Assessment of Constructed Wetland Systems for Stormwater Pollution Control in Luxembourg: A Water Quality Monitoring Approach in Compliance with Environmental Regulations

Auteur : Beirós de Sousa, Patrick
Promoteur(s) : 12783; Wellens, Joost
Faculté : Faculté des Sciences
Diplôme : Master en sciences et gestion de l'environnement, à finalité spécialisée
Année académique : 2025-2026
URI/URL : http://hdl.handle.net/2268.2/26533

Faculty of Science, Technology and Medicine

LIÈGE université Sciences Arlon Campus Environnement

Master in Sustainable Development
Focus: Energy and Environment (Uni.lu)

Master’s in environmental sciences and management
Focus: Renewable Energies and Sustainable Buildings (uliege)

Master Thesis

By

Patrick Beiros de Sousa

023260574E

Assessment of Constructed Wetland Systems for Stormwater Pollution Control in Luxembourg: A Water Quality Monitoring Approach in Compliance with Environmental Regulations

Supervisor: Prof. Dr.-Ing. Joachim Hansen

Co-Supervisor: Prof Dr.-Ing Joost Wellens

Reviewer: Dr. Yamini Mittal

Academic Year 2025-2026

Auteur du présent document : BEIROS DE SOUSA Patrick,

Beirospatrick.pb@gmail.com

Abstract

Urban stormwater runoff is a major source of diffuse pollution in urban and peri-urban environments. During rainfall events, runoff from impervious surfaces such as roads, rooftops and parking areas can mobilise suspended solids, nutrients, heavy metals, hydrocarbons and organic matter, thereby degrade receiving water bodies and increase hydrological pressure on drainage systems.

To address these environmental challenges, sustainable stormwater treatment strategies are increasingly required, particularly in the context of urban expansion and climate variability. Among these, constructed wetlands (CW) are widely recognised as a promising nature-based solution because they combine pollutant removal with hydraulic buffering and low-energy operation. Their performance, however, depends strongly on local design conditions, hydraulic loading and rainfall variability. In particular, the first-flush phenomenon can influence the timing and magnitude of pollutant transport during storm events, making event-based monitoring essential for a reliable assessment of treatment efficiency.

In a European context, stormwater management (SM) is guided by regulatory frameworks such as the Water Framework Directive (WFD) and technical guidelines including DWA-A 102, which emphasise the control of particulate pollution, particularly fine fraction of suspended solids (<63 µm) (AFS63), due to their strong association with pollutant transport.

This thesis evaluates the performance of CW systems (CWs) for stormwater pollution control in Luxembourg, with a particular focus on the AFS63 and associated macropollutants (MaPs). Two case study sites, Raemerich and Steinfort, were selected because they represent contrasting runoff conditions and treatment system configurations.

The study is based on water-quality monitoring during rainfall events and examines pollutant dynamics, first-flush behaviour and treatment performance under real operating conditions. By comparing observed concentrations and loads with relevant emission-based assessment frameworks and current environmental regulations, this work aims to provide a site-specific evaluation of CW performance and to support the development of more effective and compliant SM strategies in Luxembourg.

Résumé

Les eaux de ruissellement urbaines constituent une source majeure de pollution diffuse dans les environnements urbains et périurbains. Lors des événements pluvieux, le ruissellement provenant de surfaces imperméables telles que les routes, les toitures et les parkings peut mobiliser des matières en suspension, des nutriments, des métaux lourds, des hydrocarbures et de la matière organique, dégradant ainsi les milieux récepteurs et augmentant les contraintes hydrauliques sur les systèmes de drainage.

Afin de répondre à ces défis environnementaux, des stratégies de gestion durable des eaux pluviales sont de plus en plus nécessaires, en particulier dans un contexte d'urbanisation croissante et de variabilité climatique. Parmi celles-ci, les zones humides construites (constructed wetlands) (CW) sont largement reconnues comme une solution fondée sur la nature prometteuse, car elles combinent l'élimination des polluants avec une régulation hydraulique et un fonctionnement à faible consommation énergétique. Toutefois, leurs performances dépendent fortement des conditions locales de conception, des charges hydrauliques et de la variabilité des précipitations. En particulier, le phénomène de « first flush » peut influencer le moment et l'intensité du transport des polluants lors des événements pluvieux, rendant un suivi basé sur les événements indispensable pour une évaluation fiable de l'efficacité du traitement.

Dans un contexte européen, la gestion des eaux pluviales est encadrée par des cadres réglementaires tels que la Directive-cadre sur l'eau ainsi que par des guides techniques, notamment la DWA-A 102, qui mettent l'accent sur le contrôle de la pollution particulaire, en particulier les matières en suspension fines (AFS63), en raison de leur forte association avec le transport des polluants.

Ce travail de thèse évalue les performances de systèmes de zones humides construites pour le traitement des eaux pluviales au Luxembourg, avec un accent particulier sur la fraction fine des matières en suspension (AFS63) et les macropolluants associés. Deux sites d'étude, Raemerich et Steinfort, ont été sélectionnés car ils représentent des conditions de ruissellement et des configurations de systèmes de traitement contrastées.

L'étude repose sur un suivi de la qualité de l'eau lors d'événements pluvieux et analyse la dynamique des polluants, le comportement du first flush et les performances de traitement dans des conditions réelles d'exploitation. En comparant les concentrations et les charges observées avec des cadres d'évaluation basés sur les émissions ainsi qu'avec les réglementations environnementales actuelles, ce travail vise à fournir une évaluation spécifique aux sites des performances des zones humides construites et à soutenir le développement de stratégies de gestion des eaux pluviales plus efficaces et conformes au cadre réglementaire au Luxembourg.

Acknowledgements

I would like to express my sincere gratitude to Dr. Professor Joachim Hansen from the University of Luxembourg for supervising this thesis and for welcoming me into his team. His guidance, valuable insights, and continuous support throughout this work have been greatly appreciated. Being part of his research environment has been an enriching experience that contributed significantly to both my academic and professional development.

I also wish to thank Dr. Yamini Mittal for her role as reviewer and for her scientific support throughout this project. Her constructive feedback, methodological guidance, and availability have been instrumental in shaping the quality and direction of this research.

I also wish to thank Dr. Silvia Venditti, who contributed to the definition of the thesis topic and facilitated the initial coordination of this work. Her support during the early stages of the project is gratefully acknowledged.

Table of content

List of Figures

List of Tables

List of Abbreviations

AFS63 - Fine Fraction of Suspended Solids (<63 µm)

AS - Autosampler / automated Sampling

BMPs - Best Management Practices

Cl^- - Chloride

COD - Chemical Oxygen Demand

Cu - Copper

CW - Constructed Wetland

CWs - Constructed Wetland Systems

DO - Dissolved Oxygen

EC - Electrical Conductivity

EU - European Union

FE - Final Effluent

GS - Grab Sampling

HLR - Hydraulic Loading Rate

HRT - Hydraulic Retention Time

IC - Inorganic Carbon

ICs - Inlet channels

LID - Low Impact Development

MaPs - Macropollutants

MPs - Micropollutants

N - Nitrogen

Na^+ - sodium

NBS - Nature-Based Solutions

NH_4^+ - Ammonium

ORP - redox potential

OPs - Organic Pollutants

P - Phosphorus

pH - Potential of Hydrogen

SM - Stormwater Management

SO_4^{2-} - Sulphate

TC - Total Carbon

TOC - Total Organic Carbon

TSS - Total Suspended Solids

UWWTD - Urban Wastewater Treatment Directive

VF - Vertical Flow

VFCW - Vertical Flow Constructed Wetland

WFD - Water Framework Directive

Zn - Zinc

1 Introduction

1.1 Background and Context

Urbanisation and climate change have significantly modified the hydrological behaviour of catchments, particularly in urban and peri-urban environments. The expansion of impervious surfaces such as roads, rooftops and parking areas reduces infiltration capacities, increases runoff volumes, and accelerates flow velocities during rainfall events Consequently, urban stormwater runoff plays a crucial role in the mobilisation and transport of particulate and dissolved pollutants originating from impervious urban surfaces (Lucas et al., 2014; Meyer et al., 2011).

In developed catchments, stormwater runoff is now recognised as a dominant source of diffuse pollution, often exceeding point-source contributions during wet weather conditions. Pollutant mobilisation from urban surfaces occurs primarily through wash-off processes, atmospheric deposition, and erosion of sediments accumulated on impervious areas and within drainage systems. These processes typically generate short-lived but highly concentrated pollution pulses, which can lead to acute stress on aquatic ecosystems (Meyer et al., 2011).

A key characteristic of stormwater pollution is its strong temporal variability during rainfall events. Numerous studies have documented the so-called *first flush* phenomenon, where a disproportionate fraction of the total pollutant load is transported during the initial phase of runoff. This effect has been observed for suspended solids, metals, hydrocarbons, pesticides and pharmaceuticals, particularly in small to medium-sized urban catchments (Meyer et al., 2011). This is mainly because these catchments exhibit short runoff travel times and limited mixing processes, which allow early pollutant peaks to be more clearly observed and directly linked to the initial runoff phase. Such event-driven dynamics challenge conventional monitoring approaches and complicate the assessment of stormwater impacts on surface water quality.

To address these challenges, nature-based solutions (NBS) have increasingly been promoted as sustainable alternatives to conventional grey infrastructure in urban water management. Among these solutions, CW have been widely studied for their capacity to treat stormwater through a combination of sedimentation, filtration, adsorption and biological transformation processes. CW are characterised by low energy demand, operational simplicity and the provision of additional ecosystem services such as biodiversity support and landscape integration (Simperler et al., 2020).

However, the treatment performance of CWs is highly dependent on local conditions, including hydraulic loading, rainfall characteristics, sediment accumulation and internal biogeochemical processes. Research has shown that sediments within wetlands can function both as sinks and potential secondary sources of pollutants, particularly nutrients and sediment-bound contaminants, which may affect long-term treatment efficiency if not properly managed (Venditti et al., 2022). This highlights the need for detailed, event-based water quality monitoring to capture pollutant behaviour under realistic stormwater conditions.

At the regulatory level, European SM strategies are increasingly aligned with the objectives of the revised Urban Wastewater Treatment Directive (UWWTD) (*Directive (EU) 2024/3019*, 2024), which reinforces the control of pollution from urban drainage systems, including during wet-weather events. In this context, emission-based approaches are increasingly emphasised. The guideline DWA-A 102-2 establishes assessment criteria and target values for suspended solids and sediment-associated pollutants in stormwater discharges, explicitly encouraging decentralised treatment systems and NBS as part of integrated urban drainage strategies (*Arbeitsblatt DWA-A 102-2/BWK-A 3-2*, 2022). Although developed in Germany, this framework is increasingly referenced across Europe as a technical benchmark for stormwater pollution control.

These European regulatory principles provide the general framework within which national strategies are developed and implemented.

In Luxembourg, the management of aquatic environments faces significant pressure from urban expansion and the resulting diffuse pollution. The Water Management Agency (AGE) established a national strategy in July 2020, targeting a minimum of 80% elimination efficiency for key indicator substances, specifically Diclofenac, Carbamazepine, Clarithromycin, and Benzotriazole (Brunhoferova, 2022; Venditti et al., 2022). While advanced treatments like ozonation are suited for large facilities, rural catchments such as the Sûre and Mess river basins require sustainable, low-energy alternatives. NBS have emerged as a technically viable approach for improving water quality in small and sensitive catchments, particularly where conventional intensive treatments are not suitable. CWs represent one such solution, offering low-energy operation, hydraulic buffering and pollutant retention through a combination of physical, chemical and biological processes. These characteristics make CWs particularly relevant for decentralised SM in rural and peri-urban areas (Venditti et al., 2022).

Within this context, CWs represent a promising option for stormwater pollution control in Luxembourg, aligning with European regulatory trends and national sustainability objectives. Nevertheless, robust, site-specific performance assessments based on continuous and eventoriented water quality monitoring are still required to support their effective implementation. Addressing this knowledge gap is essential for improving SM practices and ensuring the protection of receiving water bodies under current and future hydrological conditions.

1.2 Problem Statement

Despite the growing recognition of stormwater runoff as a major source of diffuse pollution, its contribution to surface water degradation remains insufficiently quantified and managed, particularly under event-driven conditions. A major technical challenge in managing urban runoff is the high affinity of contaminants for the AFS63 of total suspended solids (TSS). According to the DWA-A 102-2 framework, particles between 0.45 µm and 63 µm are responsible for transporting approximately 70% to 90% of the total pollutant mass in urban runoff, as they provide a large reactive surface for the adsorption of metals and hydrophobic organic compounds. Traditional monitoring strategies, which often rely on low-frequency or grab sampling (GS), rarely account for this particulate-bound transport, leading to a systematic underestimation of the toxic loads discharged into sensitive receiving waters (*Arbeitsblatt DWA-A 102-2/BWK-A 3-2*, 2022)

In urban catchments, pollutant transport is highly episodic and strongly controlled by rainfall characteristics, antecedent dry periods and catchment reactivity. As a result, conventional water quality assessments based on average concentrations fail to capture peak pollutant loads occurring during storm events, particularly during the initial phase of runoff. This limitation is especially critical for sediment-bound pollutants associated with AFS63, which are mobilised rapidly during rainfall events and may generate short-lived but highly concentrated pollution pulses (Lucas et al., 2014; Meyer et al., 2011).

In Luxembourg, this issue is exacerbated by the country’s geomorphological and hydrological characteristics. Catchments are generally small, steep and highly reactive, such as those of the Mess and the Sûre rivers. These conditions favour a pronounced first-flush phenomenon, during which a significant fraction of pollutant loads is transported within a very short time window. Field observations in similar contexts have shown that such storm-driven pulses can frequently exceed Environmental Quality Standards (EQS), while remaining undetected by conventional low-frequency monitoring programmes. This creates a substantial knowledge gap regarding the true magnitude of stormwater-related pollution in Luxembourgish river basins (Meyer et al., 2011).

This limitation is particularly relevant for decentralised stormwater treatment systems such as CWs. While CWs are widely promoted as NBS for stormwater pollution control, their performance under highly dynamic hydraulic and pollutant loading conditions remains insufficiently documented. Most existing studies focus on long-term average removal efficiencies, providing limited insight into short-term processes such as first-flush dynamics, sediment mobilisation and transient pollutant breakthrough during storm events. Consequently, there is a lack of robust, event-based evidence demonstrating whether CWs are capable of effectively controlling AFS63-associated pollutant loads under real stormwater conditions (Lucas et al., 2014).

From a regulatory and technical perspective, this knowledge gap represents a critical challenge for the practical implementation of SM strategies. While emission-based assessment frameworks such as DWA-A 102-2 emphasise the importance of event-related pollutant loads, their application remains difficult under highly dynamic stormwater conditions. In parallel, national water management strategies in Luxembourg have introduced ambitious performance targets for micropollutant reduction (Brunhoferova, 2022). Although originally defined for wastewater effluents, these benchmarks increase expectations regarding the protection of surface waters and highlight the need for reliable, event-based performance assessments of stormwater treatment systems.

While NBS are increasingly promoted within this regulatory context, there is currently a lack of site-specific field data demonstrating that CWs particularly those incorporating innovative treatment media such as activated biochar admixtures, can consistently meet such performance expectations under fluctuating hydraulic loads. Without an event-based monitoring approach capable of capturing AFS63 dynamics and first-flush behaviour, the technical adequacy and regulatory relevance of CWs in the Luxembourgish context remain insufficiently validated.

1.3 Research Objectives

The primary objective of this study is to assess the effectiveness of CWs for stormwater pollution control in Luxembourg, with a specific focus on the removal of the AFS63 and associated MaPs under real rainfall conditions. The study aims to evaluate whether CWs operated as decentralised stormwater treatment systems are capable of meeting emission-oriented performance expectations commonly applied in the Luxembourgish context (Brunhoferova, 2022).

To address this overall objective, the following specific objectives are defined:

- Examining two different stormwater runoff sites in Luxembourg namely Raemerich and Steinfort with different pollution profile and catchment characteristics equipped with CWs for stormwater runoff treatment.
- Characterizing stormwater pollutant dynamics during rainfall events, with particular emphasis on the temporal variability and first-flush behaviour of AFS63 along with MaPs in small Luxembourgish catchments.
- To quantify, at both sites, the relationship between hydrological conditions (rainfall intensity, runoff volume and hydraulic loading) and pollutant removal efficiency, with particular attention to the stability of treatment performance under variable hydraulic loads.
- To assess treatment efficiency by comparing pollutant concentrations at inlet channels (ICs) and CW effluent (outlet) points, with particular attention to variations during rainfall events and first flush conditions, and in relation to emission-based regulatory benchmarks (e.g., DWA-A 102-2 for AFS63).
- To provide operational insights and recommendations for SM using CWs, supporting the implementation of emission-oriented stormwater control strategies.

1.4 Research Questions and Hypotheses

Based on the identified research problem and the defined objectives, this study is guided by a set of research questions focusing on stormwater pollutant dynamics and the performance of CWs under event-driven conditions in Luxembourg. The questions are formulated to explicitly address sediment-bound pollution, first-flush processes and regulatory performance expectations.

Research Questions

1. How do concentrations and loads of the AFS63 and MaPs such as COD, ammonium (NH_4^+) and orthophosphate evolve during storm events in small Luxembourgish catchments?
2. To what extent do CWs reduce AFS63 and MaPs loads under real stormwater conditions, particularly during rainfall events characterised by strong first-flush behaviour?
3. How do rainfall characteristics and hydraulic loading conditions influence the pollutant removal efficiency of CWs during storm events?
4. Do stormwater discharges treated by CWs comply with emission-based performance benchmarks for AFS63 defined in the DWA-A 102-2 framework and with nationally applied reference targets for MaPs reduction in Luxembourg?

