximum capacity. In this case, water overflows from the outlets or floods from the nodes. The second scenario took place when the pump is inactive, and the system didn't recharge water back to the aquifer through the biofilter. Instead, rainwater continued to flow into the system, resulting in water loss through overflow.

Table 5.10.3.: Total rechargeable water and water loss in different pump regimes (from PySWMM)

Pump closed time (hours)	Total water that can be recharged (m^3)	Water Loss (m^3)
2	4929	107
4	4843	193
6	4756	280
10	4602	434
16	4038	998
24	3132	1904

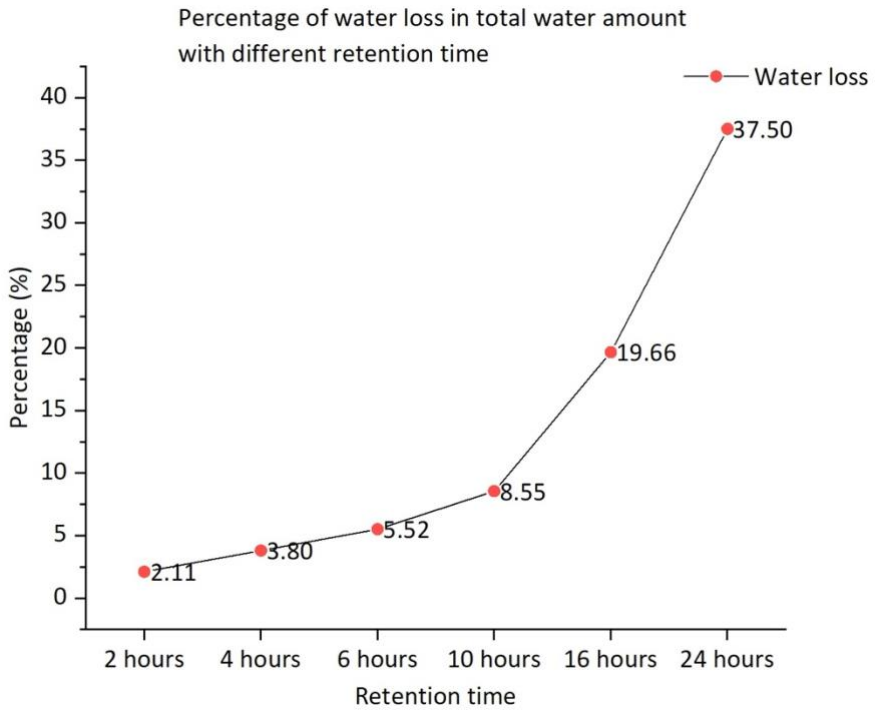

Figure 5.10.8.: Percentage of water loss in total water amount with different retention time.

The results from SWMM are presented in the table above, detailing different retention periods, rechargeable water, and water losses. Results indicate that with a 2-hour retention period, most of the water was recharged to the aquifer, resulting in a 2% annual volume loss. However, when the retention period extends to 24 hours, the loss increases to 37% of the annual volume. The curve representing the total water loss experiences a notable shift in slope during the 6-hour retention period. From the previous water quality analysis, no significant correlation was found between the removal of particulate metals, solids, and phosphorus and the retention time. Moreover, for effective nitrogen removal, the retention period shouldn't be overly prolonged. To maximize water recharge, it's beneficial to operate for shorter retention time and longer pumping durations. To balance both water quality and quantity, the biofilter‘s retention time should ideally range between 4 and 6 hours.

6. Conclusion

This thesis evaluates the BlueBloqs Circular water system from FieldFactors. This thesis focuses on the role of retention time in the BlueBloqs system's biofilter, which is crucial for both the quality and quantity of the effluent. The main challenge was to optimize retention time to enhance water quality and maximize aquifer recharge. The thesis aims to assess the biofilter's water quality performance and water quantity estimation under various retention times, utilizing water quality measurements and SWMM modeling. To achieve this aim, the research was divided into two main parts. The first part focuses on water quality, investigating the impact of varying retention time (2 hours ,6 hours, 16 hours, and 24 hours) on the biofilter's effluent quality during the dry period of the biofilter. In the water quality analysis, the pollutant removal efficiencies of mixed-material (A: MnO + technical sand, C: MnO + lime + technical sand) and single-material (B and D: only technical sand) biofilters were compared across various influents. Key pollutants analyzed included turbidity, nitrate, phosphorus, dissolved and particulate metals, as well as UV254 and DOC. For water quantity part, the initial step in the second part involved setting up the Cromvliet Park model by SWMM. The simulation calculated the total volume of water that can be recharged into the aquifer in a year under various retention periods (2, 4, 6, 10, 16 and 24 hours). By integrating the insights from both water quality and quantity analyses, a comprehensive operational strategy for the system was proposed.

6.1 Water quality

The water quality part evaluated the pollutant removal performance of the biofilter using retention time as a control variable. The experiments included four biofilters made of mixed materials (A: MnO + technical sand, C: MnO + lime + technical sand) and single material (B and D: only technical sand) in the Green Village with two types of influents (surface water and stormwater). Turbidity, ammonium, nutrients (nitrate and phosphorus), particulate and dissolved metals, UV254, and DOC were target pollutants.

First, the biofilter was efficient at removing most particulate pollutants. The turbidity removal efficiency of the biofilter ranged from 40 to 90%, with solid particles being removed through the filtration media. Phosphorus removal efficiencies in the biofilter ranged from 35 to 70%, with only one single event of leaching (-22%) observed in all samples. The phosphorus was mostly in particulate form, and its removal was mainly achieved through adsorption by the filter media.

Among the metals measured (Mn, Ca, Mg, Ba, and Zn), most of those in the particulate phase are observed being removed by the biofilter, with removal efficiencies from 10 to 100%. However, leaching events were observed in the measurements of particulate magnesium and

calcium. This removal of metals occurred through negatively charged adsorption by the filtration media. As for dissolved metal, dissolved manganese exhibited stable removal (>85 %), while the biofilter's efficiency in removing dissolved barium, calcium and magnesium was variable (-100 to 60%).

When the influent was surface water, the removal efficiencies for particulate Ca and Mg are higher in mixed-material biofilters A: MnO + technical sand and C: MnO + lime + technical sand, compared to single-material biofilters B and D: only technical sand. With removal of particulate Ca in mixed material biofilters A and C of 29-100%; and in single material biofilter B and D of -100-52%; and particulate Mg in mixed material biofilters of 50-98%, and single material biofilters of-24-50%. The MnO's high specific surface area and crystal structure enhance its adsorption capabilities [97], while lime contributes to the removal of Ca and Mg by adsorption. Moreover, the removal of other metals (Mn, Ba, and Zn) is not significant with the biofilter material. This could be attributed to the significantly higher concentration of particulate Ca and Mg in the surface water compared to other metals, enhancing the binding of Ca and Mg to the adsorption sites. The correlation between the removal efficiency of Ca and Mg in stormwater and the biofilter material was found to be insignificant. This was attributed to the considerably lower concentrations of calcium and magnesium in stormwater compared to surface water.

The removal efficiency of dissolved zinc in the biofilter was found to correlate with the type of influent. When processing stormwater, the biofilter's removal efficiency for dissolved zinc ranged from 10 to 60%. In contrast, with surface water as the influent, this efficiency varied from -100 to 0%. This variation can be zinc's lower adsorption priority in the presence of multiple metals and the competitive effect other metals have on zinc adsorption.

Ammonium was not detected in the effluent when the influent was surface water and influent ammonium was 0.97 mg/L. For shorter retention times (2 and 6 hours), the nitrate removal efficiency ranged from 12 to 49%. However, as the retention time extended to 16 hours and 24 hours, nitrification gradually increased, leading to a decrease in removal efficiency and observed nitrate leaching (-84 to 13%, -6 to 0%). The dissolved oxygen concentrations in the effluent at 24 hours retention time indicated that nitrification happened, which led to the leaching of nitrate.

UV254 and DOC, as indicators of organic matter, showed a correlation with the biofilter material in both stormwater and surface water influents. The removal efficiencies for UV254 and DOC are higher in mixed-material biofilters mixed material biofilters A (UV254: 65-87%, DOC: 45-80%) and C (UV254: 60-74%, DOC: 41-82%) compared to single-material filters B (UV254: -7 to 15%, DOC: 0 to 56%) and D (UV254: -4 to 50%, DOC: 2 to 40%).

Table 6.1.1.: Summary of removal efficiencies for target pollutants

Parameters	Removal efficiency (%)
Turbidity	From 40 to 90%
Nitrate	2-6 hours retention time:12 to 49%, 16 hours:-84 to 13%, 24hours: -6% to 0%.
Ammonia	No ammonia in the effluent samples
Phosphorus	35 to 70%, one leaching event (-22%)
Particulate metal (Mn, Ba and Zn)	Most of particulate Mn, Ba and Zn can be effective removed (>10%)
Particulate metal (Ca and Mg)	Show a higher removal efficiency in mixed material biofilter. (particulate Ca, mixed material biofilters: 29-100%; single material biofilter: -100-52%) (particulate Mg, mixed material biofilters: 50-98%; single material biofilter: -24-50%)
dissolved Mn	> 85%
dissolved Ba, Ca and Mg	-100 to 30%
dissolved Zn	Correlated with the type of influent stormwater: 10 to 60% surface water: -100 to 0%
UV254 and DOC (stormwater as influent)	mixed material biofilters A (UV254: 68-83%, DOC: 20-61%) C (UV254: 24-85%, DOC: 18-60%) single-material filters B (UV254:- 8 to 44%, DOC: -25 to 37%) D (UV254: -10 to 45%, DOC: -8 to 35%)
UV254 and DOC (surface water as influent)	mixed material biofilters A (UV254: 65-87%, DOC: 45-80%) C (UV254: 60-74%, DOC: 41-82%) single-material filters B (UV254: -7 to 15%, DOC: 0 to 56%) D (UV254: -4 to 50%, DOC: 2 to 40%)

6.2 Water quantity

The water quantity part was carried out using the SWMM model, combined with the PySWMM package, to simulate various pump regimes. The aim was to determine the volume of stormwater that can be recharged and to compute water losses over an extended rainfall duration. The simulation was performed with retention time of 2, 4, 6, 10, 16, and 24 hours. The duration of the simulation was one year, and it was assumed that the water was recharged by gravity. The results indicate a sharp exponential rise in water loss for retention time exceeding ten hours. Operating the biofilter at Cromvliet Park with a 24-hour retention time results in a yearly loss of 37.5% of the stormwater. Hence, a retention time ranging between 4 and 6 hours resulted in acceptable water losses, measuring between 3.8 and 5.5%.

In summary, the combined analysis of water quality and quantity reveals that retention time impacts nitrate removal. The pollutants' removal also depends on the biofilter materials and the concentrations in the influent. Most dissolved metals show variable removal efficiencies under different retention time. The biofilter showed a high nitrate removal efficiency with a retention time of 4 to 6 hours. Operating the BlueBloqs system with a 4–6 hour retention time in one-year rainfall data resulted in a total water loss of only 3.8% to 5.5%. Furthermore, the influent concentration affects the biofilter's removal efficiency,

suggesting that incorporating pretreatment facilities to enhance influent water quality is an option to consider.

7. Recommendation

To better assess the impacts of the retention time on water quantity and quality in biofilter, more research and analysis during operation is essential. Owing to the limitations of the experimental equipment and the duration of the study, there are aspects where further refinement and improvements are needed. Future research related to this topic might consider addressing the following aspects:

(1) The thesis focused on analyzing the effluent quality changes in the biofilter under varying retention times as the control variable during the drying period. Further testing and analysis are required to determine if different pore volumes (e.g., 2-5 pore volumes) in the flushing process affect the effluent quality.

(2) Assessing improvement in effluent quality by adding different materials (materials enhancing metal adsorption or carbon sources promoting denitrification) in the layers of biofilter could offer significant insights into water treatment and system optimization.

(3) Understanding microbial dynamics within the biofilter is crucial. By investigating the species and density of microbes present in the biofilter, it's important to gain deeper insights into reaction mechanisms and enhance the biofilter's effectiveness.

(4) The water quantity primarily utilizes SWMM simulation, with the retention time serving as the control condition in this research. Future research could integrate the water quality module in SWMM to model operations using effluent water quality as the control condition. This integration would enhance the water quantity calculation and prediction within the BlueBloqs system.

8. Appendix

8.1 Appendix A

This section presents trend plots depicting the total water collected, recharge water, and water loss over time for Cromvliet Park under hourly rainfall conditions for one year after running the SWMM.inp file with PySWMM. The top graph illustrates the fluctuation in the biofilter's depth, while the bottom graph demonstrates the variation in water volume. Utilizing Python simulations allows for precise calculations of these values during the SWMM run. Python also simplifies the process of displaying and outputting the calculated results and conducting subsequent calculations based on these outcomes.

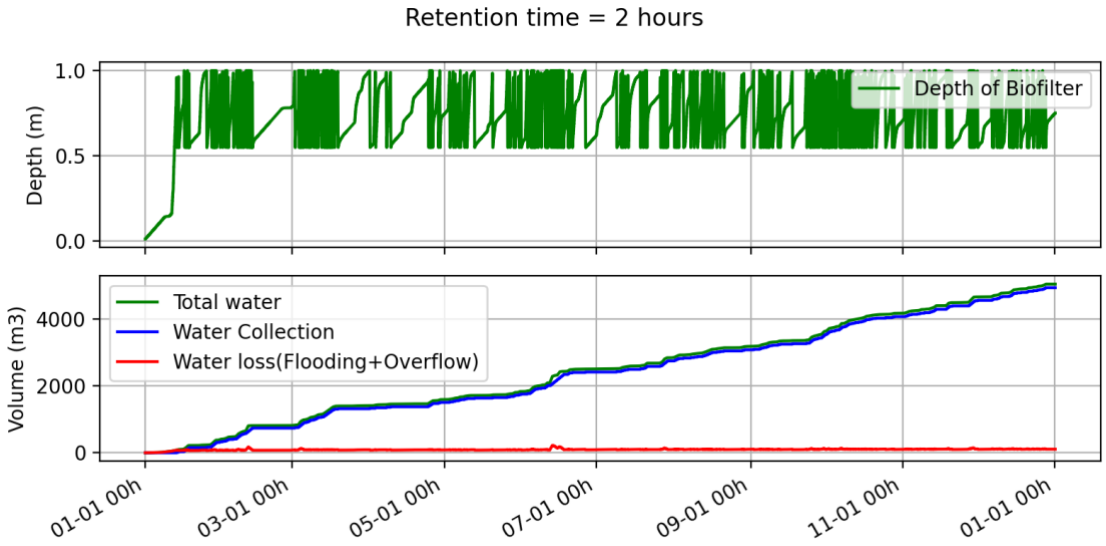

Figure Appendix A.1.: “Top”: Variation in biofilter’s depth. “Bottom”: One-year water prediction of the BlueBloqs system under 2 hours retention time: total water amount, rechargeable groundwater, and water Loss.