Research Hypotheses

Based on existing scientific literature, regulatory assumptions and the hydrological context of Luxembourg, the following hypotheses are formulated:

- H1: Stormwater pollutant loads in Luxembourgish catchments are dominated by a pronounced first-flush effect, whereby a significant proportion of AFS63 associated mass is transported during the initial phase of runoff.
- H2: CWs achieve substantial reductions of AFS63 and associated MaPs during storm events through the combined action of physical retention, adsorption processes biological mechanisms and vegetation/plant uptake and assimilation.
- H3: Pollutant removal efficiency in CWs decreases during high-intensity rainfall events when hydraulic retention time (HRT) are reduced, and hydraulic loading temporarily exceeds system capacity.
- H4: Under typical stormwater conditions CWs represent a technically viable solution for achieving emission-based performance benchmarks for sediment-bound pollution and MaPs reduction commonly applied in the Luxembourgish context.

1.5 Scope and Limitations

This study assesses the performance of CWs implemented for stormwater treatment in Luxembourg, with particular attention to rural and peri-urban catchments characterised by rapid hydrological responses. The analysis is based on event-based monitoring of stormwater runoff during rainfall events, which represent critical periods for pollutant mobilisation and transport. Emphasis is placed on the fine fraction of suspended solids (AFS63; 0.45-63 µm) as an indicator of sediment-bound pollution, following emission-based SM frameworks such as DWA-A 102-2. In addition, selected MaPs relevant to surface water protection are analysed to evaluate treatment performance under realistic stormwater conditions.

The performance of CWs is assessed based on site-specific monitoring data collected under real operating conditions at two study sites, Raemerich and Steinfort. The Raemerich site receives motorway runoff and is designed with a CW primarily targeting sediment-bound pollution, whereas the Steinfort site collects mixed urban runoff from roads and rooftops and consists of a multi-stage CWs. These sites therefore represent contrasting catchment characteristics and pollution profiles, enabling a comparative evaluation of treatment performance under different hydrological and water quality conditions. As such, the results reflect the specific characteristics of the investigated systems, including wetland design, hydraulic capacity, catchment properties and rainfall variability.

A key limitation of this study is its focus on short-term, event-based treatment performance during the monitoring period. Long-term processes such as wetland ageing, progressive substrate saturation, vegetation succession and multi-annual sediment accumulation are beyond the scope of this research and would require extended observation periods incompatible with the temporal framework of this study.

Furthermore, although internal removal mechanisms such as adsorption, phytoremediation and bioremediation are recognised as contributing to pollutant attenuation, the study does not aim to quantify each mechanism individually. Instead, the assessment focuses on overall system performance at the outlet, emphasising effluent quality and emission reduction under dynamic stormwater conditions.

1.6 Structure of the Thesis

This thesis is structured into five chapters.

Chapter 1 introduces the scientific, regulatory and hydrological context of stormwater pollution control in Luxembourg. It presents the research problem, defines the objectives, research questions and hypotheses, and outlines the scope and limitations of the study.

Chapter 2 provides a critical review of the scientific literature related to stormwater pollution processes, first-flush dynamics, sediment-bound contaminants and the application of CWs as NBS treatment systems. Attention is given to emission-based assessment frameworks such as DWA-A 102-2 and their relevance for the Luxembourgish context.

Chapter 3 describes the study area and the applied methodology. This chapter details the characteristics of the investigated catchments and CWs, the event-based monitoring strategy, the analytical methods used for AFS63 determination and MaPs analysis, as well as data processing and evaluation procedures.

Chapter 4 presents and discusses the results of the monitoring campaigns. Stormwater pollutant dynamics CWs treatment performance, first-flush behaviour and compliance with emission-based performance benchmarks are analysed in relation to hydrological conditions and system design.

Chapter 5 summarises the main findings of the study, draws conclusions regarding the effectiveness of CWs for stormwater pollution control in Luxembourg, and provides recommendations for future research and SM practice.

2 Literature Review

2.1 European Regulatory Framework for Urban Wastewater and Stormwater Management

Urban water management within the European Union (EU) is governed by a regulatory framework designed to protect water bodies and limit pollution originating from urban areas. A central component of this framework is the revised UWWTD (Directive (EU) 2024/3019, 2024), which establishes requirements for the collection, treatment and discharge of urban wastewater to prevent negative impacts on receiving waters and aquatic ecosystems. The directive defines urban wastewater as a mixture that may include domestic wastewater, industrial wastewater and precipitation-derived flows collected in urban drainage systems, indicating that rainfall-derived runoff forms part of the urban wastewater system in certain drainage configurations.

In addition to conventional wastewater discharges, the directive recognises that stormwater runoff and overflow events can contribute significantly to urban water pollution. During precipitation events, runoff generated on impervious urban surfaces such as roads, rooftops and other built structures can mobilise accumulated pollutants and transport them into drainage systems and ultimately into receiving water bodies. These discharges may contain suspended solids, organics, inorganics, nutrients, heavy metals and other pollutants/contaminants that can affect the ecological and chemical status of surface waters.

To address these challenges, the revised directive introduces the requirement for Integrated Urban Wastewater Management Plans (Article 5). These plans aim to assess the contribution of wet-weather discharges to pollution loads and to define appropriate mitigation strategies. In this context, stormwater overflows are used as a regulatory threshold to identify critical system conditions, particularly when they exceed 2% of the annual collected urban wastewater load under dry weather conditions. Such exceedance reflects a significant contribution of wet-weather discharges to pollution loads and triggers the need for targeted management and mitigation measures within Integrated Urban Wastewater Management Plans (Article 5; Annex V).

These requirements are further detailed in Annex V, which specifies that Integrated Urban Wastewater Management Plans must include the identification of pollution sources, the assessment of environmental risks related to stormwater discharges, and the implementation of mitigation measures designed to reduce pollutant loads from urban drainage systems. In response to these challenges, the directive also promotes the implementation of sustainable approaches such as NBS to reduce pollutant transport from urban runoff and improve SM.

Overall, the revised UWWTD highlights the increasing importance of SM within European water policy. By requiring integrated planning, improved monitoring and the implementation of mitigation measures, it establishes a regulatory framework aimed at reducing pollution associated with wet-weather flows. Within this context, understanding the environmental importance of urban stormwater runoff and its associated pollutant transport processes becomes essential.(*Directive (EU) 2024/3019*, 2024)

2.2 Environmental Importance of Urban Stormwater Runoff Pollution

Urban stormwater runoff is a major pathway of diffuse pollution in urban environments. The expansion of impervious surfaces such as roads, rooftops and parking areas reduces infiltration and accelerates runoff, promoting the mobilisation and transport of accumulated pollutants to receiving water bodies (Lieske et al., 2021; Y.-Y. Yang & Lusk, 2018).

Stormwater runoff typically contains a broad spectrum of pollutants originating from urban activities and materials present within the catchment. These pollutants/contaminants include suspended solids, organics, inorganics, nutrients, heavy metals, hydrocarbons and other MaPs /micropollutants (MPs). Their presence results from various sources such as atmospheric deposition, traffic-related emissions, building material weathering, urban landscaping practices and other anthropogenic activities. Because these pollutants/contaminants accumulate on surfaces during dry periods and are subsequently washed off during rainfall events, stormwater runoff represents a complex and highly variable source of contamination for receiving waters (Lieske et al., 2021).

Among the different pollutant groups detected in urban runoff, heavy metals are frequently reported and are primarily associated with traffic-related activities. Zinc (Zn), copper (Cu) and lead commonly originate from tyre wear, brake abrasion, vehicle corrosion and atmospheric deposition. Once mobilised by rainfall, these metals are transported through stormwater systems and may accumulate in sediments of receiving water bodies, where they can pose long-term ecological risks (Tsihrintzis & Hamid, 1997). Nutrients such as nitrogen (N) and phosphorus (P) also represent an important category of stormwater pollutants. Their sources include fertilisers, organic debris, atmospheric deposition, pet waste and leaking sewer infrastructure.

Excessive nutrient inputs can lead to eutrophication in receiving water bodies, causing algal blooms, oxygen depletion and degradation of aquatic ecosystems (Y.-Y. Yang & Lusk, 2018).

In addition to these conventional pollutants, recent research has highlighted the growing importance of organic MPs in urban stormwater runoff. These compounds include pharmaceuticals, personal care products, pesticides and other trace organic chemicals originating from urban activities such as road runoff, building materials and landscape management practices. Although typically present at low concentrations, these substances may still pose significant ecological risks due to their persistence, toxicity and potential bioaccumulation (Zheng et al., 2025).

A defining characteristic of stormwater pollution is the strong association between many contaminants and suspended particulate matter. Pollutants such as heavy metals and hydrophobic organic compounds tend to adsorb onto particle surfaces, particularly fine particles with large reactive surface areas. Consequently, suspended solids play a crucial role in the transport and fate of pollutants in urban runoff systems, and parameters related to suspended solids have historically been widely used as indicators for assessing stormwater pollution and evaluating the environmental impact of runoff discharges (Baum et al., 2018; Maniquiz-Redillas et al., 2022).

Because stormwater pollution is closely linked to rainfall-driven runoff processes, pollutant concentrations often vary significantly during storm events. The temporal dynamics of pollutant transport during storm events play an important role in stormwater pollution processes and are further discussed in the following section.

2.3 First Flush Phenomenon and Transport of Particle-Bound Pollutants

The first flush phenomenon describes the tendency for the initial portion of stormwater runoff during rainfall events to contain disproportionately high pollutant concentrations compared with later stages of the event. This occurs because pollutants and contaminants accumulate on urban surfaces during antecedent dry periods and are rapidly mobilised once precipitation begins (Maniquiz-Redillas et al., 2022).

Quantitatively, the first flush effect is often described using empirical indicators. A commonly cited definition suggests that a significant proportion of the total pollutant load may be transported within a relatively small fraction of the runoff volume, particularly during the initial phase of rainfall events when highly concentrated pollutant pulses are generated.

These early runoff volumes can contribute disproportionately to the total contaminant load discharged to drainage systems and receiving waters within a very short time window. However, the magnitude of this phenomenon varies considerably depending on rainfall intensity, catchment characteristics, surface type, and the duration of the antecedent dry period. Consequently, the first flush effect is highly site-specific and may differ significantly between urban catchments (Maniquiz-Redillas et al., 2022).

To better understand this phenomenon, it is essential to analyse the temporal relationship between flow, pollutant concentration, and resulting pollutant loads during storm events. This relationship is typically represented using hydrographs and pollutographs, as illustrated in Figure 1. In addition, cumulative load-volume (L-V) relationships provide a complementary

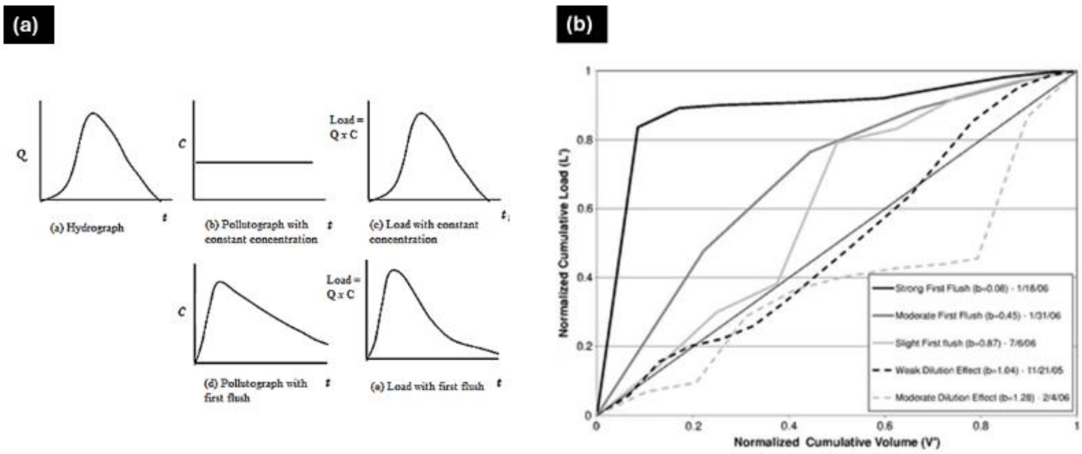


Figure 1. *Conceptual representation of stormwater pollutant transport dynamics:* ***(a)*** *hydrograph, pollutograph and load curves;* ***(b)*** *cumulative load (L') versus runoff volume (V') illustrating first flush behaviour.*

approach to assess how pollutant loads are distributed over the course of a rainfall event and to identify first flush behaviour.(Hathaway et al., 2012; Prodanoff, s. d.)

As shown in Figure 1, the hydrograph represents the temporal evolution of flow, while the pollutograph describes the variation of pollutant concentration over time. Under constant concentration conditions, the pollutant load follows the shape of the hydrograph. However, in the presence of a first flush effect, pollutant concentrations peak early in the event, leading to a pronounced initial load that exceeds what would be expected under uniform conditions. This reflects a temporal decoupling between peak flow and peak pollutant concentration.

This behaviour is further illustrated by cumulative load-volume relationships (Figure 1b). Under uniform transport conditions, the cumulative pollutant load (L') increases proportionally with the cumulative runoff volume (V'), following the 1:1 line.

Deviations above this line indicate that a large fraction of the total pollutant load is transported during the early stages of runoff, which is characteristic of a first flush effect. The magnitude of this deviation can be used to assess the strength of the phenomenon.

Together, these representations demonstrate that pollutant transport during storm events is highly dynamic and often concentrated in the initial phase of runoff. This reinforces the need for event-based analysis to accurately capture short-term pollution peaks that are not reflected in average conditions.

A fundamental characteristic of stormwater pollution during first flush events is the strong association between contaminants and suspended particulate matter. Numerous studies have demonstrated that a large proportion of pollutants present in urban runoff are not transported in dissolved form but are instead adsorbed onto suspended particles. Fine particles are particularly important because they provide large reactive surface areas that facilitate the adsorption of heavy metals and hydrophobic organic compounds (Baum et al., 2018; Dierschke, 2014).

Particles ranging between 0.45 µm to 63 µm, commonly referred to AFS63, are of particular importance in urban stormwater systems. Due to their small size and low settling velocity, these particles remain suspended in the water column and are easily transported through drainage networks into receiving water bodies. At the same time, their large specific surface area enables strong adsorption of pollutants such as Zn, Cu, and lead originating from traffic-related activities. Consequently, AFS63 acts as a major vector for contaminant transport in urban runoff systems(Baum et al., 2018; Dierschke, 2014).

The particle size distribution within the AFS63 fraction is not uniform and depends strongly on the type of contributing surface and local environmental conditions. Studies have shown that the fine fraction (<63 µm) can represent approximately 40% to 90% of TSS in urban runoff, with typical values ranging between 60% and 70% (Dierschke, 2014). However, this proportion varies significantly depending on the source of runoff. For example, roof runoff may contain a substantial proportion of coarser particles (>63 µm), particularly due to pollen, corrosion products or roof material abrasion. In contrast, runoff from traffic surfaces is generally dominated by fine particles originating from tyre wear, brake abrasion and atmospheric deposition.

Further insight into the internal structure of AFS63 has been provided by particle size distribution analyses. Dierschke (2014) observed that approximately one third of particles within the PM63 fraction fall within the size range of 0.45 to 25 µm under certain urban runoff conditions. This indicates that a significant proportion of AFS63 consists of very fine particles, which are particularly relevant due to their high mobility, low settling velocity and strong pollutant adsorption capacity. These finer fractions play a key role in pollutant transport processes and contribute substantially to the elevated contaminant loads observed during the initial stages of stormwater runoff.(Dierschke, 2014)

***Table 1**. Simplified internal subdivision of the AFS63 fraction based on particle size (adapted from Dierschke, 2014)*

Size range (µm)	Fraction description	Indicative proportion	Characteristics
e0.45 - 25	Very fine particles	~30% of AFS63	Highly mobile, strong adsorption capacity, dominant role in pollutant transport
25 - 63	Fine particles	Remaining fraction	Lower mobility, more influenced by sedimentation processes

As shown in Table 1, a considerable proportion of the AFS63 fraction consists of very fine particles, highlighting their key role in driving pollutant transport dynamics in urban stormwater systems.

Beyond their size distribution, the origin and composition of these particles also influence their behaviour. Urban runoff particles originate from a variety of sources, including road dust, tyre and brake wear, atmospheric deposition and corrosion products from urban infrastructure. Their rapid mobilisation during rainfall events contributes significantly to the elevated pollutant concentrations typically observed during the early stages of stormwater runoff (Dierschke, 2014; Lieske et al., 2021).

Because of the strong relationship between fine particles and pollutant transport, the first flush phenomenon represents a critical factor in SM. A large fraction of the total pollutant mass may be discharged during the initial runoff phase, potentially causing short-term but intense pollution pulses in receiving water bodies. Consequently, effective stormwater treatment strategies increasingly focus on capturing or treating the first portion of runoff and on technologies capable of removing fine suspended solids and particle-bound pollutants (Lieske et al., 2021; Maniquiz-Redillas et al., 2022).

Understanding these particle-driven pollutant transport processes is therefore essential for selecting appropriate indicators to assess stormwater pollution and for interpreting treatment performance under event-based conditions.

This is particularly important because the environmental relevance of runoff pollution is strongly linked to the fine suspended fraction, which acts as the main carrier of many sediment-bound contaminants.

2.4 Stormwater Quality Indicators: From COD and TSS to AFS63

The assessment of stormwater pollution relies on water quality indicators that describe pollutant concentrations and loads in runoff. While parameters such as COD and TSS have historically been used as general indicators, several studies have demonstrated the high variability of these parameters in urban stormwater systems.

Reported concentrations in urban runoff show a wide range depending on catchment characteristics and rainfall conditions. For example, TSS concentrations typically range from approximately 50 to over 500 mg/L, while chemical oxygen demand (COD) values commonly vary between 40 and 300 mg/L as summarised in Table 2 (Baum et al., 2018; Fletcher et al., 2015). These variations highlight the dynamic nature of stormwater pollution and the limitations of using bulk parameters alone to characterise pollutant transport processes.

Table 2. *Typical ranges of common stormwater quality indicators reported in literature*

Parameter	Typical range (mg/L)	Source
TSS	50 - 500	(Fletcher et al., 2015)
COD	40 - 300	(Baum et al., 2018)

As shown in Table 2, commonly used bulk parameters such as TSS and COD exhibit high variability across different studies, making it difficult to directly compare stormwater quality or assess treatment performance based on these indicators alone.

In addition to this variability, previous studies have shown that a large proportion of pollutants in urban runoff is associated with the fine fraction of suspended particles. This has led to the development of more specific indicators targeting particle-bound transport processes.

These findings have led to the development of more specific indicators targeting the fine particle fraction. In this context, the parameter AFS63 is used in European SM guidelines to represent the concentration of particles within the size range of 0.45-63 µm and associated sediment-bound pollutants. Compared with traditional parameters such as COD or TSS, AFS63 provides a more process-oriented representation of pollutant transport in urban runoff systems.

This shift towards particle-based indicators is reflected in the German SM guideline DWA-A 102, which uses AFS63 as a central parameter for assessing stormwater emissions and defining acceptable discharge loads. The increasing use of such indicators demonstrates the need to better account for the role of fine particles in pollutant transport and environmental impact.

Understanding these developments is essential for interpreting modern SM strategies. The following section therefore examines the German framework DWA-A 102, which represents one of the most advanced emission-based approaches currently applied in Europe.

2.5 Stormwater Management Framework in Germany (DWA-A 102)

In Germany, stormwater runoff management in separate sewer systems is regulated through technical guidelines developed by the German Association for Water, Wastewater and Waste (DWA). One of the most important frameworks is the guideline DWA-A 102-2/BWK-A 3-2, which establishes an emission-based approach for assessing pollutant loads from urban stormwater discharges into receiving surface waters. The guideline focuses on evaluating pollutant emissions from urban catchments and defining acceptable discharge levels to protect aquatic ecosystems from sediment-associated pollution.

A central concept of the DWA-A 102 framework is the use of AFS63 as a key parameter for assessing stormwater pollution. Within this framework, AFS63 specifically targets the fine suspended solids fraction relevant for pollutant transport, as defined in the guideline. The use of this parameter reflects the recognition that pollutant emissions in urban runoff are strongly linked to this particle size range. The guideline therefore establishes standardised calculation values for the concentration and area-specific discharge of AFS63 in stormwater runoff to enable consistent evaluation of pollutant emissions from urban drainage systems.

The guideline classifies urban surfaces into different pollution categories, reflecting the expected pollutant loads generated from various types of impervious surfaces. For each category, standardised concentration values and area-specific pollutant discharge values for AFS63 are defined. According to these calculations, typical mean concentrations of AFS63 in stormwater runoff are approximately 50 mg/L for category I, 95 mg/L for category II, and 136 mg/L for category III, reflecting increasing pollution levels depending on land use and surface characteristics.

Based on these categories, the guideline defines a reference area-specific pollutant discharge for AFS63 of 280 kg per hectare and year for stormwater discharges into surface waters. This value is not derived from direct measurements but represents a model-based reference used for regulatory assessment and standardised evaluation of stormwater emissions. While this value provides a useful benchmark for regulatory assessment, its practical representativeness can be questioned, as stormwater pollutant loads are known to vary significantly depending on rainfall characteristics, event dynamics and catchment conditions (Baum et al., 2018; Fletcher et al., 2015). This variability suggests that fixed emission thresholds may not fully capture real-world conditions and should therefore be interpreted with caution when applied to diverse urban environments.

The DWA-A 102 framework therefore emphasises the importance of quantifying pollutant loads generated by urban surfaces and controlling emissions at the catchment scale. By combining land-use-based pollution categories with emission limits for fine suspended particles, the guideline provides a systematic methodology for assessing stormwater pollution and determining the required level of treatment. This approach reflects the increasing recognition that fine suspended particles play a dominant role in pollutant transport in urban runoff systems (*Arbeitsblatt DWA-A 102-2/BWK-A 3-2*, 2022; Baum et al., 2018; Dierschke, 2014).

2.6 Stormwater Treatment Approaches

Historically, SM systems were primarily designed to control hydraulic aspects, such as reducing peak flow and preventing urban flooding. Conventional infrastructure therefore focused on detention basins, retention ponds and storage systems designed to temporarily store runoff and regulate discharge rates. However, these systems were not originally designed for pollutant removal and often show limited effectiveness in reducing contaminant loads, particularly for dissolved pollutants and fine suspended particles (Y.-Y. Yang & Lusk, 2018).

As scientific understanding of stormwater pollution has improved, the focus of SM has progressively shifted from purely hydraulic control towards integrated water quality management. Modern stormwater treatment systems aim to reduce pollutant loads through a combination of physical, chemical and biological processes, including sedimentation, filtration, adsorption, microbial degradation and plant uptake.

Stormwater treatment technologies can generally be classified into structural and non-structural approaches, reflecting the transition from traditional hydraulic control towards more integrated water quality management strategies. Structural measures include engineered systems designed to treat runoff directly, while non-structural approaches focus on source control strategies such as land-use planning, pollution prevention and public awareness (Y.-Y. Yang & Lusk, 2018).

To better distinguish between these two categories, their main characteristics, objectives and implementation strategies are summarised in Table 3.

Table 3. *Comparison of structural and non-structural SM approaches (adapted from Yang & Lusk, 2018).*

Criteria	Structural approaches	Non-structural approaches
Definition	Engineered systems designed to physically treat and manage stormwater runoff	Management strategies aimed at reducing pollution at the source
Main objective	Direct treatment and removal of pollutants from runoff	Prevention and reduction of pollutant generation
Implementation scale	Localised systems (e.g., site or facility level)	Catchment or urban planning scale
Typical measures	Retention ponds, detention basins, CW, filtration systems	Land-use planning, street cleaning, pollution prevention, public awareness
Treatment mechanism	Physical, chemical and biological processes (e.g., sedimentation, filtration, adsorption)	Source control and behavioural or regulatory measures
Advantages	High pollutant removal efficiency, controlled treatment performance	Cost-effective, preventive approach, reduces load at the source
Limitations	Higher cost, maintenance requirements, space demand	Less direct control over pollutant removal, dependent on human behaviour

As illustrated in Table 3, structural and non-structural approaches differ not only in their implementation scale and technical design, but also in their underlying management philosophy, with structural measures focusing on pollutant treatment and non-structural approaches emphasising prevention and source control.

Recent studies have demonstrated that both structural and non-structural approaches can contribute to reducing suspended solids, nutrients and heavy metals, although their performance is strongly influenced by site-specific conditions and rainfall variability.

Among these approaches, particular attention has been given to decentralised systems that manage runoff close to its source and aim to improve water quality while enhancing urban resilience.

The following sections therefore focus on key SM concepts, including Low Impact Development (LID), Best Management Practices (BMPs) and CW, which are examined in greater detail.

2.6.1 Low Impact Development (LID) and Best Management Practices (BMPs)

LID and BMPs represent decentralised strategies for SM that aim to reduce the environmental impacts of urban runoff. Unlike traditional drainage systems designed primarily to convey water rapidly away from urban areas, LID approaches attempt to replicate natural hydrological processes by promoting infiltration, retention and on-site treatment of stormwater (Fletcher et al., 2015).

Typical LID measures include green roofs, permeable pavements, vegetated swales, infiltration systems and biofiltration units. These systems are implemented close to the source of runoff generation and are designed to reduce runoff volumes, slow down flow velocities and enhance pollutant removal through a combination of sedimentation, filtration and biological processes (Fletcher et al., 2015). By controlling stormwater near its origin, LID practices contribute to restoring aspects of the natural water cycle that are often disrupted by urbanisation.

BMPs encompass a broader set of structural and non-structural measures aimed at reducing pollutant loads in stormwater. Structural BMPs include detention basins, infiltration facilities and treatment systems, while non-structural measures focus on source control strategies such as land-use planning and pollution prevention. Previous studies have shown that this distinction is fundamental in SM, with structural BMPs defined as engineered systems designed to control and treat runoff, while non-structural BMPs aim to prevent pollutant generation and reduce runoff at the source through planning and management practices (Martin et al., 2007; Pradhanang & Jahan, 2021). Together, these approaches aim to reduce the transport of suspended solids and associated pollutants into receiving water bodies (Zheng et al., 2025).

Because of their decentralised nature and their ability to combine hydraulic control with pollutant removal, LID and BMP strategies have become essential components of modern SM frameworks. However, their effectiveness can vary depending on rainfall characteristics, catchment properties and system design, which highlights the need for complementary treatment systems capable of efficiently removing fine suspended particles and associated contaminants from stormwater runoff.

2.6.2 Constructed Wetlands for Stormwater Treatment

CW are increasingly recognised as effective NBS for stormwater treatment, particularly due to their ability to combine hydraulic buffering with pollutant removal under real urban conditions. Several field studies have demonstrated their performance in treating stormwater runoff. For instance, a CWs in Strasbourg (France) achieved removal efficiencies exceeding 90% for TSS and up to 70-98% for COD under variable rainfall conditions (Schmitt et al., 2015).

Similar findings have been reported in other studies, confirming their capacity to remove suspended solids, nutrients and organic contaminants under real stormwater conditions (Lucas et al., 2014).

The main pollutant removal processes occurring in CW are illustrated in Figure 2.

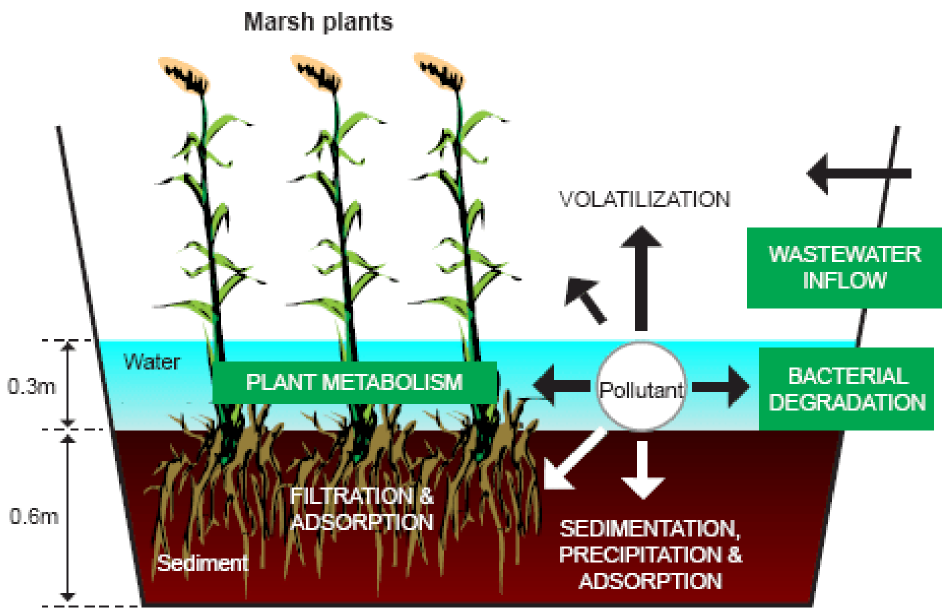


Figure 2. *Main pollutant removal processes in constructed wetlands, including sedimentation, filtration, adsorption and plant uptake.*

As shown in Figure 2, stormwater enters the system carrying suspended solids and dissolved pollutants. Coarse particles are primarily removed through sedimentation as flow velocity decreases, while finer particles are retained through filtration within the substrate layer. At the same time, adsorption processes occurring on sediment and plant surfaces contribute to the removal of dissolved contaminants. Biological processes also play a key role, as microorganisms in the substrate promote bacterial degradation of organic matter, while vegetation enhances pollutant uptake and supports microbial activity. Additionally, volatilisation may occur for certain compounds. These combined physical, chemical and biological processes explain the high pollutant removal efficiency observed in CW.

Beyond pollutant removal, CWs offer additional advantages compared to conventional systems. They operate as passive treatment systems requiring little or no external energy input, which significantly reduces operational costs. In addition, CWs provide multiple ecosystem services, including habitat creation, landscape integration and enhanced urban biodiversity. The review by Biswal and Balasubramanian (2022) further highlights that CW performance is influenced by system design parameters such as HRT, vegetation type and substrate characteristics, which in turn affect treatment stability and long-term functionality. (Biswal & Balasubramanian, 2022)

Different CW configurations used in stormwater treatment are presented in Figure 3.

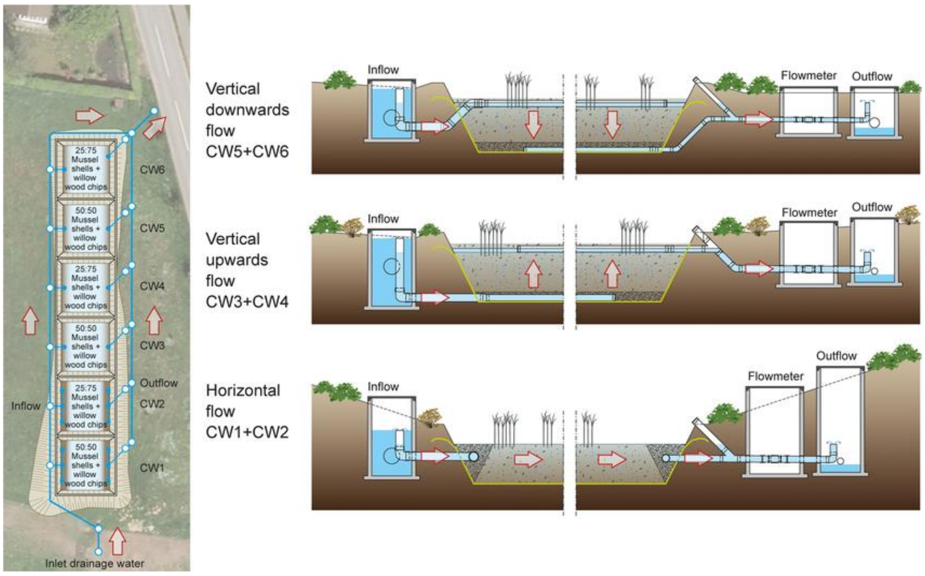


__Figure 3.__ Schematic representation of different CW configurations, including horizontal flow, vertical upward flow and vertical downward flow systems used for stormwater treatment.

CWs are generally classified into free water surface (FWS) systems and subsurface flow (SSF) systems, including horizontal and vertical flow (VF) configurations (Figure 3). Their performance depends on the interaction between hydraulic conditions, substrate properties and vegetation, which together control sedimentation, filtration and adsorption processes.

The performance of CW is strongly influenced by key design parameters. Among the most important factors are HRT, which determines the contact time between pollutants and the treatment media and is considered a critical parameter controlling treatment efficiency. Water depth also plays a key role, as it influences oxygen transfer and sedimentation processes. Substrate type and grain size are equally important, as they control filtration efficiency and adsorption capacity while providing surfaces for microbial growth. In addition, vegetation selection contributes to pollutant uptake and enhances microbial activity in the root zone.

Hydraulic loading rate (HLR) and system geometry must also be carefully designed to ensure uniform flow distribution and avoid short-circuiting. These parameters interact to control overall treatment performance, making their combined optimisation essential for achieving stable and efficient long-term operation under variable stormwater conditions (Kadlec & Wallace, 2009; Vymazal, 2010).

Despite these design considerations, the efficiency of CWs remains strongly influenced by site-specific conditions such as hydraulic loading, rainfall variability and system design. Long-term performance may also be affected by sediment accumulation, which can act both as a pollutant sink and a potential secondary source if not properly managed. This has been highlighted in studies conducted under Luxembourg conditions, emphasising the importance of continuous monitoring and site-specific design to ensure stable treatment performance (Venditti et al., 2022).

To summarise the main findings reported in the literature, selected studies on CWs are presented in Table 4.

Table 4. *Overview of selected studies on CWs, including system types, target pollutants, and key findings.*

Study	Location	Type of CW	Target pollutants	Key findings
(Schmitt et al., 2015)	France	VFCW	TSS, COD, nutrients	High removal efficiency under real conditions (TSS >90%, COD 70-98%)
(Lucas et al., 2014)	International	Various CWs	TSS, nutrients, organic pollutants	Pollutant removal driven by combined physical and biological processes
(Biswal & Balasubramanian, 2022)	Review (global)	FWS & SSF CWs	TSS, nutrients, metals	Performance influenced by design parameters (HRT, vegetation, substrate)

As shown in Table 4, CW have demonstrated strong potential for stormwater treatment under real conditions, particularly for the removal of suspended solids, organic matter and nutrients. However, the reported performance varies according to CW configuration, design parameters and site-specific operating conditions.