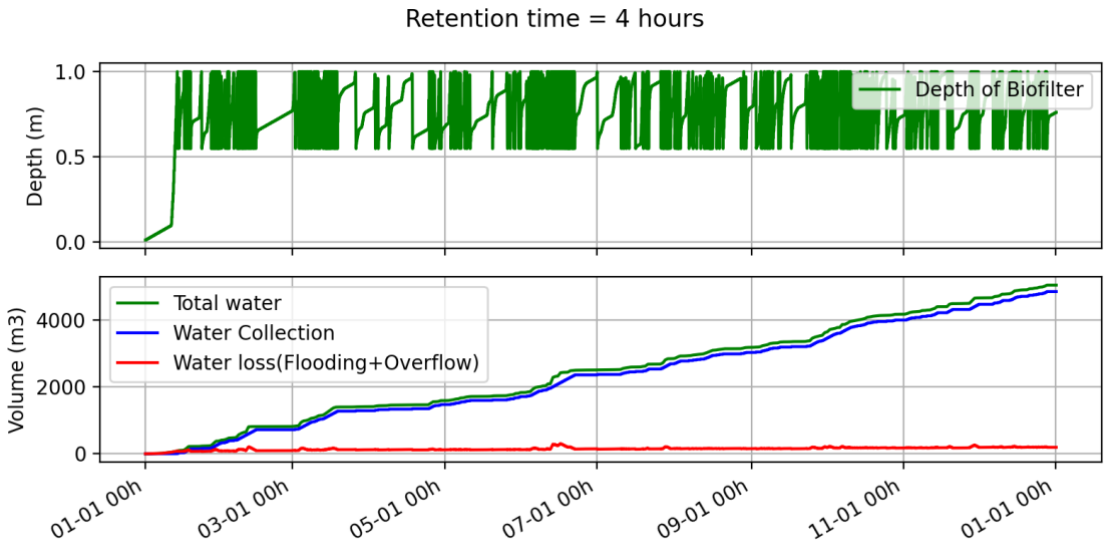

Figure Appendix A.2.: "Top": Variation in biofilter's depth. "Bottom": One-year water prediction of the BlueBloqs system under 4 hours retention time: total water amount, rechargeable groundwater, and water Loss.

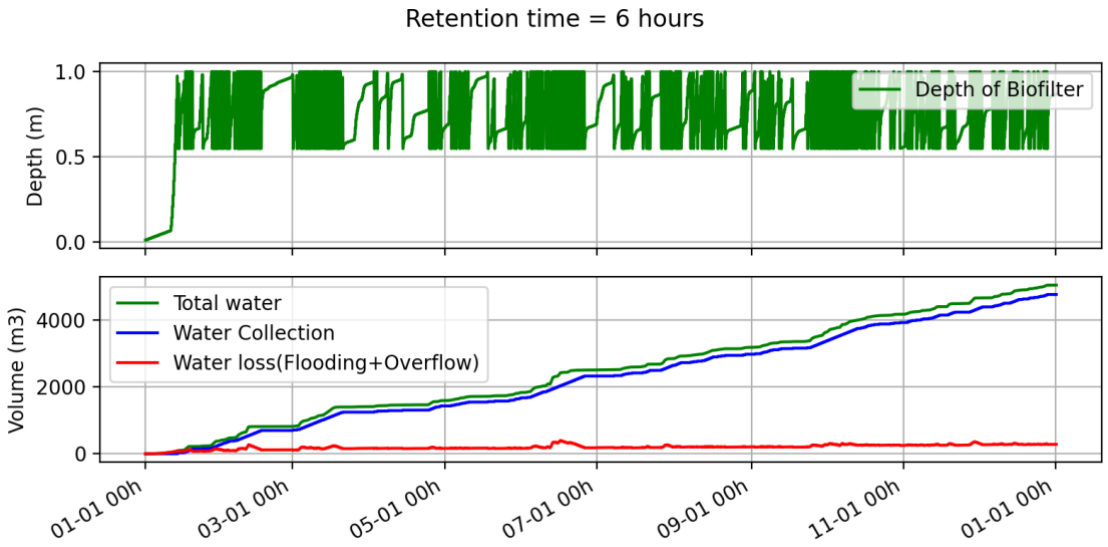

Figure Appendix A.3.: "Top": Variation in biofilter's depth. "Bottom": One-year water prediction of the BlueBloqs system under 6 hours retention time: total water amount, rechargeable groundwater, and water Loss.

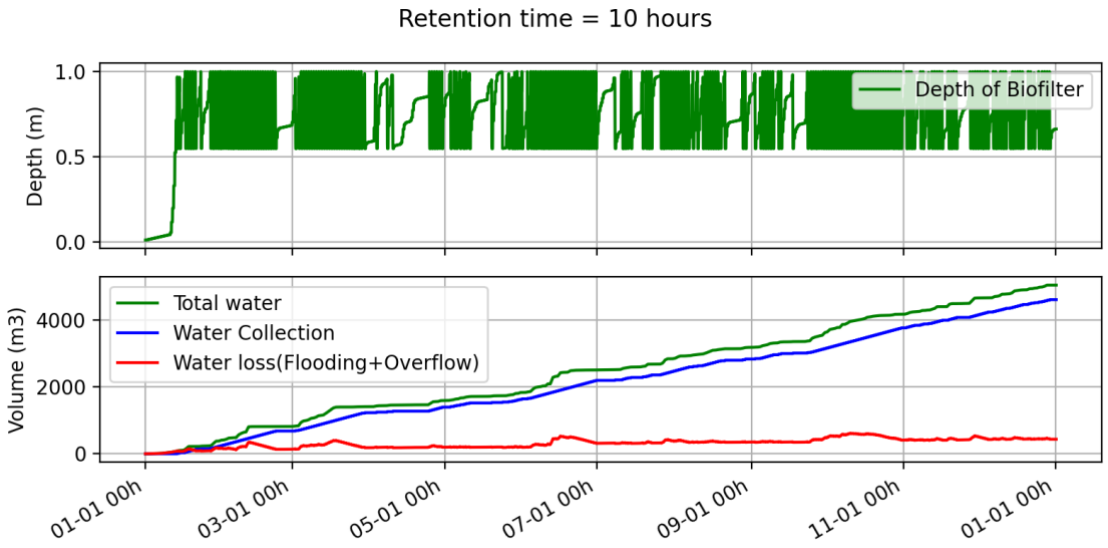

Figure Appendix A.4.: "Top": Variation in biofilter's depth. "Bottom": One-year water prediction of the BlueBloqs system under 10 hours retention time: total water amount, rechargeable groundwater, and water Loss.

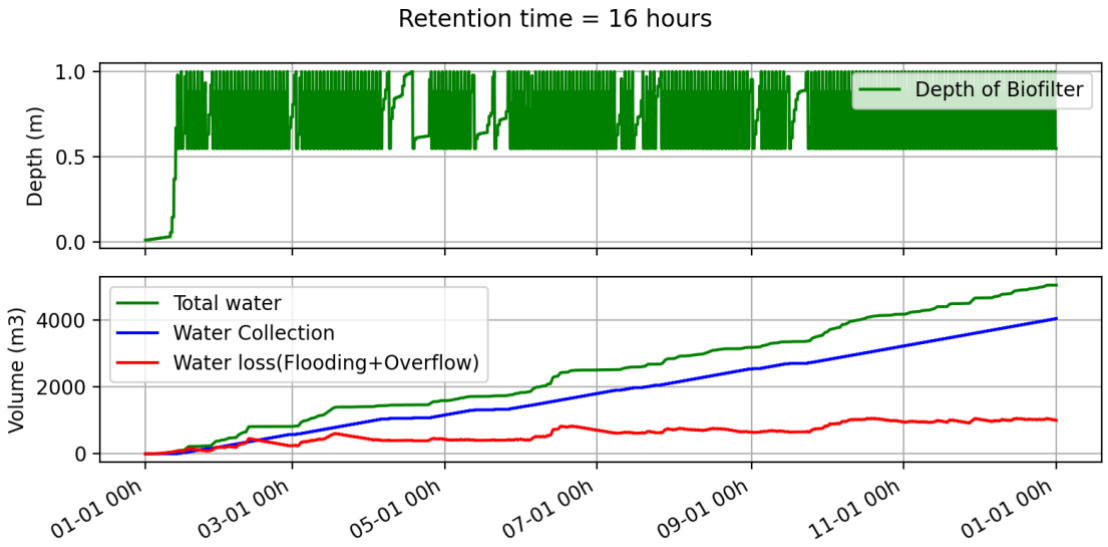

Figure Appendix A.5.: "Top": Variation in biofilter's depth. "Bottom": One-year water prediction of the BlueBloqs system under 16 hours retention time: total water amount, rechargeable groundwater, and water Loss.

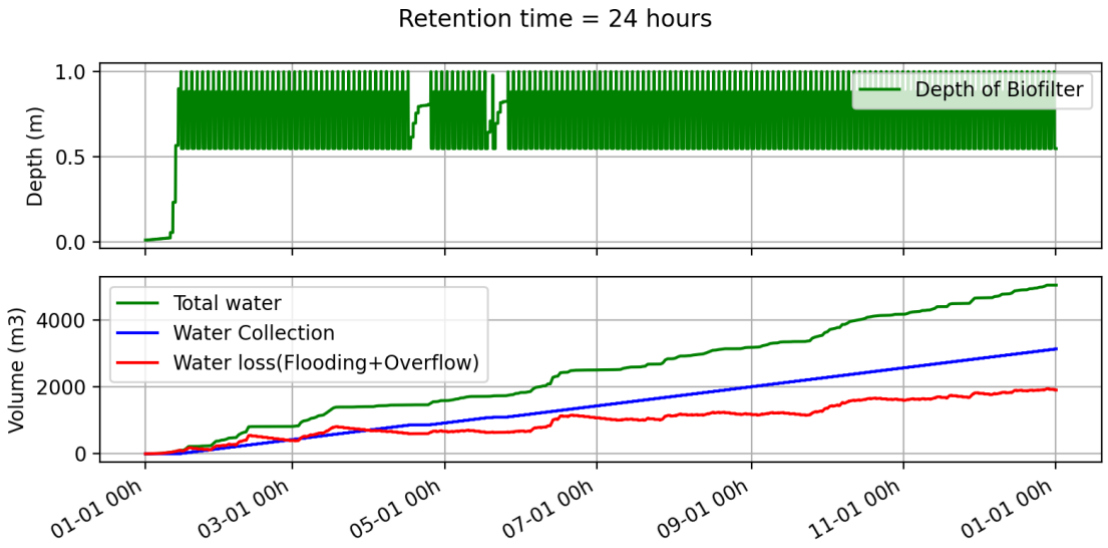

Figure Appendix As6.: "Top": Variation in biofilter's depth. "Bottom": One-year water prediction of the BlueBloqs system under 24 hours retention time: total water amount, rechargeable groundwater, and water Loss.

8.2 Appendix B

This section presents water quality data for both influent and effluent at various retention time and under different influent conditions in the experiments. The table also displays the removal efficiencies of the parameters and the standard deviations of the results.

Table Appendix B.1.: Water quality results of **Mn**, influent is **Surface water**.

	Mn, Influent: Surface Water (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	0.45	99.45	0.15	A	0.65	99.11	0.42	A	0.03	99.97	0.06	A	0.02	99.97	0.05
	B	0.65	99.24	-	B	0.91	98.77	-	B	0.00	100.00	-	B	0.49	99.20	-
	C	1.24	98.50	0.68	C	0.54	99.25	0.10	C	0.36	99.56	0.47	C	0.09	99.86	0.24
	D	0.73	99.14	0.12	D	1.05	98.58	0.40	D	0.55	99.37	1.09	D	0.00	100.00	0.00
-	Influent	89.19			Influent	74.10			Influent	105.82			Influent	61.95		
Particulate	A	0.08	99.06	0.85	A	0.00	100.00	0.00	A	0.00	100.00	0.00	A	0.43	97.56	4.22
	B	0.00	100.00	-	B	0.11	99.31	-	B	0.00	100.00	-	B	0.00	100.00	-
	C	0.04	99.52	0.54	C	0.10	99.34	0.43	C	0.06	85.33	14.92	C	0.00	100.00	0.00
	D	0.06	99.29	1.22	D	0.07	99.58	0.52	D	0.09	80.31	34.11	D	0.00	100.00	0.00
-	Influent	8.75			Influent	16.13			Influent	0.55			Influent	18.10		

Table Appendix B.2. Water quality results of **Mn**, influent is **Stormwater**.

	Mn, Influent: Stormwater (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	4.47	86.70	3.30	A	4.94	84.56	9.23	A	2.20	88.27	11.70	A	3.40	86.01	3.44
	B	1.26	96.93	-	B	3.37	87.44	-	B	0.16	99.16	-	B	2.33	90.64	-
	C	3.82	88.60	3.36	C	2.99	89.41	1.57	C	1.55	91.34	3.48	C	2.97	88.20	18.03
	D	0.30	99.12	1.13	D	0.00	100.00	0.00	D	0.12	99.32	0.59	D	0.00	100.00	0.00
-	Influent	25.38			Influent	22.69			Influent	16.76			Influent	25.26		
Particulate	A	0.38	54.10	79.50	A	0.00	100.00	0.00	A	1.25	12.65	51.63	A	0.67	40.91	24.80
	B	0.04	94.70	-	B	0.00	100.00	-	B	0.00	100.00	-	B	0.05	95.40	-
	C	0.00	100.00	0.00	C	0.00	100.00	0.00	C	1.16	14.42	21.79	C	1.08	11.21	101.87
	D	1.00	31.15	113.63	D	0.08	90.54	4.49	D	0.00	100.00	0.00	D	0.06	94.36	7.97
-	Influent	0.83			Influent	0.79			Influent	1.27			Influent	1.18		

Table Appendix B.3. Water quality results of **Ba**, influent is **Stormwater**.