2.7 Existing Research in Germany and Research Gap in Luxembourg

A substantial body of research on stormwater pollution and treatment has been developed in Germany over the past decades. German studies have contributed significantly to the understanding of pollutant transport mechanisms in urban runoff, particularly regarding the role of fine suspended particles. One of the most influential works is the dissertation by Dierschke (2014), which investigated the quantification and behaviour of fine particles (PM63) in stormwater runoff. This study demonstrated that a considerable proportion of pollutants in urban runoff is associated with fine particulate fractions, which exhibit low settling velocities and therefore remain suspended for extended periods. Therefore, conventional stormwater treatment technologies based primarily on sedimentation may show limited efficiency in removing these fine particles and their associated contaminants (Dierschke, 2014).

Building on the previous findings regarding the role of fine particles in stormwater pollution, the characterisation and monitoring of particulate pollutants have become key aspects in urban drainage research. In this context, harmonised analytical approaches have been developed to better quantify the fine suspended fraction and its contribution to pollutant transport. The parameter AFS63 is commonly used to represent the fine suspended solid fraction in stormwater runoff and has become increasingly relevant for assessing pollutant loads, as fine particles often carry heavy metals, hydrocarbons and other urban contaminants. The growing recognition of particle-bound pollutant transport has directly influenced the development of technical guidelines and management strategies for urban stormwater treatment in Germany, including the recommendations provided in the DWA-A 102 framework.

In addition to fundamental research on pollutant transport processes, several studies have evaluated the performance of decentralised stormwater treatment systems under real operating conditions. Long-term monitoring studies conducted in Germany indicate that conventional sedimentation-based treatment units often exhibit moderate removal efficiencies for TSS and significantly lower efficiencies for fine particle fractions. For example, field investigations of decentralised stormwater treatment systems reported average removal efficiencies of approximately 29 % for TSS and around 19 % for fine particles (TSS63), highlighting the challenges associated with removing fine particulate matter from stormwater runoff (Lieske et al., 2021).

Alongside conventional treatment systems, increasing attention has been given to NBS for SM CWs, biofilters and other decentralised treatment systems combine physical filtration, adsorption and biological processes to remove pollutants from runoff. International studies show that such systems can achieve substantial pollutant removal efficiencies, often exceeding 60-80 % for certain contaminants depending on system design and operational conditions (Zheng et al., 2025).

Despite the extensive research carried out in Germany and internationally, the scientific literature addressing stormwater pollution and treatment in Luxembourg remains comparatively limited. Existing studies in the Luxembourgish context primarily focus on the occurrence of MPs in aquatic systems or on the performance of CWs for wastewater treatment.

For example, investigations of vertical flow constructed wetlands (VFCW) in the Greater Region have demonstrated the potential of these systems to remove MPs through adsorption and microbial degradation processes (Venditti et al., 2022, 2024). However, comprehensive field-based studies examining the behaviour and treatment of urban stormwater runoff under Luxembourgish environmental conditions are still scarce.

Consequently, a significant research gap remains regarding the characterisation of stormwater pollution and the evaluation of treatment performance in Luxembourg, particularly for systems receiving urban runoff. Differences in urban structure, hydrological conditions and catchment characteristics may influence pollutant transport and treatment efficiency, making it necessary to generate site-specific data. Addressing this gap is essential for improving SM strategies and supporting the implementation of effective treatment solutions adapted to local environmental conditions.

3 Methodology

3.1 Study Area and Investigated Systems

Two monitoring site-equipped CWs were investigated in Luxembourg, located in Raemerich and Steinfort. Both systems are designed as VFCW and treat stormwater runoff from distinct catchments. These sites were selected to enable a comparative assessment of stormwater pollution under contrasting environmental conditions.

The Raemerich site, located at the Luxembourg-France border, is characterised by stormwater runoff originating exclusively from a motorway catchment. The site is managed by the Administration des Ponts et Chaussées and represents a typical high-traffic road runoff system. The total contributing catchment area is approximately 16.8 ha and is divided into three inlet ICs (IC1, IC2, and IC3). IC1 accounts for approximately 12% of the catchment (2.01 ha), IC2 represents the largest portion with about 55% (9.24 ha), and IC3 covers the remaining 33% (5.54 ha). These areas correspond primarily to impervious road surfaces, significantly influencing runoff generation and pollutant transport.

The treatment system consists of a collection pond followed by a CW designed as a retention soil filter, specifically targeting the removal of suspended solids in stormwater runoff. The system provides a total retention volume of approximately 3,900 m³ and operates with an outflow of about 28.5 L/s, enabling effective hydraulic buffering and pollutant removal during storm events.

To better illustrate the overall configuration of the system, Figure 4 presents a general overview of the Raemerich stormwater treatment layout, including the inlet structures (IC1-IC3), the collection pond, and the VFCW.

Figure 4. *Overview of the Raemerich stormwater treatment system, showing inlet structures (IC1-IC3), the collection pond, and the VF CW.*

To further clarify the internal functioning of the Raemerich system, the hydraulic and structural design of the CW must be considered. The system operates as a VF treatment unit preceded by a retention pond, which plays a key role in flow regulation and initial sedimentation.

Stormwater runoff is first collected and temporarily stored in the retention basin, where a reduction in flow velocity promotes the settling of coarse suspended solids. The regulated outflow is then conveyed towards the CW through controlled inlet structures. Within the wetland, water is distributed across a vegetated filtration surface composed of layered substrate materials, including gravel and sand, which ensure both hydraulic conductivity and pollutant retention.

The VF configuration allows water to percolate through the substrate, thereby enhancing filtration and adsorption processes while maintaining aerobic conditions that support microbial degradation.

Specific design elements such as drainage layers, perforated pipes and flow control structures ensure uniform water distribution and prevent short-circuiting. Additionally, erosion protection measures and overflow structures are integrated to maintain system stability during high-intensity rainfall events.

This design reflects a treatment strategy focused on optimising hydraulic retention, maximising contact between pollutants and the treatment media, and ensuring robust performance under variable stormwater conditions.

To properly evaluate the performance of the system, it is essential to understand the origin and characteristics of pollutants entering the CW.

To better understand the origin of pollutants entering the Raemerich CW, the contributing catchment and its surrounding land uses were analysed. The catchment is not defined by a simple spatial radius but rather by the drainage network directing runoff towards the three ICs (IC1, IC2, and IC3). Each inlet receives runoff from distinct surfaces, including motorway infrastructure, local roads, and adjacent urban and semi-industrial areas. Therefore, identifying the surrounding land uses is essential for interpreting the observed water quality and pollutant dynamics.

A visual assessment of the surrounding environment was conducted using aerial imagery and site observations to identify potential pollutant sources. Areas with a probable hydraulic connection to the inlet structures were considered as effective contributors to the CWs. Surrounding land uses were therefore classified based on their likelihood of contributing runoff, distinguishing between confirmed, likely, and uncertain sources.

The Raemerich site is primarily influenced by high-traffic road infrastructure, particularly the A4 motorway and associated ramps, which represent the dominant source of stormwater runoff. Additional contributions may originate from local road networks, urban surfaces, and nearby technical or industrial facilities. In contrast, more distant industrial areas, such as the ArcelorMittal site, are not considered part of the contributing catchment due to the absence of clear drainage connectivity, however, atmospheric deposition of particulates emitted from industrial chimneys may settle during or after rainfall and subsequently be transported via roadway surfaces to the Raemerich inlets.

To better characterise the contribution of different surrounding land uses to stormwater pollution, the identified sources and their potential impacts are summarised in Table 5. To provide a clearer and more synthetic overview of their relative importance, these sources are additionally grouped into broader land-use categories and illustrated in Figure 5.

Table 5. Surrounding Land Use and Potential Pollution Sources at the Raemerich Site:

Surrounding element	Relation to site	Linked inlet(s)	Potential pollutants	Likelihood of contribution	Note
A4 motorway and ramps	Confirmed drainage source within catchment	IC2 mainly, partly IC3	Heavy metals (Zn, Cu), hydrocarbons, PAHs, tire wear particles	High	Dominant source of stormwater pollution
Roundabout and local road section	Confirmed or highly likely drainage source	IC1 mainly	Brake dust, metals, hydrocarbons	High	Strong first flush effect due to braking
Open or disturbed soil areas	Possible source depending on site conditions	IC2 / IC3	Suspended solids (TSS), sediments	Moderate	More relevant during or after construction phases
Industrial/technical facilities (e.g. Sudcal S.A.)	Nearby land use with uncertain drainage connectivity	Uncertain	Hydrocarbons, industrial residues	Low to moderate	Considered potential but not confirmed contributor
Urban infrastructure (buildings, parking areas)	Nearby urban surfaces	Possibly IC1 / IC3	Organic matter, light metals, oils	Low to moderate	Secondary contribution compared to road runoff
ArcelorMittal industrial area	Located nearby but outside confirmed drainage area but visible smoke released via chimeys to atmosphere	Possible	Industrial residues, metals, atmospheric deposition after rainfall	Moderate	Not considered part of contributing catchment
Vegetated and buffer areas	Surrounding green spaces	All	Low pollutant generation, potential filtration	Minor	May reduce particulate transport locally

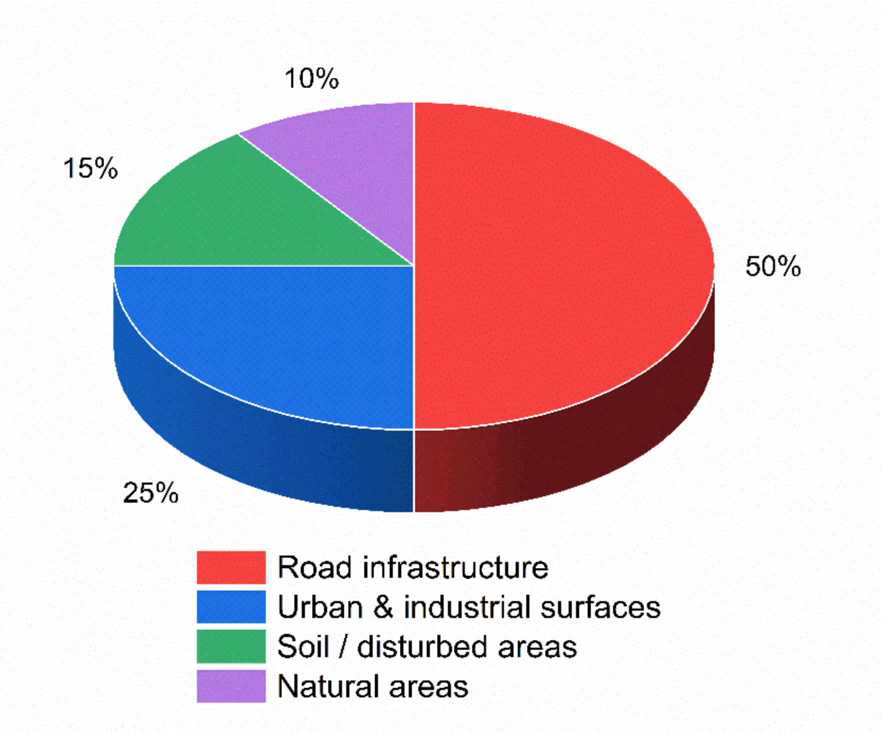


Figure 5. *Relative contribution of surrounding land-use categories to stormwater pollution at the Raemerich site, based on qualitative assessment of pollutant sources.*

As shown in Table 5 and Figure 5, the Raemerich catchment is predominantly influenced by traffic-related sources, with the motorway and associated road infrastructure representing the main contributors to pollutant loads. High pollutant inputs are primarily associated with road surfaces and parking areas, mainly due to hydrocarbons, heavy metals, and brake-related emissions.

In contrast, other land-use categories such as open or vegetated areas show a significantly lower contribution, although they may still influence sediment transport and runoff dynamics under specific conditions. Overall, the combined analysis highlights the dominant role of road infrastructure while confirming the secondary influence of urban and natural surfaces within the catchment.

The combined analysis confirms the dominant role of road infrastructure in pollutant generation, while highlighting the more limited contribution of other land-use categories under typical conditions.

The Steinfort site, located at the Luxembourg-Belgium border, receives stormwater runoff from a mixed urban catchment including residential, commercial, and road surfaces. The site is managed by the Municipality of Steinfort and represents a decentralised stormwater treatment system under low-traffic conditions. The total contributing catchment area is approximately 17 ha and is divided into three inlet zones.

Inlet 1 covers approximately 1 ha, Inlet 2 represents the largest portion with about 14 ha, and Inlet 3 covers approximately 2 ha. The runoff originates mainly from rooftops, pavements, and minor roads, resulting in a different pollution profile compared to motorway-dominated systems. The treatment system consists of two CW units with a total area of approximately 3,400 m², connected to a retention pond of about 6,000 m³ with a storage volume of 2,421 m³ and a depth of approximately 1.5 m. The system includes four outlet structures (CW1-CW4), allowing staged treatment

The overall configuration of the system is illustrated in Fig. 6.

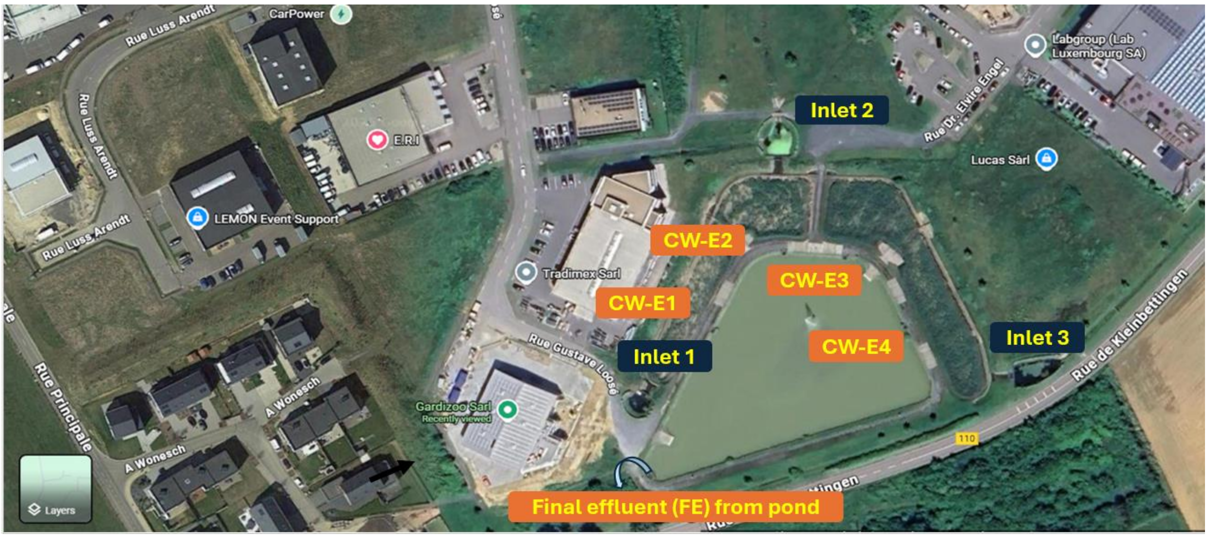


Figure 6. Overview of the Steinfort stormwater treatment system showing inlet structures (Inlet 1-3), CW and units (CW-E1 to CW-E4), and the retention pond with final effluent (FE).

As shown in Figure 6, the operational design of the Steinfort system is characterised by a multi-stage treatment configuration that integrates several hydraulic control and treatment elements. In contrast to the Raemerich site, which relies on a single VF unit, the Steinfort system combines multiple treatment components to manage more heterogeneous runoff conditions.

Stormwater is first conveyed through inlet structures and directed towards the CW units, which are designed to operate under controlled hydraulic conditions (V = HQ2). Within these units, water flows through vegetated substrate layers, allowing pollutant removal through sedimentation, filtration, adsorption, and biological processes.

The system also incorporates several hydraulic control features, including flow regulation structures, manholes, and bypass valves, which ensure stable operation under varying inflow conditions. During high-intensity rainfall events, excess flow can be diverted through overflow structures and peripheral ditches, preventing hydraulic overloading of the treatment units.

Downstream of the CW, a retention pond (V = HQ10-HQ2) provides additional storage capacity and contributes to further sedimentation of suspended solids.

Specific elements such as underflow baffles and sludge traps are integrated to enhance sediment retention and prevent the remobilisation of accumulated particles.
Overall, this design reflects a flexible and robust treatment strategy that combines hydraulic control and multi-stage pollutant removal processes, making it particularly suitable for catchments with variable land uses and heterogeneous pollutant inputs.
While this technical configuration defines how stormwater is hydraulically managed and treated, understanding the origin and nature of incoming pollutants remains essential to fully interpret system performance.
To better understand the origin of pollutants entering the Steinfort CWs, the contributing catchment and its surrounding land uses were analysed. Like the Raemerich site, the catchment is defined by the drainage network directing runoff towards the inlet structures rather than by a simple spatial boundary. Each inlet receives runoff from distinct areas characterised by different land uses, resulting in a more heterogeneous pollution profile.
A visual assessment of the surrounding environment was conducted using aerial imagery and site observations to identify potential pollutant sources. Only areas with a probable hydraulic connection to the inlet structures were considered as effective contributors to the CWs. Surrounding land uses were therefore classified based on their likelihood of contributing runoff, distinguishing between confirmed, likely, and uncertain sources. In addition, the site is used as a public recreational area, which may contribute organic matter and microbial pollution.
The Steinfort catchment is primarily influenced by mixed urban and peri-urban land uses. Inlet 1 receives runoff mainly from local roads, parking areas, and nearby commercial and service buildings, associated with moderate traffic and typical urban pollutants such as hydrocarbons, metals, and organic matter. Inlet 2, representing the largest portion of the catchment, collects runoff from a combination of light industrial and commercial zones, including large buildings, storage areas, and parking surfaces. Inlet 3 drains a smaller catchment composed mainly of road infrastructure and adjacent agricultural land, where contributions may include suspended solids and nutrients. In contrast to the Raemerich site, traffic intensity is lower and pollutant inputs are more diffuse and variable, reflecting the diversity of land uses within the catchment.
The surrounding land uses and their potential contributions to stormwater pollution are summarised in Table 6, while their relative importance based on activity sectors is illustrated in Figure *7*.