	Ba, Influent: Stormwater (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	1.98	51.08	1.83	A	2.17	64.23	2.30	A	1.35	73.12	17.26	A	1.88	61.09	5.37
	B	6.27	-26.81	-	B	4.40	17.57	-	B	4.50	8.71	-	B	3.99	19.25	-
	C	2.85	29.33	2.23	C	2.08	62.94	3.94	C	1.66	64.95	6.20	C	2.26	54.42	50.43
	D	4.68	-25.05	16.51	D	4.01	18.67	2.74	D	4.38	1.94	19.52	D	3.98	14.67	4.60
-	Influent	3.07			Influent	4.51			Influent	4.44			Influent	5.01		
Particulate	A	1.59	33.02	115.20	A	0.00	100.00	0.00	A	0.49	28.35	111.41	A	0.16	-8.27	101.02
	B	0.00	100.00	-	B	0.00	100.00	-	B	0.13	32.49	-	B	0.34	-100.00	-
	C	0.14	93.31	11.58	C	0.07	56.14	26.58	C	0.14	27.37	38.59	C	0.45	33.33	115.47
	D	0.46	67.78	55.80	D	0.16	-18.20	84.46	D	0.00	100.00	0.00	D	0.06	0.00	141.42
-	Influent	1.42			Influent	0.13			Influent	0.17			Influent	0.02		

Table Appendix B.4. Water quality results of **Ba**, influent is **Surface water**.

	Ba, Influent: Surface Water (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	6.10	33.64	2.21	A	7.16	29.63	4.24	A	5.26	19.06	5.57	A	12.67	-17.36	71.57
	B	29.42	-100.00	-	B	26.61	-100.00	-	B	30.20	-100.00	-	B	36.82	-100.00	-
	C	14.13	-16.96	71.92	C	7.94	21.11	2.85	C	13.06	-25.50	64.53	C	9.32	3.02	13.49
	D	22.52	-58.15	72.49	D	28.33	-100.00	0.00	D	24.17	-64.45	61.57	D	26.39	-100.00	0.00
-	Influent	9.93			Influent	10.31			Influent	8.22			Influent	9.75		
Particulate	A	0.12	33.33	115.47	A	0.00	100.00	0.00	A	0.08	60.99	67.56	A	0.60	33.33	115.47
	B	0.00	100.00	-	B	0.88	19.71	-	B	0.00	100.00	-	B	0.00	100.00	-
	C	0.00	100.00	0.00	C	0.10	90.78	7.99	C	0.41	33.33	115.47	C	0.00	100.00	0.00
	D	0.00	100.00	0.00	D	1.20	33.33	115.47	D	0.00	100.00	0.00	D	0.00	100.00	0.00
-	Influent	0.11			Influent	1.10			Influent	0.24			Influent	0.83		

Table Appendix B.5. Water quality results of **Ca**, influent is **Surface water**.

	Ca, Influent: Surface Water (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	56.45	32.32	12.95	A	73.28	5.38	6.75	A	72.21	4.28	8.80	A	103.83	16.87	10.67
	B	87.75	-1.55	-	B	66.01	15.44	-	B	97.39	-16.96	-	B	91.97	28.12	-
	C	60.41	27.89	10.58	C	61.07	20.36	8.15	C	81.69	-8.01	6.85	C	113.52	10.59	10.60
	D	66.46	22.92	13.78	D	63.53	19.08	4.66	D	86.22	-4.19	16.40	D	120.02	2.94	5.95
-	Influent	90.13			Influent	78.49			Influent	95.13			Influent	128.84		
Particulate	A	1.92	85.52	25.08	A	2.06	90.44	16.55	A	7.23	77.22	21.03	A	22.97	-30.80	76.11
	B	6.56	52.56	-	B	21.98	-1.27	-	B	27.36	24.14	-	B	49.29	-100.00	-
	C	9.61	29.58	52.82	C	15.20	28.84	38.23	C	8.01	75.72	21.12	C	0.08	99.54	0.80
	D	12.15	12.14	98.55	D	14.59	32.98	68.16	D	17.93	49.23	63.20	D	21.41	-5.81	82.57
-	Influent	14.43			Influent	21.82			Influent	41.20			Influent	18.01		

Table Appendix B.6. Water quality results of **Ca**, influent is **Stormwater**.

	Ca, Influent: Stormwater (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	15.35	-73.02	27.80	A	15.02	-7.78	17.58	A	10.93	12.80	56.49	A	15.12	-63.53	4.19
	B	8.49	21.78	-	B	15.18	-20.88	-	B	13.84	-12.61	-	B	11.54	-21.85	-
	C	25.08	-100.00	0.00	C	18.92	-45.18	19.88	C	15.77	-33.64	35.01	C	17.56	-31.42	79.39
	D	11.28	-39.74	42.66	D	12.23	-5.04	22.05	D	12.43	-11.72	11.72	D	11.14	-25.04	29.31
-	Influent	6.73			Influent	10.61			Influent	11.07			Influent	9.59		
Particulate	A	2.04	32.79	62.60	A	0.46	89.58	18.05	A	0.57	79.73	23.61	A	0.00	100.00	0.00
	B	4.96	-13.33	-	B	0.00	100.00	-	B	0.00	100.00	-	B	1.36	-100.00	-
	C	0.17	95.08	8.53	C	2.40	33.59	57.74	C	2.78	9.65	95.35	C	2.17	16.81	104.15
	D	1.68	54.31	79.13	D	2.86	7.96	82.95	D	1.01	63.75	62.78	D	0.38	0.00	141.42
-	Influent	2.71			Influent	2.86			Influent	2.78			Influent	3.32		

Table Appendix B.7. Water quality results of **Mg**, influent is **Stormwater**.

	Mg, Influent: Stormwater (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	1.88	-100.00	0.00	A	1.90	-68.03	16.62	A	1.77	-72.36	36.38	A	2.01	-100.00	0.00
	B	0.65	-15.17	-	B	1.14	-12.25	-	B	1.30	-32.62	-	B	1.16	-47.10	-
	C	2.20	-100.00	0.00	C	1.71	-62.99	23.58	C	1.54	-60.04	35.99	C	1.39	-77.54	17.86
	D	0.66	-55.99	50.55	D	0.95	-1.39	17.37	D	1.10	-23.80	14.12	D	1.01	-37.05	35.34
-	Influent	0.35			Influent	0.86			Influent	0.89			Influent	0.80		
Particulate	A	0.37	12.31	67.19	A	0.00	95.50	7.80	A	0.22	33.33	115.47	A	0.00	100.00	0.00
	B	0.47	-10.98	-	B	0.00	100.00	-	B	0.00	100.00	-	B	0.05	83.80	-
	C	0.04	89.02	19.01	C	0.27	-33.33	115.47	C	0.19	-33.33	115.47	C	0.35	-11.43	101.94
	D	0.29	8.32	82.17	D	0.26	-33.33	115.47	D	0.04	33.33	115.47	D	0.02	93.15	9.69
-	Influent	0.26			Influent	0.06			Influent	0.00			Influent	0.31		

Table Appendix B.8. Water quality results of **Mg**, influent is **Surface water**.