Table 6. Classification of surrounding land uses and activity sectors at the Steinfort site, including their potential pollutants and likelihood of contribution to stormwater pollution.

Surrounding element / Activity sector	Relation to site	Linked inlet(s)	Potential pollutants	Likelihood of contribution	Note
Road infrastructure (motorway, ramps)	Confirmed drainage source within catchment	IC2 mainly, partly IC3	Heavy metals (Zn, Cu), hydrocarbons, PAHs, tire-wear particles	High	Dominant source of stormwater pollution
Construction & Building Services	Confirmed / highly likely drainage source	IC1 mainly	Suspended solids, metals, hydrocarbons	High	Major contributor due to construction activities
Industrial & Manufacturing	Nearby land use with partial drainage connection	IC1 / IC2	Hydrocarbons, industrial residues, metals	Moderate to high	Significant contribution depending on activities
Commercial & Business Services	Nearby urban surfaces	IC1 / IC2	Organic matter, light metals, oils	Moderate	Secondary contribution linked to urban runoff
Automotive & Transport activities	Confirmed / likely drainage source	IC1 / IC2	Oils, hydrocarbons, heavy metals (Zn, Cu)	High	Frequent vehicle-related contamination
Residential areas	Nearby urban surfaces	IC1	Organic matter, nutrients, trace metals	Moderate	Diffuse urban runoff contribution
Soil / disturbed areas	Possible source depending on site conditions	IC2 / IC3	Suspended solids (TSS), sediments	Moderate	More relevant during construction phases
Environmental & natural areas (vegetation, buffer zones)	Surrounding green spaces	All	Low pollutant generation, retention/filtration potential	Minor	Can reduce pollutant transport locally

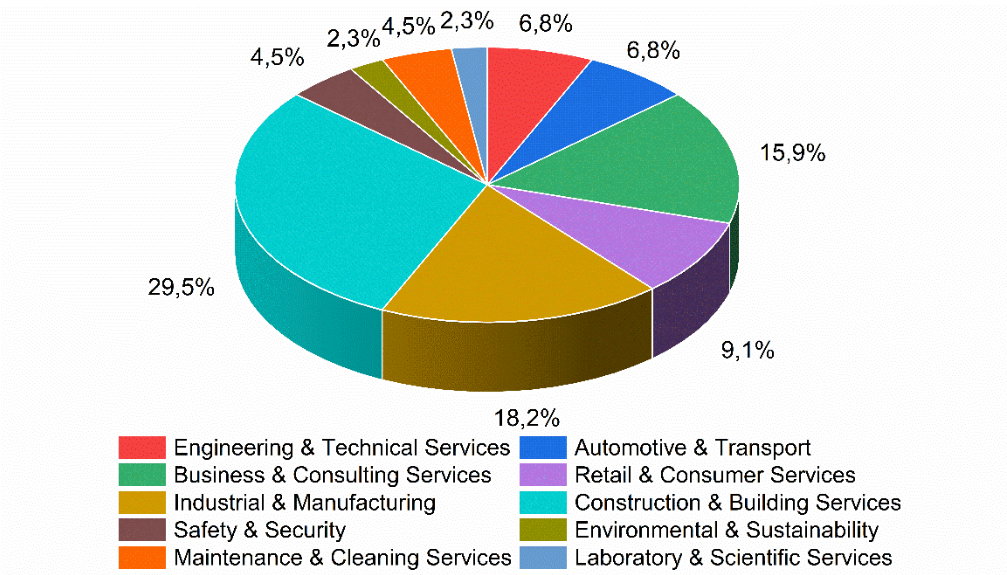


Figure 7. *Distribution of surrounding activity sectors at the Steinfort site, showing their relative contribution (%) based on the classification of companies within the catchment.*

As shown in Table 6 and Figure 7, the Steinfort catchment is characterised by a diverse combination of urban, commercial, and semi-natural land uses, resulting in a more heterogeneous and diffuse pollution profile compared to the Raemerich site. While road-related sources remain important contributors, additional inputs from commercial areas, light industrial activities, and residential zones play a significant role in shaping overall water quality.

The distribution of activity sectors indicates that construction and building services, industrial and manufacturing activities, and business-related services represent a substantial share of the surrounding functions. However, unlike Raemerich, no single source dominates the system, and pollutant inputs are more evenly distributed across different land-use categories.

This variability highlights the importance of considering land-use diversity when interpreting pollutant dynamics in decentralised stormwater treatment systems, as it directly influences both the type and temporal variability of contaminants entering the system.

3.2 Monitoring Strategy and Sampling Design

The monitoring strategy was designed to characterise pollutant dynamics entering and leaving the CWs under both dry weather conditions and rainfall events. Sampling campaigns were planned based on weather forecasts, allowing targeted deployment of equipment prior to precipitation events.

At both sites (Raemerich and Steinfort), a combination of manual GS and automated sampling (AS) was applied. During dry weather conditions, grab samples were collected manually at all monitoring points, including inlet structures (Inlet 1-3) and the final effluent (FE), providing baseline water quality conditions.

For rainfall events, portable ISCO 6712 autosamplers (AS) (Teledyne ISCO, Lincoln, Nebraska, USA) were installed prior to precipitation and programmed to collect samples during runoff events. These systems were configured for event-based sampling, allowing the capture of the first flush effect, which is characterised by elevated pollutant concentrations during the initial phase of stormwater runoff. The AS were triggered automatically by a pressure sensor measuring water level within the system, ensuring that sampling started immediately once predefined threshold conditions were exceeded.

Two types of ISCO AS were used, both equipped with 24 bottles but differing in volume capacity.

One system used 1 L bottles, allowing direct collection of individual samples, while the other was equipped with 500 mL bottles, requiring the combination of two bottles to obtain equivalent sample volumes when needed.

This configuration enabled the collection of discrete samples at defined intervals throughout each runoff event, providing a high temporal resolution of pollutant concentration dynamics.

The AS were retrieved after each event and reinstalled during subsequent campaigns to ensure spatial coverage of all inlet structures and the effluent.

Sampling campaigns were conducted jointly by two operators to ensure consistency in field procedures. At the Raemerich site, several monitoring campaigns were conducted, combining dry-weather GS and event-based AS deployment, with sampling covering all three *ICs* and the effluent. At the Steinfort site, similar campaigns were carried out, including both GS and AS-based monitoring across inlet structures and constructed wetland units, reflecting the more distributed and heterogeneous catchment conditions.

The AS operated via a suction line connected to the sampling point, allowing water to be drawn into the system upon triggering. The sampling program was defined prior to deployment, including trigger conditions (*i.e.* water level threshold) and sampling intervals, ensuring that samples were collected throughout the event duration. This setup allowed time-resolved monitoring of pollutant concentrations and improved representation of stormwater dynamics compared to manual sampling alone.

Overall, the combined use of GS under dry conditions and automated event-based sampling during rainfall events provided a comprehensive dataset, capturing both baseline conditions and transient pollutant peaks associated with stormwater runoff, particularly those related to first flush dynamics.

This approach is particularly relevant for CWs, where treatment performance is strongly influenced by hydraulic and pollutant variability during storm events.

The AS system and its main components, including the bottle configuration, suction line, and pressure sensor, are illustrated in Figures 8.

Figure 8. *Auto sampling system and key components:* ***(a)*** *ISCO Autosampler unit;* ***(b)*** *24-bottle sampler;* ***(c)*** *pressure sensor;* ***(d)*** *suction intake.*

3.3 Water Quality Parameters and Analytical Methods

Water quality analyses were performed to characterise both dissolved and particulate pollutant fractions in stormwater samples collected from the CW. The analytical workflow combined field measurements, laboratory-based physicochemical analyses, and sample preparation steps for advanced chemical characterisation.

The overall analytical workflow applied to stormwater samples is summarised in Figure 9. After collection, samples were processed through successive filtration steps to distinguish particulate and dissolved fractions. A first separation at 63 µm (via sieve) removed larger particles, followed by filtration at 1.5 µm using glass fibre filter paper for suspended solids analysis. The resulting filtrate was then used for the determination of physicochemical parameters, organic pollution indicators, nutrients and inorganic ions.

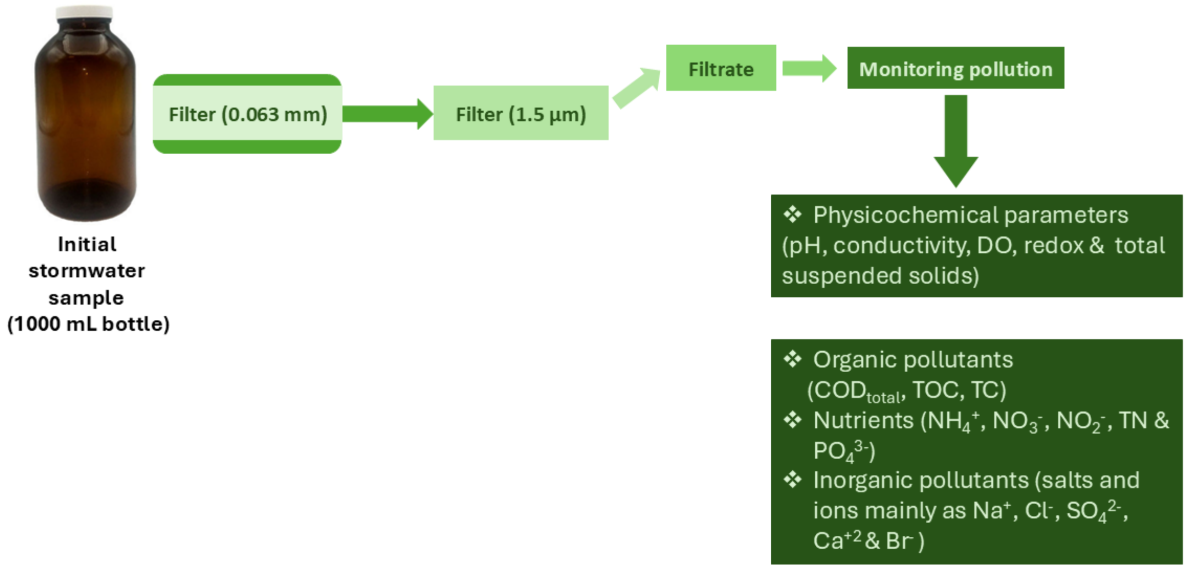


Figure 9. *Overview of the analytical workflow applied to stormwater samples, including filtration steps and monitored water quality parameters.*

Sample preparation for suspended solids analysis followed a gravimetric procedure. As illustrated in Figure 10, glass-fibre filter papers (MN 439, 1.5 µm, Ø 70 mm; Macherey-Nagel GmbH & Co. KG, Düren, Germany) were first prepared and handled under controlled laboratory conditions. The filters were placed in aluminium containers and pre-weighed using an OHAUS Adventurer precision balance (OHAUS Corporation, Parsippany, NJ, USA) to determine their initial mass.

A known volume of each sample was then filtered using a vacuum filtration setup equipped with a glass flask, filter holder, and a KFG vacuum pump (KFG Maschinenbau GmbH, Germany). After filtration, the filters containing retained particles were dried in a laboratory oven under controlled conditions to remove residual moisture. Once dried, the filters were weighed again to determine their final mass.

TSS concentrations were calculated based on the mass difference before and after filtration, normalised by the filtered sample volume as shown in Equation (Eq.) 1.

$$TSS\left(\frac{mg}{L}\right) = \frac{(\text{m\_final} - \text{m\_initial})}{V} X\ 1000 \qquad Eq.1$$

where *m_final* is the mass of the filter after drying (mg), *m_initial* is the pre-weighed filter mass (mg), and *V* is the filtered sample volume (mL).

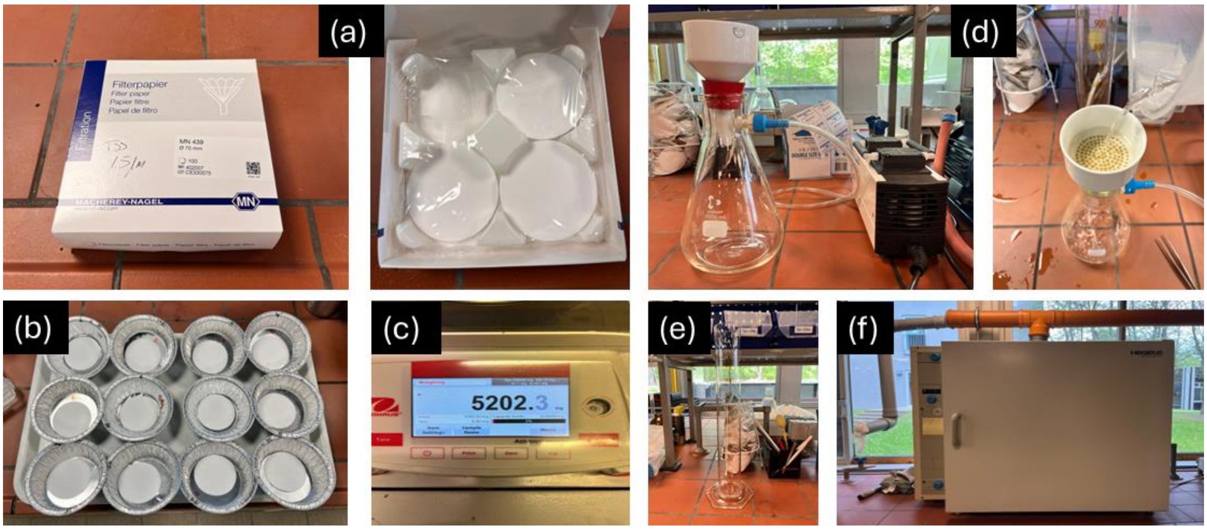


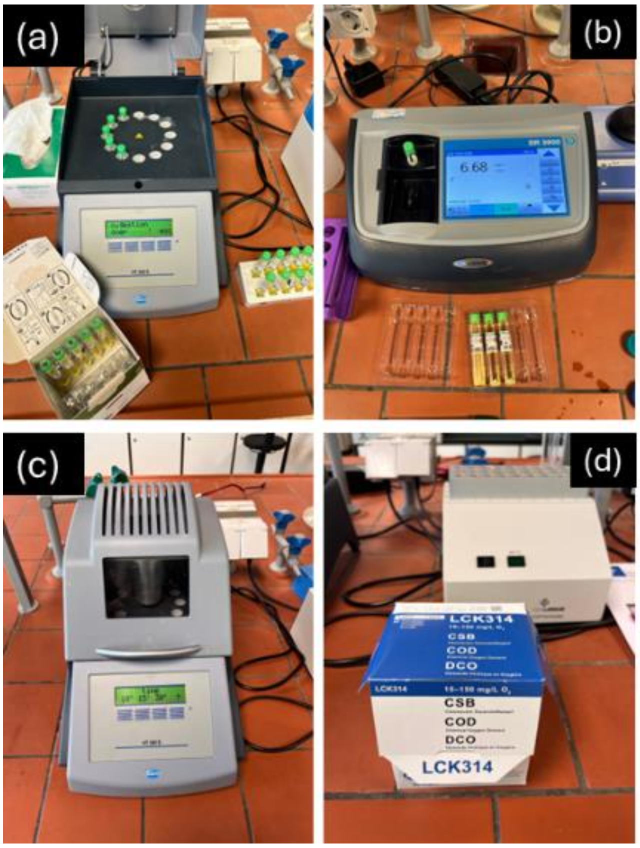
Figure 10. *TSS analysis procedure:* ***(a)*** *glass fibre filters;* ***(b)*** *pre-weighed filters in aluminium containers;* ***(c)*** *analytical balance;* ***(d)*** *vacuum filtration setup;* ***(e)*** *filtered sample volume measurement;* ***(f)*** *drying oven.*

Prior to laboratory analyses, all samples were carefully homogenised to ensure representativeness. Unfiltered water samples were first analysed to determine key physicochemical parameters, including pH, electrical conductivity (EC), dissolved oxygen (DO), and temperature, using portable multiparameter probes, including WTW ProfiLine pH 3310 and Cond 3310 devices (Xylem Analytics Germany Sales GmbH & Co. KG, Weilheim, Germany) and a Hanna Instruments HI9146 dissolved oxygen meter (Hanna Instruments Inc., Woonsocket, RI, USA) (Figure 11).

These measurements provided an initial characterisation of water quality conditions and allowed rapid comparison between sampling locations and events.