	Mg, Influent: Surface Water (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	6.13	47.98	9.63	A	8.25	34.64	4.68	A	7.55	48.33	6.58	A	12.75	37.08	12.23
	B	12.96	-6.10	-	B	9.86	21.90	-	B	14.65	-0.31	-	B	13.78	32.02	-
	C	7.02	41.17	16.28	C	6.09	51.76	5.57	C	9.61	34.19	29.39	C	11.61	42.72	5.94
	D	9.03	26.18	23.39	D	9.36	25.84	2.22	D	11.97	18.03	29.76	D	17.84	11.95	14.53
-	Influent	12.74			Influent	12.63			Influent	14.60			Influent	20.27		
Particulate	A	0.09	97.65	4.08	A	0.25	90.93	15.70	A	0.70	85.32	13.17	A	3.09	-43.67	97.57
	B	3.85	3.81	-	B	3.52	-24.88	-	B	3.93	27.31	-	B	7.17	-100.00	-
	C	1.12	71.74	24.76	C	1.37	50.75	33.08	C	1.13	78.13	24.23	C	0.02	98.99	1.74
	D	1.45	63.92	43.64	D	2.41	14.74	78.59	D	2.29	57.11	69.92	D	3.08	-11.57	77.98
-	Influent	4.18			Influent	2.83			Influent	6.18			Influent	2.10		

Table Appendix B.9. Water quality results of **Zn**, influent is **Surface water**.

	Zn, Influent: Surface Water (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	9.80	-49.28	43.36	A	11.51	-43.49	25.87	A	9.48	-34.12	36.75	A	9.02	25.94	9.44
	B	12.22	-79.22	-	B	9.37	-15.96	-	B	12.80	-64.19	-	B	13.02	-4.58	-
	C	12.43	-87.90	11.31	C	10.60	-33.44	25.20	C	11.04	-56.67	18.56	C	14.68	-18.85	13.80
	D	12.52	-83.74	24.51	D	15.70	-50.68	43.10	D	13.32	-65.89	37.44	D	9.55	19.08	20.02
-	Influent	7.11			Influent	8.12			Influent	8.90			Influent	12.54		
Particulate	A	1.01	33.33	115.47	A	0.00	100.00	0.00	A	1.54	38.58	98.58	A	4.14	6.97	100.73
	B	0.00	100.00	-	B	0.00	100.00	-	B	2.76	-1.60	-	B	0.00	100.00	-
	C	0.00	100.00	0.00	C	1.40	33.33	115.47	C	1.23	55.46	77.15	C	0.00	100.00	0.00
	D	0.93	31.83	81.61	D	1.17	27.27	110.60	D	1.50	41.69	100.99	D	0.31	86.11	18.21
-	Influent	1.42			Influent	1.55			Influent	3.11			Influent	2.21		

Table Appendix B.10. Water quality results of **Zn**, influent is **Stormwater**.

	Zn, Influent: Stormwater (TGV)															
	2hours				6hours				16hours				24hours			
-	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc. (µg/L)	Removal efficiency(%)	St.Dev
Dissolved	A	11.91	62.25	18.17	A	8.72	72.94	4.23	A	9.06	61.11	37.73	A	8.67	8.67	2.06
	B	19.69	49.55	-	B	11.62	58.71	-	B	7.61	66.02	-	B	8.83	8.83	-
	C	14.99	53.36	33.15	C	17.83	41.00	34.33	C	7.36	65.80	20.33	C	10.13	10.13	12.71
	D	20.78	30.80	25.76	D	19.74	24.52	29.49	D	14.98	26.14	30.93	D	13.77	13.77	0.52
-	Influent	24.19			Influent	23.79			Influent	20.17			Influent	34.05		
Particulate	A	0.73	79.90	20.90	A	0.21	95.89	7.12	A	0.99	70.73	21.29	A	3.49	-15.56	108.64
	B	4.96	-35.89	-	B	0.02	99.50	-	B	0.42	87.71	-	B	1.16	62.16	-
	C	2.60	28.73	64.27	C	1.67	64.08	62.21	C	1.33	59.72	34.92	C	3.10	-1.19	134.03
	D	0.95	73.84	45.31	D	1.18	73.09	46.61	D	0.54	82.67	19.83	D	0.25	91.76	11.65
-	Influent	3.65			Influent	3.97			Influent	3.10			Influent	3.12		

Table Appendix B.11. Water quality results of **NO_3**, influent is **Surface water**.

NO3, Influent: Surface Water (TGV)																
2hours				6hours				16hours				24hours				
Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
A	0.89	12.29	1.78	A	0.91	43.07	1.05	A	1.22	-80.64	25.81	A	0.88	-5.57	11.47
B	0.73	30.19	-	B	0.91	43.47	-	B	0.56	13.11	-	B	0.87	-2.29	-
C	0.83	18.56	7.32	C	0.80	49.31	0.56	C	1.54	-84.84	26.26	C	0.86	-0.58	-
D	0.81	22.56	6.59	D	1.04	36.02	2.48	D	1.01	-58.81	41.00	D	0.89	-6.55	34.62
Influent	1.09			Influent	1.62			Influent	0.74			Influent	0.86		

Table Appendix B.12. Water quality results of **PO_4**, influent is **Surface water**.

PO4, Influent: Surface Water (TGV)																
2hours				6hours				16hours				24hours				
Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
A	0.61	60.99	0.22	A	-	-	-	A	0.51	69.44	1.59	A	0.54	35.37	3.87
B	0.73	54.91	-	B	0.88	53.18	-	B	0.54	70.54	-	B	1.03	-22.36	-
C	0.62	62.51	-	C	-	-	-	C	0.52	71.85	-	C	-	-	-
D	0.60	63.51	0.34	D	0.69	63.87	1.03	D	0.52	71.78	0.66	D	0.73	14.24	2.00
Influent	1.70			Influent	1.89			Influent	2.10			Influent	0.85		

Table Appendix B.13. Water quality results of **Turbidity**, influent is **Stormwater**.

Turbidity, Influent: Stormwater (TGV)																
2hours				6hours				16hours				24hours				
Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev
A	0.44	88.37	2.04	A	0.60	71.25	6.99	A	0.51	86.43	1.62	A	0.61	45.15	3.64
B	1.00	73.61	-	B	0.22	89.76	-	B	0.36	90.53	-	B	0.49	55.98	-
C	0.71	81.24	7.66	C	0.51	75.52	5.71	C	0.77	79.56	2.60	C	0.75	33.33	3.38
D	0.31	91.91	0.66	D	0.28	86.81	3.40	D	0.25	93.30	0.21	D	0.28	75.33	2.57
Influent	3.79			Influent	2.10			Influent	3.78			Influent	1.12		

Table Appendix B.14. Water quality results of **Turbidity**, influent is **Surface water**.