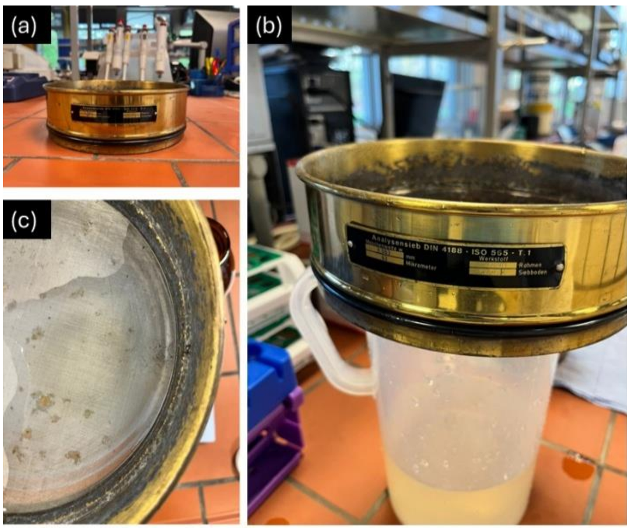
Figure 11. *Portable multiparameter probes used for in-situ measurements:* ***(a)*** *handheld devices for pH, conductivity, and DO;* ***(b)*** *complete measurement setup including probes and cables.*

COD was determined on unfiltered samples using sealed digestion vials (HACH LCK kits; HACH Lange GmbH, Berlin, Germany). A defined sample volume was introduced into the vials, followed by thermal digestion at high temperature (175 °C) for approximately 15 minutes using a HACH HT200S thermostatic reactor (HACH Lange GmbH, Berlin, Germany).



After digestion, COD concentrations were measured photometrically using a HACH DR3900 spectrophotometer (HACH Lange GmbH, Berlin, Germany). The applied kits covered different concentration ranges depending on site conditions, ensuring appropriate measurement sensitivity for both Raemerich and Steinfort samples.

Figure 12. *COD analysis procedure using HACH LCK kits: **(a)** preparation of digestion vials; **(b)** photometric measurement system; **(c)** thermal digestion unit; **(d)** COD reagents and kits used for different concentration ranges.*



To separate particulate fractions, samples were first passed through a 63 µm sieve to remove larger suspended materials. This step was performed after physicochemical measurements and prior to fine filtration. The sieved water was then processed under controlled conditions to ensure that larger particles did not interfere with subsequent filtration steps. An example of retained material is shown in (Figure 13c).

Figure 13. *Sieving step using a 63 µm mesh: **(a)** sieve used for particle separation; **(b)** filtration of stormwater samples through the sieve; **(c)** example of retained particulate matter.*

For dissolved-phase analyses, an additional filtration step at 0.45 µm was performed to remove remaining fine particulate matter. The filtration was carried out using syringe filters, ensuring that only dissolved fractions were retained for further analysis (Figure 14a-b). The filtrate was then transferred into pre-labelled sample vials using pipettes under controlled laboratory conditions to avoid contamination (Figure 14c).

These samples were subsequently analysed for Total Organic Carbon (TOC), Total Carbon (TC), and Inorganic Carbon (IC) using a Shimadzu TOC-L analyser coupled with a TNM-L total nitrogen module (Shimadzu Corporation, Kyoto, Japan) (Figure 14d).

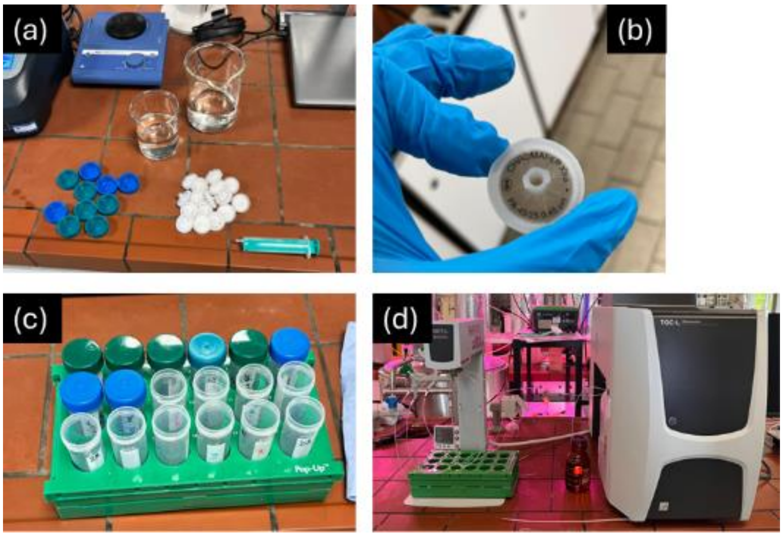


Figure 14. *Sample preparation and analysis for dissolved-phase measurements:* ***(a)*** *syringe and filtration setup;* ***(b)*** *0.45 µm membrane filter;* ***(c)*** *collection of filtrates in sample vials;* ***(d)*** *TOC analyser used for TC and TOC determination.*

In parallel, ionic species were analysed using ion chromatography (IC) with dedicated systems for anion and cation measurements (Figure 15). Analyses were performed using a Thermo Scientific Dionex Inuvion IC system (Thermo Fisher Scientific, Sunnyvale, CA, USA).

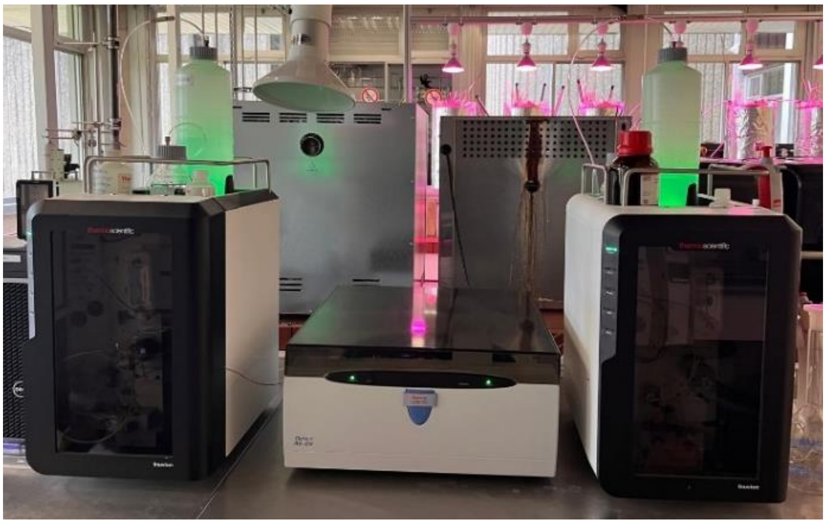


Figure 15. *Ion chromatography (IC) systems used for ionic analysis: anion analysis unit (left) and cation analysis unit (right).*

3.4 Data Analysis

The collected dataset was processed to investigate stormwater pollution characteristics and temporal dynamics in CWs, with a particular focus on suspended solids, associated pollutants, and first-flush behaviour during rainfall events.

Data were structured according to sampling locations (inlet structures IC1-IC3 and FE, monitoring campaigns, and hydrological conditions (dry weather and rainfall events). This organization enabled consistent comparison of pollutant concentrations across sites, sampling points, and event types.

The analysis focused on key water quality parameters relevant for stormwater pollution assessment, including TSS, COD, TOC, TC, and selected IC. In addition, physicochemical parameters such as pH, EC, temperature, and DO were used to characterize general water quality conditions.

Attention was given to suspended solids, as they play a central role in pollutant transport in urban runoff. The analysis therefore considered TSS concentrations as well as the relevance of fine particles associated with pollutant loads, in line with emission-based regulatory frameworks such as DWA-A 102 (AFS63).

Event-based datasets obtained from AS measurements were analysed to assess temporal variations in pollutant concentrations during rainfall events. This approach enabled the identification of first flush effects, characterized by elevated pollutant concentrations at the beginning of storm events, and allowed the observation of pollutant evolution over time.

In addition, treatment performance of the CWs was assessed by comparing pollutant concentrations between inlet and outlet sampling points. Rather than applying detailed efficiency calculations, this evaluation was based on the graphical representation of concentration differences under varying hydrological conditions, particularly during rainfall events.

Comparative analyses between the two study sites (Raemerich and Steinfort) were performed to evaluate how different catchment characteristics influence pollutant dynamics and treatment behaviour.

Data processing and visualization were carried out using Microsoft Excel. Graphical representations were used as the primary tool to interpret pollutant dynamics, first flush behaviour, and treatment performance, while detailed discussion of these results is provided in the Results and Discussion section.

4 Results and Discussion

4.1 Overview of Monitoring Campaigns and Hydrological Conditions

Monitoring campaigns at the Raemerich and Steinfort CWs were conducted during rainfall events to investigate stormwater quality dynamics under variable hydraulic conditions. Water quality monitoring included both GS and AS collected at different locations throughout the treatment systems.

Rainfall events generated measurable increases in water level and flow at both sites, suggesting that changing hydraulic conditions could influence pollutant transport within the CWs. Temporal variations observed during the monitoring campaigns further suggest that stormwater quality could evolve dynamically throughout rainfall events and could be closely associated with hydrological fluctuations.

The influence of rainfall intensity, runoff dynamics, and hydraulic conditions on pollutant mobilisation and attenuation is discussed in the following sections.

4.2 Physicochemical Water Quality Results

4.2.1 Dissolved Oxygen (DO)

DO is a key indicator of aerobic biogeochemical functioning within CWs because oxygen availability regulates microbial degradation pathways, organic matter oxidation, and nitrification processes (Mittal et al., 2022). Variations in DO therefore reflect the balance between oxygen-consuming biological reactions and oxygen replenishment through reaeration and diffusion.

At the Raemerich site (Figure 16a), monitoring revealed relatively stable inlet DO concentrations, generally ranging between approximately 6.5 and 8 mg/L. Further, lower DO concentrations at IC2 (6.51 mg/L) coincided with higher COD concentrations, indicating intensified oxygen consumption associated with elevated organic loading. Higher concentrations of biodegradable organic matter stimulate heterotrophic microbial respiration, increasing oxygen demand and consequently reducing DO levels. In contrast, lower COD concentrations at IC3 reduced microbial oxygen consumption, allowing higher DO concentrations of 8.11 mg/L to persist.

Along the Raemerich treatment train, DO progressively decreased toward the FE with an average 4-5 mg/L and lowest approaching 3.9 mg/L, suggesting that oxygen consumption within the wetland exceeded oxygen replenishment capacity. This depletion is likely associated with the high pollutant and particulate loads characteristic of motorway runoff, which enhance microbial degradation activity within substrate and biofilm zones. Accumulation of suspended solids and organic particulates within the CW matrix may also restrict oxygen diffusion under saturated conditions, further promoting oxygen depletion.

In contrast, Steinfort (Figure 16b) exhibited ICs DO (ranging 7-9 mg/L) and progressive DO depletion within intermediate CW stages (ranging 2 to 6 mg/L) followed by substantial recovery at the FE (7-8 mg/L). The initial decline indicates active aerobic degradation processes occurring within the treatment units. However, the subsequent increase in DO suggests effective reaeration before discharge. This recovery is likely related to the hydraulic configuration of the system, where treated water passes through a downstream pond that increases air-water contact time and promotes atmospheric oxygen transfer. Lower pollutant loading at Steinfort may additionally reduce overall oxygen demand, enabling partial restoration of DO concentrations.

The contrasting DO behavior between both systems demonstrates the strong influence of catchment characteristics and hydraulic design on oxygen dynamics within CWs. The motorway-dominated Raemerich catchment generated higher oxygen demand due to elevated organic and particulate pollutant loads, whereas the staged hydraulic configuration at Steinfort enhanced reaeration and oxygen recovery prior to discharge. These findings indicate that oxygen availability in CWs is controlled not only by pollutant loading but also by internal hydraulic conditions, substrate oxygen transfer limitations, and post-treatment reaeration processes (Decezaro et al., 2019; Lucas et al., 2014; Nivala et al., 2013).

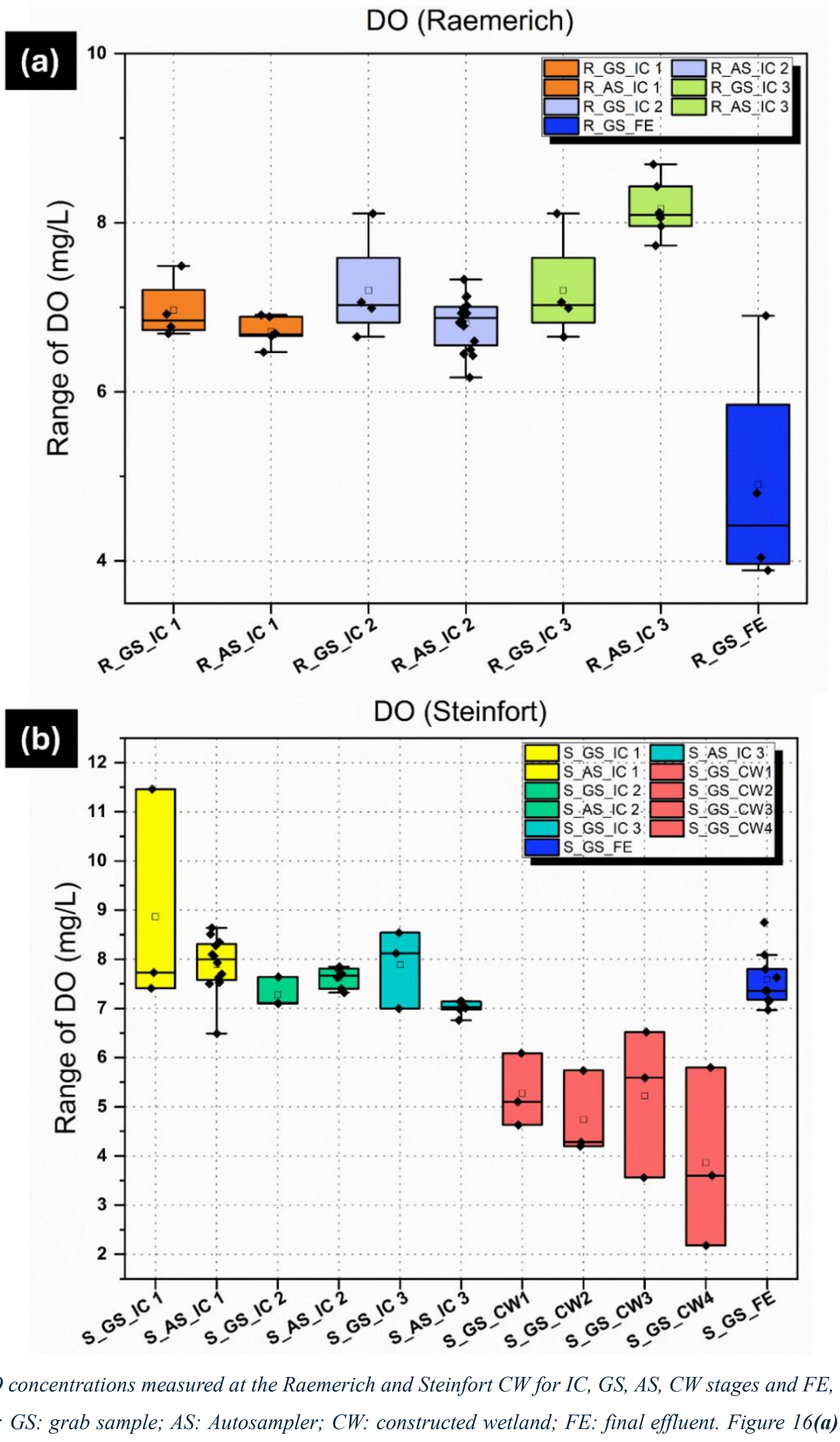


Figure 16. *DO concentrations measured at the Raemerich and Steinfort CW for IC, GS, AS, CW stages and FE, (Where: ICs: Inlet channels; GS: grab sample; AS: Autosampler; CW: constructed wetland; FE: final effluent. Figure 16**(a)**: Raemerich; Figure 16**(b)**: Steinfort).*

4.2.2 Electrical Conductivity (EC)

EC is an indicator of dissolved ionic strength and reflects the concentration of soluble inorganic constituents in stormwater runoff. In CWs, EC behaviour is primarily controlled by dissolved salt inputs, pollutant mobilisation during rainfall events, dilution effects, and the retention capacity of the treatment system for conservative ions.

The EC profiles revealed clear differences between the motorway-dominated Raemerich catchment and the mixed urban catchment at Steinfort (Figure 17). Raemerich exhibited substantially higher and more variable EC values, particularly within the AS ranging more than 8000 µS/cm, indicating rapid mobilisation of dissolved ionic pollutants during rainfall events. This behaviour is likely associated with the accumulation of road-deposited salts, vehicle-derived residues, and atmospheric particulates on impervious motorway surfaces during antecedent dry periods, followed by their rapid wash-off during storm events. The elevated EC values were consistent with the high as sodium (Na^+), chloride (Cl^-) and sulphate (SO_4^{2-}) concentrations measured at the site, suggesting that dissolved salts were the dominant contributors to conductivity.

The substantially higher EC values in AS (maximum reaching 8000 µS/cm) compared with GS (maximum reaching 3500 mg/L) further indicate strong temporal fluctuations in dissolved pollutant transport during runoff events. Such variability reflects the highly dynamic hydrology of motorway runoff, where short-duration first-flush processes rapidly increase ionic concentrations. Although EC decreased slightly along the treatment train, elevated values persisted at the FE with median values still exceedingly approximately 1800 µS/cm, indicating limited removal of dissolved ions within the CW. This behaviour is expected because dissolved ionic species are relatively conservative and are not efficiently removed through sedimentation processes. Consequently, conductivity attenuation within CWs mainly depends on dilution, adsorption, plant uptake, and infiltration processes, which may become insufficient under high influent ionic loading conditions (Choi et al., 2021).

In contrast, Steinfort exhibited lower and more stable EC values throughout the treatment system ranging between 200 and 800 µS/cm, indicating reduced dissolved ionic loading and more buffered runoff chemistry. The smaller differences between GS and AS suggest weaker first-flush effects and lower temporal variability in pollutant mobilisation. Furthermore, the relatively stable EC values observed across the CW stages and FE indicate that the staged hydraulic configuration likely promoted dilution and stabilization of dissolved ion concentrations through increased hydraulic retention and flow buffering.

Overall, the contrasting EC behaviour demonstrates that dissolved ion dynamics were primarily governed by catchment characteristics and runoff composition. The motorway runoff at Raemerich generated high ionic loading and strong conductivity fluctuations due to rapid mobilisation of accumulated dissolved pollutants, whereas the mixed urban runoff at Steinfort produced more chemically stable conditions with lower dissolved pollutant stress. The results further suggest that CWs are more effective at buffering short-term conductivity fluctuations than at removing conservative dissolved ionic compounds (Choi et al., 2021; Lieske et al., 2021; Zhao et al., 2024).

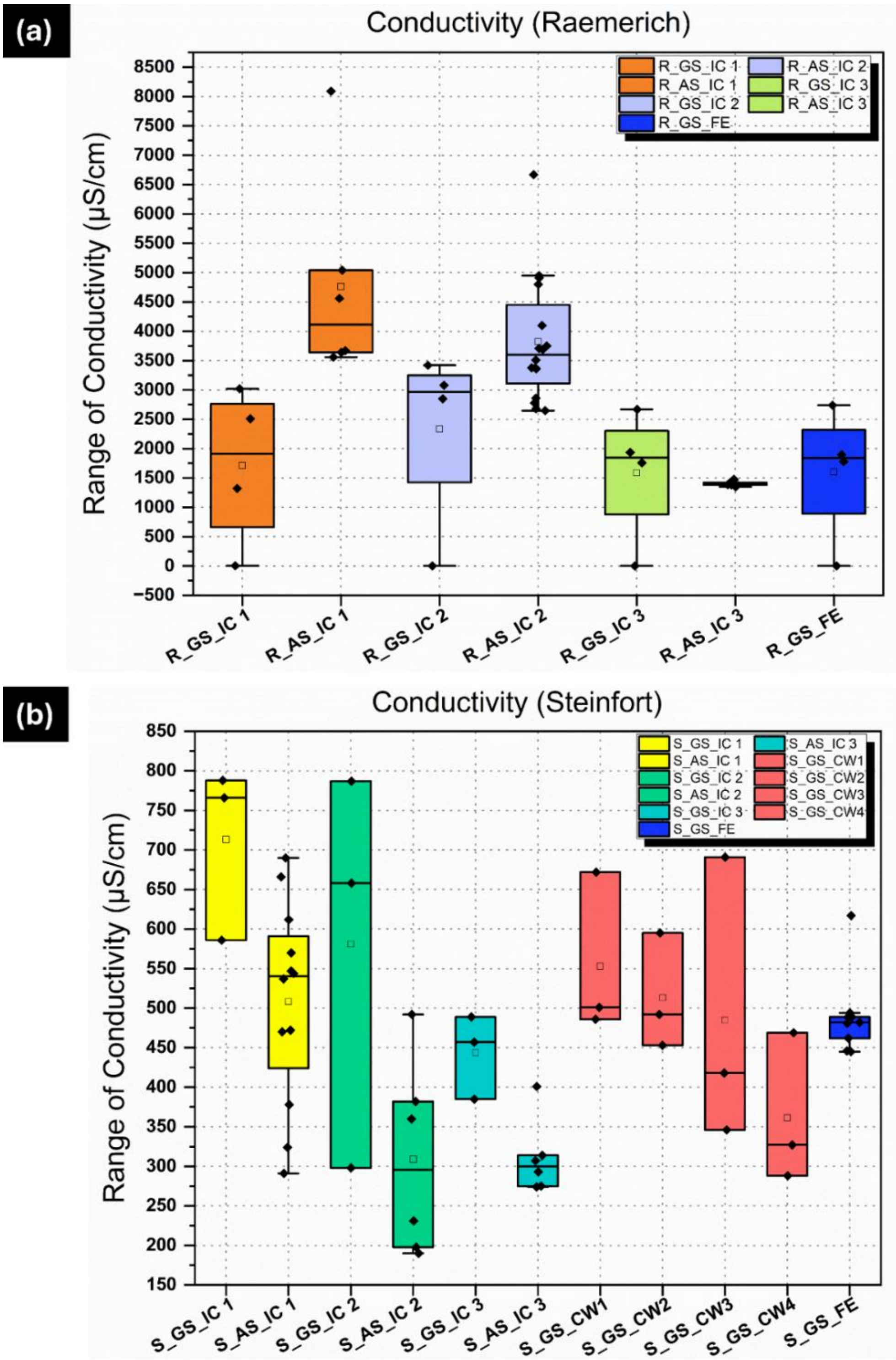


Figure 17. *EC **(a)**: Raemerich; **(b)**: Steinfort (Where ICs: Inlet channels; GS: Grab sample; AS: Autosampler; CW: Constructed wetland; FE: Final effluent).*

4.3 pH and Redox Conditions

pH and redox potential (ORP) control key geochemical processes in CWs by regulating microbial activity, metal speciation, and the thermodynamic feasibility of redox reactions governing pollutant transformation. Their behaviour reflects the buffering capacity of the system and the balance between oxidative processes (driven by oxygen availability) and localized reductive processes within anoxic microzones.

Across both sites, pH remained close to neutrality (≈7-8), indicating strong buffering against acidifying or alkalinizing inputs from stormwater. This stability is primarily attributed to carbonate buffering in soils and sediments and the rapid neutralization of acidic/basic inputs through mixing and contact with wetland substrates. Such near-neutral conditions thermodynamically favour microbial activity and maintain metals in relatively less mobile forms by limiting extreme pH-driven solubility shifts.

ORP values remained moderately positive (≈ +200 mV), indicating dominance of oxidizing conditions in the bulk water phase. This reflects continuous oxygen input through surface reaeration and inflow of oxygenated stormwater, which sustains aerobic respiration and oxidative degradation of organic matter. The absence of strongly negative ORP conditions suggests that complete depletion of electron acceptors did not occur at the system scale during the monitored events.

However, the coexistence of positive bulk ORP with simultaneous pollutant transformation implies the development of steep redox gradients at microscale levels. Within saturated substrates and biofilms, oxygen diffusion limitation creates localized anoxic zones where alternative electron acceptors (e.g., NO_3^-, Fe(III), SO_4^{2-}) drive denitrification, iron/sulphur reduction, and anaerobic organic matter degradation. Such spatial redox compartmentalization is a defining feature of CW functioning and is essential for coupled aerobic-anaerobic pollutant removal pathways.

The overall stability of pH and ORP despite variable hydraulic loading indicates strong internal buffering capacity and resilience of the system's biogeochemical equilibrium. This stability ensures that redox-sensitive processes such as nitrification-denitrification coupling and metal sorption-precipitation cycles can proceed without disruption under fluctuating stormwater inputs. Similar system-level redox stability in CWs has been reported by Brunhoferova (Brunhoferova, 2022), who highlighted the role of substrate buffering and oxygen transfer dynamics in maintaining stable biogeochemical conditions.

Overall, the pH and ORP results demonstrate that both CWs operate under a stable bulk oxidative regime, while simultaneously supporting localized anaerobic niches. This redox duality is critical for sustaining parallel aerobic and anaerobic pathways, thereby enabling efficient transformation of organic and inorganic pollutants under variable stormwater conditions.

4.4 Organic Matter and Carbon Dynamics

Organic matter dynamics are key indicators for evaluating stormwater pollution and treatment performance in CW. In the present work, organic pollution was assessed through COD together with carbon fractions including TC, TOC, and IC. These parameters provide complementary information regarding the mobilisation, transformation, and retention of dissolved and particulate organic matter during rainfall events. Santos et al. (2024) highlighted that pollutant attenuation in CW strongly depends on hydraulic conditions, retention time, and internal biogeochemical processes occurring within the treatment system (Santos et al., 2024).

Because organic matter degradation is directly associated with oxygen consumption, elevated COD concentrations may strongly influence DO dynamics within CW, particularly during high-flow conditions and first-flush periods. The interaction between organic matter loading, oxygen availability, and hydraulic variability therefore plays a major role in overall treatment performance. Recent studies further demonstrated that dissolved organic matter removal and carbon transformation processes in CWs are closely controlled by hydraulic residence time, microbial degradation, and seasonal variability (Jones et al., 2025).

The following sections examine the temporal evolution and attenuation behaviour of COD and carbon fractions at the Raemerich and Steinfort sites under contrasting stormwater runoff conditions.

4.4.1 Chemical Oxygen Demand (COD)

COD represents the total oxidisable organic load transported in stormwater runoff and reflects both dissolved and particulate organic fractions. In CWs, COD dynamics are primarily controlled by pollutant accumulation during antecedent dry periods, rainfall-driven wash-off processes, hydraulic transport, and microbial degradation within the treatment media.

At the Raemerich site (Figure 18a), COD exhibited a pronounced first-flush response strongly associated with rainfall intensity and rapid increases in water level. Initial GS concentrations remained moderate (approximately 40-75 mg/L), whereas AS concentrations rapidly increased to peak values of approximately 160-165 mg/L during the early stages of the rainfall event, coinciding with rainfall intensities of around 0.4 mm and a sharp rise in water level to nearly 30 mm. This behaviour indicates rapid mobilisation of accumulated organic-rich particulates and dissolved pollutants from highly impervious motorway surfaces. Traffic-derived materials such as hydrocarbons, tyre wear particles, brake abrasion residues, and fine road dust likely contributed substantially to the elevated COD concentrations. Similar first-flush dynamics in traffic-dominated runoff systems have been widely reported in stormwater studies (Lieske et al., 2021; Maniquiz-Redillas et al., 2022).

Following the initial peak in AS samples, COD progressively decreased from 160 mg/L to 50–80 mg/L despite continued rainfall fluctuations and elevated water levels. This decline likely reflects depletion of readily mobilisable pollutant stocks combined with dilution under increasing runoff volumes. Partial attenuation within the CW may additionally have occurred through sedimentation of particulate organic matter and aerobic microbial degradation within substrate and biofilm zones. However, FE concentrations remained around 40 mg/L, indicating incomplete removal of dissolved and fine colloidal organic fractions, which are less efficiently retained within CWs. The simultaneous DO depletion observed previously further supports active aerobic degradation of incoming organic matter during treatment. Similar COD attenuation behaviour under variable hydraulic loading has been reported for stormwater CWs by (Schmitt et al., 2015).

In contrast, Steinfort (Figure 18b) exhibited substantially lower and more stable COD concentrations throughout the monitored event. GS concentrations ranged approximately between 10 and 35 mg/L, while AS concentrations mostly remained between 8 and 28 mg/L. Unlike Raemerich, no pronounced first-flush peak was observed despite increases in rainfall intensity (~0.6 mm) and water level (15–25 mm). This weaker concentration response suggests lower antecedent pollutant accumulation and more diffuse organic matter inputs from the mixed urban catchment.

The comparatively stable COD profile at Steinfort additionally indicates stronger hydraulic buffering within the staged CW configuration. Longer hydraulic residence times likely reduced rapid pollutant transport while promoting progressive sedimentation and microbial degradation before discharge. The downstream pond may also have enhanced oxygen transfer and stabilised treatment conditions, supporting sustained aerobic degradation processes. Consequently, COD fluctuations remained moderate throughout the event, and FE concentrations stayed relatively low (around 8 mg/L), indicating more effective organic matter attenuation compared with Raemerich. Similar relationships between hydraulic retention and pollutant attenuation in CWs were discussed by (Zhao et al., 2024).

Overall, the COD dynamics demonstrate that rainfall intensity, hydrological response, and catchment characteristics strongly controlled organic pollutant mobilisation and attenuation within both systems. Raemerich showed rapid first-flush mobilisation and strong concentration spikes due to the highly impervious motorway catchment, whereas Steinfort exhibited more buffered organic matter dynamics associated with lower pollutant accumulation and longer hydraulic retention. These findings highlight the importance of hydraulic regulation and oxygen availability for maintaining stable organic matter attenuation in stormwater CWs.

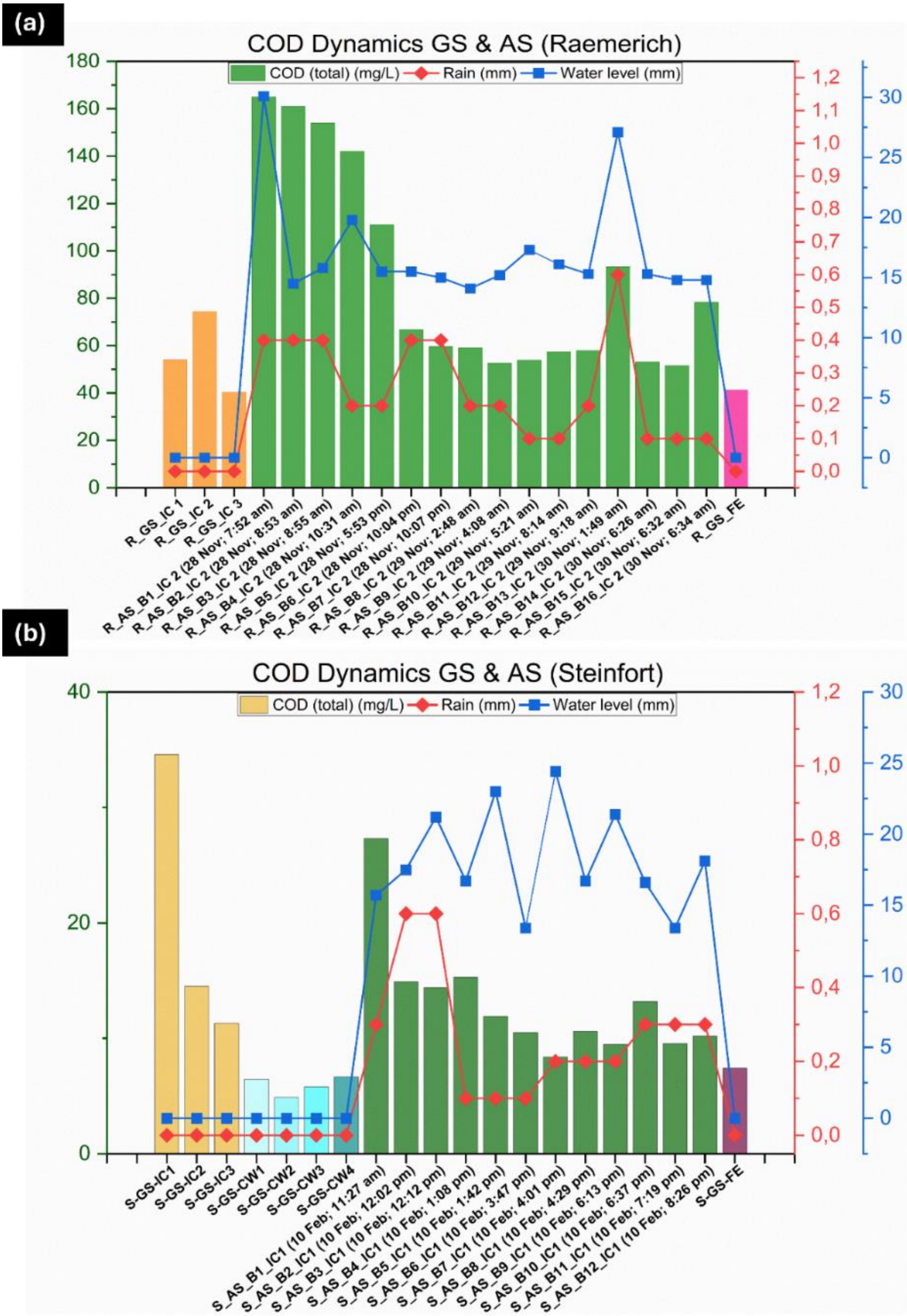


Figure 18. *COD dynamics measured during GS and AS campaigns at the Raemerich and Steinfort CWs, including rainfall and water-level evolution. Figure 18**(a)**: Raemerich; Figure 18**(b)**: Steinfort (Where ICs: Inlet channels; GS: Grab sample; AS: Autosampler; CW: Constructed wetland; FE: Final effluent).*

4.4.2 Carbon Fractions (TC, TOC, IC)

Carbon fractions provide insight into the sources, mobility, and transformation of organic and inorganic matter within CWs. TOC mainly reflects dissolved and particulate organic pollutants (OPs) transported during runoff events, whereas IC is associated with carbonate-bicarbonate buffering and mineral dissolution processes. Consequently, the relative contribution of TOC and IC can indicate whether carbon dynamics are dominated by organic pollutant mobilisation or geochemical buffering processes.

At the Raemerich site (Figure 19a), TC concentrations were substantially higher and more variable than at Steinfort, indicating stronger carbon loading associated with motorway runoff. During the AS campaign, TC generally ranged between 50 and 80 mg/L, while an exceptionally high GS concentration (160 mg/L) was observed at IC2 and was predominantly composed of IC (123 mg/L). The dominance of IC suggests strong mineral and carbonate inputs, likely originating from concrete infrastructure, road dust, and mineral-rich particulates commonly associated with motorway environments.

TOC concentrations at Raemerich increased progressively during the rainfall event, reaching values above 50 mg/L in later AS samples, particularly near IC3. This trend coincided with the rainfall and water-level fluctuations previously observed in the COD analysis, indicating hydraulic mobilisation of organic-rich suspended particles and dissolved organic matter during runoff transport. The delayed increase in TOC further suggests remobilisation of organic material stored within the drainage network and CW compartments as hydraulic conditions evolved throughout the event.