Turbidity, Influent: Surface Water (TGV)												
2hours				6hours				16hours				24hours			
Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(NTU)	Removal efficiency(%)	St.Dev
A	0.47	65.89	7.94	A	0.45	65.27	5.13	A	0.42	72.57	0.93	A	0.48	61.08	22.23
B	0.47	65.87	-	B	0.72	43.95	-	B	0.52	65.79	-	B	0.47	62.02	-
C	0.61	56.06	2.98	C	0.51	60.72	5.29	C	0.56	63.11	17.51	C	0.63	49.60	9.81
D	0.56	59.52	6.99	D	0.44	66.20	3.98	D	0.52	65.75	7.93	D	0.52	57.85	5.17
Influent	1.38			Influent	1.29			Influent	1.52			Influent	1.24		

Table Appendix B.15. Water quality results of **UV254**, influent is **Surface water**.

UV254, Influent: Surface Water (TGV)												
2hours				6hours				16hours				24hours			
Biofilter	Conc.	Removal efficiency(%)	St.Dev	Biofilter	Conc.	Removal efficiency(%)	St.Dev	Biofilter	Conc.	Removal efficiency(%)	St.Dev	Biofilter	Conc.	Removal efficiency(%)	St.Dev
A	0.11	75.27	1.94	A	0.13	69.65	0.70	A	0.06	86.84	1.68	A	0.14	65.91	9.33
B	0.37	14.88	-	B	0.41	2.17	-	B	0.49	-7.54	-	B	0.40	-1.25	-
C	0.17	59.53	40.12	C	0.11	73.75	1.48	C	0.13	71.32	34.31	C	0.12	70.18	2.79
D	0.26	39.15	37.83	D	0.40	4.51	3.45	D	0.23	49.37	28.43	D	0.41	-3.93	7.73
Influent	0.43			Influent	0.41			Influent	0.45			Influent	0.40		

Table Appendix B.16. Water quality results of **UV254**, influent is **Stormwater**.

UV254, Influent: Stormwater (TGV)												
2hours				6hours				16hours				24hours			
Biofilter	Conc.	Removal efficiency(%)	St.Dev	Biofilter	Conc.	Removal efficiency(%)	St.Dev	Biofilter	Conc.	Removal efficiency(%)	St.Dev	Biofilter	Conc.	Removal efficiency(%)	St.Dev
A	0.05	70.54	1.34	A	0.05	68.86	0.60	A	0.05	68.07	0.60	A	0.05	83.27	0.55
B	0.19	-8.14	-	B	0.17	1.20	-	B	0.17	0.60	-	B	0.16	44.09	-
C	0.04	74.22	2.04	C	0.13	24.35	84.36	C	0.05	72.09	0.35	C	0.04	85.30	0.36
D	0.19	-9.69	10.01	D	0.16	3.19	0.69	D	0.16	5.42	0.60	D	0.15	45.40	0.55
Influent	0.17			Influent	0.17			Influent	0.17			Influent	0.28		

Table Appendix B.17. Water quality results of **DOC**, influent is **Surface water**.

DOC, Influent: Surface Water (TGV)												
2hours				6hours				16hours				24hours			
Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
A	6.03	52.38	2.74	A	6.80	44.92	2.07	A	3.98	69.85	3.06	A	2.77	79.57	1.15
B	5.48	56.74	-	B	12.26	0.65	-	B	10.26	22.21	-	B	10.74	20.74	-
C	7.50	40.81	31.64	C	6.13	50.29	1.32	C	5.77	56.29	25.84	C	2.53	81.33	0.44
D	9.68	23.58	28.90	D	12.09	2.05	0.86	D	7.96	39.67	22.45	D	8.70	35.83	1.85
Influent	12.67			Influent	12.34			Influent	13.19			Influent	13.55		

Table Appendix B.18. Water quality results of **DOC**, influent is **Stormwater**.

DOC, Influent: Stormwater (TGV)												
2hours				6hours				16hours				24hours			
Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev	Biofilter	Conc.(mg/L)	Removal efficiency(%)	St.Dev
A	6.66	46.00	8.24	A	7.45	31.04	10.78	A	6.62	19.76	2.18	A	4.37	60.95	1.58
B	7.75	37.17	-	B	10.87	-0.65	-	B	10.37	-25.64	-	B	8.20	26.75	-
C	6.61	46.43	13.47	C	7.53	30.26	6.45	C	6.76	18.14	6.00	C	4.53	59.53	1.08
D	11.54	6.48	6.99	D	10.96	-1.48	6.99	D	8.93	-8.19	4.83	D	7.27	35.04	3.51
Influent	12.34			Influent	10.80			Influent	8.25			Influent	11.19		

8.3 Appendix C

This section contains the code for running and calling the SWMM file using the PySWMM package. The code encompasses tasks such as installing the PySWMM package, configuring the file, specifying control conditions, running the file, performing secondary calculations, and generating images.

8.3.1 PySWMM code block

```
pip install pyswmm
# install pyswmm package, delete "#" and run the code
# You just need to install the package once; you do not need to install this package every time
```

```
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
from pyswmm import Simulation, Nodes, Links, Output,Subcatchments,RainGages,SystemStats
%load_ext autoreload
%autoreload 2
import pandas as pd
from pandas.plotting import scatter_matrix
import numpy as np
import pyswmm.toolkitapi as tka
```

```
"""
System Info:

"""
with Simulation(r'file_name.inp') as sim:  # run SWMM file, SWMM file is .inp file
print("Simulation info")
flow_units = sim.flow_units
print("Flow Units: {}".format(flow_units))  # print project Flow Unit
system_units = sim.system_units
print("System Units: {}".format(system_units))
print("Start Date: {}".format(sim.start_time))  # print Start Date
print("Start Date: {}".format(sim.end_time))  # print End Date
```

```
"""
Control:

"""

# Add control rules
```

```
control_object_1 = Control(name='R1',
                    conditions=[Control._Condition('IF', 'PUMP', '20', 'TIMEOPEN', '>', 2)],
                    actions_if=[Control._Action('PUMP', '20', 'STATUS', '=', 'OFF')],
                     priority=2)
control_object_2 = Control(name='R2',
                     conditions=[Control._Condition('IF', 'PUMP', '20', 'TIMECLOSED', '>', 24)],
                     actions_if=[Control._Action('PUMP', '20', 'STATUS', '=', 'ON')],
                     priority=3)

inp = SwmmInput('file_name.inp')
inp.add_obj(control_object_1)
inp.add_obj(control_object_2)  # Add control rules
inp.write_file("file_name.inp")    # Write rules to SWMM
```

```
"""
SWMM Run:

"""

swmm5_run('file_name.inp', progress_size=100)
with Simulation(r'file_name.inp') as sim:
    Bio = Nodes(sim)["Biofilter"]
    Buffer = Nodes(sim)["Buffer"]
    Ground1 = Nodes(sim)["Groundwater"]
    Link20 = Links(sim)['20']
    Link21 = Links(sim)['21']
    system_routing = SystemStats(sim)
    sump = Nodes(sim)["Pumpsump"]

    # Initialize Lists for storing data
    time_stamps = []  # Time
    node_depth = []  # Depth of Biofilter
    link20_flow = []  # Flow rate that from pumpsump to biofilter
    link21_flow = []  # Flow rate that from biofilter to groundwater
    Gvolume = []  # Infiltration water
    totalwater = []  # Total volume of water

    sim.step_advance(3600)
    for ind, step in enumerate(sim):    # Launch a simulation
        time_stamps.append(sim.current_time)  # Append time
        node_depth.append(Bio.depth)  # Depth of biofilter
        link20_flow.append(Link20.flow)
        link21_flow.append(Link21.flow)
        Gvolume.append(Ground1.volume)  # Append water that infiltration to the groundwater
        totalwater.append(system_routing.routing_stats['wet_weather_inflow'])
water_loss =[totalwater[i]-Gvolume[i] for i in range(0,len(totalwater))]  # Calculate water loss, Water loss = Total water - Infiltration water
```

```
"""
Graph:

"""
fig = plt.figure(figsize=(8,4), dpi=200) #Inches Width, Height
```

```
fig.suptitle("Retention time = 24 hours")
# Plot from the results compiled during simulation time
axis_1 = fig.add_subplot(2,1,1)
axis_1.plot(time_stamps,node_depth, '-g', label="Depth of Biofilter")
# Plot from the output file
axis_1.set_ylabel("Depth (m)")
#axis_1.get_xticklabels().set_visible(False) # turns off the labels
axis_1.grid("xy")
axis_1.legend(loc="upper right")
# Second Axis
axis_2 = fig.add_subplot(2,1,2, sharex=axis_1)
axis_2.plot(time_stamps, totalwater, ls='-', color = 'g',label="Total water")
axis_2.plot(time_stamps, Gvolume, ls='-', color = 'b',label="Water Collection")
axis_2.plot(time_stamps, water_loss, ls='-', color = 'r',label="Water loss(Flooding+Overflow)")
axis_2.set_ylabel("Volume (m3)")
axis_2.xaxis.set_major_formatter(mdates.DateFormatter('%m-%d %Hh'))
axis_2.legend(loc="upper left")
axis_2.grid("xy")

fig.autofmt_xdate()
plt.tight_layout()
plt.savefig("Retention time 24 hours.PNG")
plt.show()
```

8.4 Appendix D

This section details the equipment used, outlines specific steps in the sampling process, and describes the procedures for preparing and analyzing samples.

8.4.1 Preparation

Table 8.4.1.: Equipment for sampling in the Green Village

General equipment		Measurement equipment	
Gloves	1 pair	EC meter	
Vessels	6—8	DO meter	
0.45 µm syringe filter	4	PH meter	
Buckets	2	Peristaltic pump (with tubes)	
Tissues	-	AquaSound	
Notebook+pencil	1	Cooler/ice cubes	1
Demi water bottle (refill in water lab)	1	Marker pen	1
Key of Pump Box		Racks	1/2

8.4.2 Before start

- Take peristaltic pump and tubes from water lab in cabinet.
- Check and calibrate the EC/DO/PH meters in water lab.
- Put everything in right place and wear gloves.
- Open influent well and measure EC/PH/DO, write numbers and time down.
- Open effluent well and pump system box, write down the water level.
- Measure the initial EC/DO/PH in effluent well.

8.4.3 In experiment

- Meters fixed on the side of effluent well.
- Link the effluent well and bucket with peristaltic pump.
- Turn the pump button to "Manual" and record the time.
- Open peristaltic pump to collect water, write down the flow rate of pump.
- Before taking a sample, flush container with effluent water. Close the peristaltic pump.
- Take samples from bucket (2ICP-OES, 1IC, 1DOC 1UV254, 1Turbidity) (take samples before effective pore volume, the Green Village 43 mins)
- Close biofilter pump and check how much water left in buffer tank.

8.4.4 After experiment

- Make a dissolved sample with 0.45µm syringe (filter with 0.2µm in water lab)
- Classify samples and label them.
- Clean the meters with demi water and put them into box.
- Clean the workspace and manage every equipment.
- Lock the biofilter pump box.

8.4.5 Close off

- Return equipment and key back to FieldFactors' office.
- Put water sample to fridge in water lab, still the sample.
- Measure the UV254(Absorption) and Turbidity in green lab.
- Further filter the sample with 0.2μm for ICP-OES and IC, sample acidified for ICP-OES (HNO3)(in blue lab),DOC (HCL) (in yellow lab)
- Water quality analysis in water lab and IHE Delft.

8.5 Appendix E

The biofilter at Cromvliet Park was also sampled, and the influent was a mixture of stormwater and surface water. Sampling retention times were set at 2 hours and 14 days. The sampling date was May 30. Composite sampling and grab sampling of effluent samples were collected. It is noteworthy that the biofilter at Cromvliet Park exhibits a structural similarity (biofilter material: technical sand) to that of Green Village but has a surface area of 30 m2 and a depth of 1.1m. There were no tracer test experiments were performed on the Cromvliet Park biofilter, it may exhibit preferential flow, thereby increasing the uncertainty in the water quality measurement data. The water quality results for Cromvliet Park are presented in this section.

Table 8.5.1.: Turbidity, pH, DOC and UV254 in Cromvliet park with retention time 2 hours and 14 days.

Retention time	Sample type	Turbidity (NTU)	pH	DOC (mg/L)	UV254
2 hours	Influent	3.7	7.1	10.2	0.3
	ffluent (composit	0.8	6.8	8.2	0.3
	Effluent (grab)	0.9	7	9.5	0.3
14 days	Influent	3.1	7.3	9.7	0.3
	ffluent (composit	0.8	6.9	10.1	0.3
	Effluent (grab)	0.8	7	9.6	0.3

Table 8.5.2.: Concentration of Cl^-, NO_3^-, PO_4^{3-}, SO_4^{2-} and NH_4^+ in Cromvliet park with retention time 2 hours and 14 days.

Retention time	Sample type	Cl^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	SO_4^{2-} (mg/L)	NH_4^+ (mg/L)
2 hours	Influent	14.4	4.7	1.4	30.5	0.63
	Effluent (composite)	9.5	6.6	1.6	17	0
	Effluent (grab)	13.1	8.8	1.6	28.4	0
14 days	Influent	13	4.4	1.4	27.4	0.46
	Effluent (composite)	9.6	4.4	0.8	19.7	0
	Effluent (grab)	10.9	6.6	0.8	19.4	0

Table 8.5.3.: Concentration of dissolved and particulate metals in Cromvliet park with retention time 2 hours and 14 days.

Retention time	Sample type		Ca (mg/L)	Mg (mg/L)	Sr (µg/L)	Mn (µg/L)	Ba (µg/L)	Zn (µg/L)
2 hours	Influent	Dissolved	77.74	5.24	294.42	207.66	31.25	9.19
		Particulate	8.42	0.65	13.03	5.5	0.76	5.01
	Effluent (composite)	Dissolved	77.47	4.95	314.65	17.55	23.04	11.24
		Particulate	2.22	0.38	4.67	0.12	1.07	1.11
	Effluent (grab)	Dissolved	83.81	5.25	298.51	19.37	21.16	12.22
		Particulate	1.78	0.22	9.24	1.05	0.71	0.13
14 days	Influent	Dissolved	69.4	4.73	294.78	203.8	31.13	16.71
		Particulate	18.5	1	9.76	20.75	2.77	2.35
	Effluent (composite)	Dissolved	66.13	4.61	268.44	34.66	21.97	16.3
		Particulate	8.95	0.26	4.44	0.42	0.49	4.28
	Effluent (grab)	Dissolved	53.22	3.37	259.02	19.48	20.03	13.26
		Particulate	22.23	1.48	19.14	1.2	0.46	1

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