In contrast, IC concentrations remained comparatively stable during most AS measurements (40-60 mg/L), indicating that mineral carbon dominated the overall carbon composition. This stable IC behaviour likely reflects carbonate buffering processes and continuous interaction between runoff and mineral surfaces within the catchment. The predominance of IC therefore suggests that geochemical processes exerted stronger control over carbon composition than biological organic carbon fluctuations at Raemerich.

Steinfort (Figure 19b) exhibited substantially lower and more stable TC concentrations, generally between 15 and 30 mg/L. IC again represented the dominant carbon fraction, while TOC mostly remained below 5 mg/L, with only occasional increases up to 8-9 mg/L during the AS event. The lower TOC concentrations indicate weaker mobilisation of OPs and reduced particulate organic loading compared with Raemerich.

The comparatively stable carbon profile at Steinfort suggests stronger hydraulic buffering and more effective internal attenuation mechanisms within the staged CW configuration. Longer hydraulic residence times likely promoted sedimentation of particulate organic matter and sustained microbial degradation before discharge. In addition, vegetation and substrate interactions may have enhanced carbon retention through particle trapping and biofilm-mediated degradation processes.

The predominance of IC at both sites additionally suggests ongoing mineralisation of organic carbon within the CWs. Microbial degradation progressively converts organic carbon into IC species such as bicarbonates and dissolved CO_2, particularly under aerobic and subtoxic conditions. Consequently, carbon dynamics within CWs are controlled not only by external pollutant loading but also by internal biogeochemical transformation processes regulated by oxygen availability, hydraulic residence time, and microbial activity (Jones et al., 2025).

Overall, the contrasting carbon dynamics reflect the influence of catchment characteristics and hydraulic functioning on carbon transport and attenuation. Raemerich exhibited strong temporal fluctuations and elevated TOC mobilisation associated with motorway runoff and rapid hydrological transport, whereas Steinfort displayed more stable carbon fractions due to lower pollutant loading and enhanced hydraulic buffering. These findings indicate that CW carbon attenuation depends on the interaction between particulate settling, microbial mineralisation, and geochemical buffering processes within the treatment system.

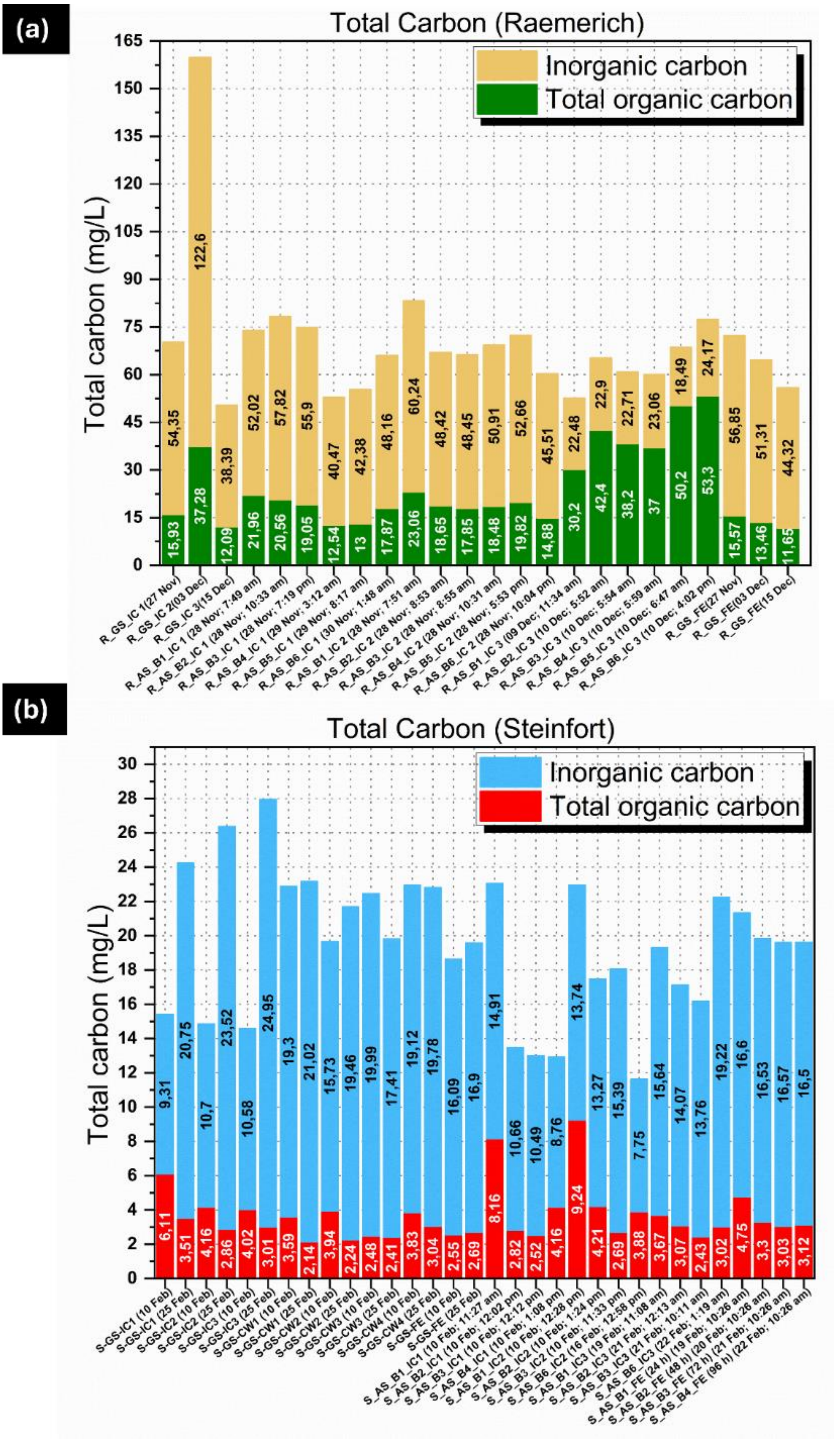


__Figure 19.__ Temporal evolution of total carbon fractions (TOC and TC) during GS and AS campaigns at the Raemerich and Steinfort CWs. Figure 19__(a)__: Raemerich; Figure 19__(b)__: Steinfort (Where ICs: Inlet channels; GS: Grab sample; AS: Autosampler; CW: Constructed wetland; FE: Final effluent).

4.5 Particulate Pollution and AFS63 Dynamics

As discussed in previous sections of thesis, particulate matter represents one of the dominant pollutant fractions in urban stormwater runoff and plays a key role in the transport of associated contaminants such as heavy metals, hydrocarbons, nutrients, and organic MPs. TSS provide an overall characterization of sediment mobilisation during rainfall events, whereas the AFS63 is considered particularly relevant because of its high mobility, prolonged suspension time, and strong pollutant adsorption capacity. Within the DWA-A 102 framework, AFS63 is therefore regarded as a key parameter for evaluating stormwater treatment performance.

The investigation of particulate dynamics during monitored rainfall events provides valuable insight into pollutant mobilisation, first-flush behaviour, sediment transport processes, and treatment efficiency within CWs. Due to the contrasting catchment characteristics of Raemerich and Steinfort, substantial differences in particulate concentration patterns and temporal variability were expected and are discussed in the following sections.

4.5.1 Total Suspended Solids (TSS - fine fraction <63 µm)

TSS concentrations in this study were determined after sieving at 63 µm; consequently, the measured fraction primarily represented fine suspended solids operationally comparable to AFS63 as defined in DWA-A 102. This fraction is particularly important because particles <63 µm exhibit high transport mobility and act as efficient carriers for traffic-related contaminants in urban runoff systems.

At the Raemerich site (Figure 20a), TSS dynamics were characterised by an intense first-flush response strongly coupled to rainfall onset and hydraulic rise within the system. Initial GS concentrations for TSS remained comparatively low (<40 mg/L), while TSS concentration in AS samples increased rapidly during the early runoff phase, reaching values exceeding 700 mg/L. The concentration maximum coincided with both the sharp increase in rainfall intensity (up to approximately 0.4 mm during the early event phase) and the abrupt rise in water level from near-baseline conditions to approximately 30 mm. This simultaneous increase indicates rapid hydraulic mobilisation and transport of previously accumulated fine particulate material from the highly impervious motorway catchment.

The observed first-flush behaviour reflects efficient wash-off of deposited sediments, tyre wear particles, brake abrasion residues, and road dust during the initial runoff phase.

The strong hydraulic connectivity of motorway surfaces likely promoted rapid runoff generation and limited infiltration losses, thereby enhancing particulate transfer into the drainage network. Because the analysed fraction mainly consisted of particles <63 µm, the observed dynamics are environmentally significant, as these fine particles remain suspended under turbulent flow conditions and contribute substantially to contaminant transport. Similar first-flush responses in traffic-dominated catchments have been reported in previous stormwater investigations (Lieske et al., 2021; Maniquiz-Redillas et al., 2022).

Following the initial peak in AS samples, TSS concentrations decreased progressively from >700 mg/L to generally <100 mg/L during the later stages of the rainfall event. This decline corresponded with decreasing rainfall intensity and stabilisation of the hydraulic regime, while water levels remained elevated at approximately 15-20 mm for an extended period. The persistence of elevated water levels despite declining TSS concentrations suggests depletion of readily mobilisable particulate material combined with dilution effects caused by sustained runoff volumes. Minor secondary concentration increases observed during the recession phase indicate continued remobilisation of deposited sediments within the drainage network and treatment compartments under variable hydraulic conditions, rather than a simple monotonic dilution process.

Despite the high TSS influent concentrations, FE concentrations remained comparatively low generally between approximately 2 and 7 mg/L as can be seen in Figure 20a. Since the analysed fraction represented predominantly fine suspended solids, the results indicate effective retention of highly mobile particulate matter within the Raemerich CWs. The attenuation likely resulted from combined sedimentation, hydraulic buffering, vegetation-assisted filtration, substrate retention, and reduced flow velocities within the treatment compartments. Comparable particulate retention efficiencies under dynamic hydraulic conditions have been documented in European CW stormwater treatment systems (Rizzo et al., 2020).

In contrast, the Steinfort site (Figure 20b) exhibited substantially lower and hydraulically buffered TSS dynamics throughout the monitored rainfall event. Initial GS concentrations remained below approximately 10 mg/L, whereas AS concentrations generally varied between approximately 10 and 60 mg/L. Unlike Raemerich, no pronounced first-flush peak was observed. Instead, concentration increases occurred progressively during the event and were associated with relatively moderate fluctuations in rainfall intensity and water level.

Water levels increased gradually to approximately 20-25 mm and remained comparatively stable throughout the event duration, indicating attenuated hydraulic variability within the system.

The smoother TSS response at Steinfort suggests a more distributed particulate mobilisation process and reduced hydraulic shock loading compared with the motorway-dominated Raemerich catchment. The lower concentration variability likely reflects diffuse pollutant inputs from the mixed urban catchment together with enhanced hydraulic retention within the multi-stage CW configuration. In particular, the downstream pond and sequential treatment compartments likely increased hydraulic residence time, reduced turbulence, and promoted continuous sedimentation during the rainfall event. Consequently, particulate transport dynamics remained comparatively stable despite ongoing rainfall inputs.

The comparative behaviour of both sites demonstrates the strong influence of catchment imperviousness, runoff hydraulics, and CW configuration on particulate pollution dynamics. Raemerich showed rapid first-flush mobilisation associated with intense motorway runoff and abrupt hydraulic increases, whereas Steinfort exhibited buffered hydraulic behaviour with lower concentration amplitudes and more gradual particulate transport. These findings are consistent with previous studies identifying rainfall intensity, antecedent dry periods, catchment characteristics, and hydraulic residence time as primary controls on stormwater particulate dynamics (Lieske et al., 2021; Maniquiz-Redillas et al., 2022).

Overall, both CWs contributed to attenuation of fine suspended solids under real rainfall conditions, although treatment behaviour differed substantially between sites. Raemerich experienced extreme but short-lived particulate loading associated with rapid hydraulic response, while Steinfort displayed lower but more persistent particulate concentrations under comparatively stable hydraulic conditions. The low FE concentrations observed at both sites indicate effective retention of the highly mobile fine suspended fraction despite considerable differences in influent loads, rainfall response, and internal water-level dynamics.

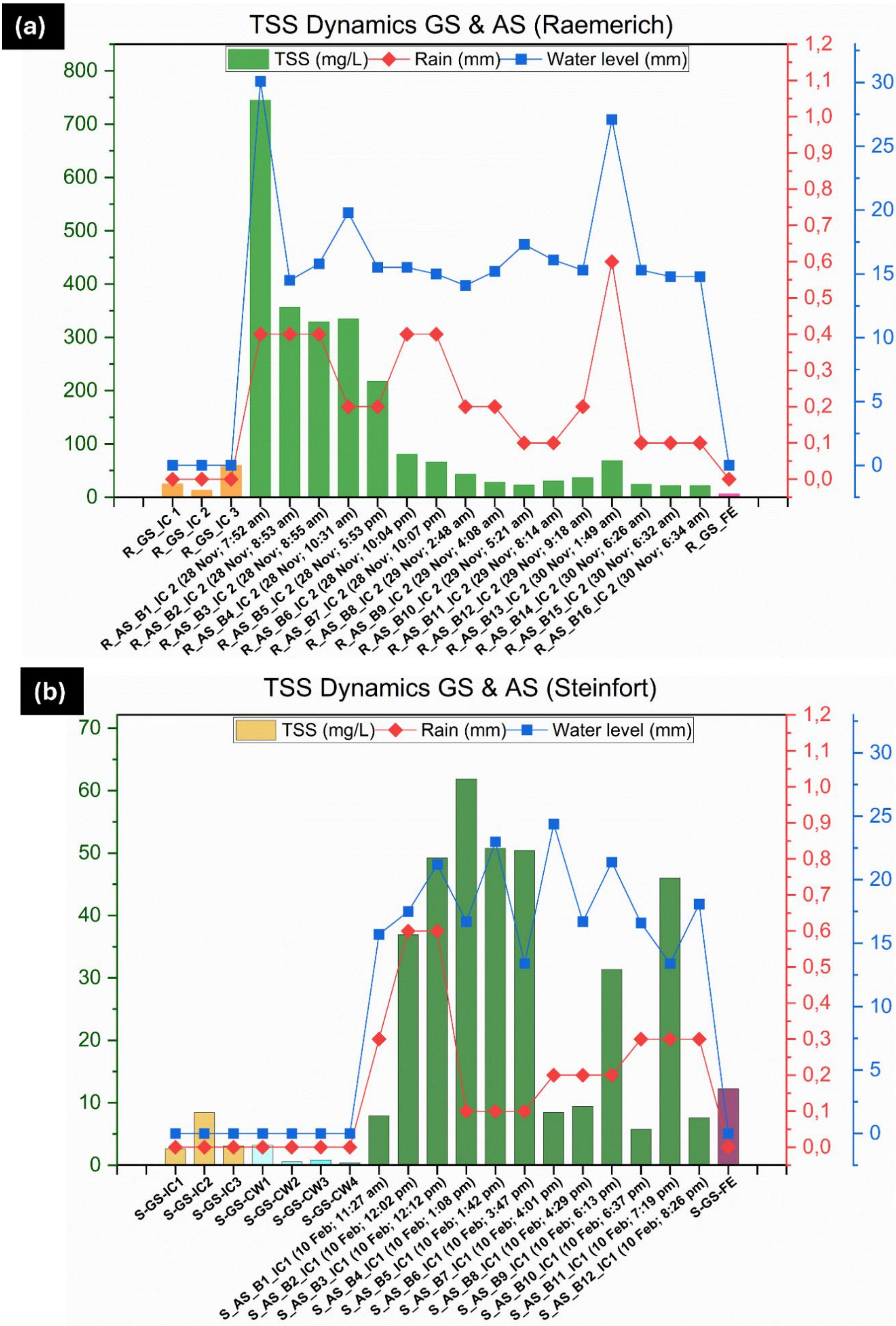


Figure 20. *TSS dynamics measured during GS and AS campaigns at the Raemerich and Steinfort CWs, including rainfall and water-level evolution. Figure 20****(a)****: Raemerich; Figure 20****(b)****: Steinfort (Where ICs: Inlet channels; GS: Grab sample; AS: Autosampler; CW: Constructed wetland; FE: Final effluent).*

4.5.2 Relevance and correlation of TSS v/s COD

The relationship between TSS and COD represents an important indicator for evaluating whether organic pollution in stormwater runoff is primarily associated with particulate transport or influenced by dissolved organic fractions. In urban runoff systems, suspended particles frequently act as carriers for organic matter, hydrocarbons, nutrients, and trace contaminants, making TSS-COD correlation analysis particularly relevant for understanding pollutant mobilisation, first-flush behaviour, and treatment dynamics within CWs (Maniquiz-Redillas et al., 2022).

A strong positive correlation generally indicates that COD is predominantly particle-bound, whereas weaker relationships suggest a more complex contribution from dissolved organic matter and heterogeneous runoff pathways (Y.-Y. Yang & Lusk, 2018). Consequently, analysing the TSS-COD relationship provides insight into whether pollutant removal within CW is mainly governed by physical retention mechanisms such as sedimentation and filtration, or whether dissolved organic fractions require additional biological degradation processes.

Within the framework of this thesis, this comparison is particularly relevant because DWA-A 102 places strong emphasis on suspended solids, especially the fine particle fraction represented by AFS63. As previously described in the methodology section, samples were pre-filtered at 63 µm prior to gravimetric TSS determination. Consequently, the measured TSS fraction largely corresponds to fine suspended particles comparable to the AFS63 fraction defined in DWA-A 102. Evaluating the relationship between TSS and COD therefore provides a practical basis for distinguishing dominant pollutant transport pathways and assessing the relative importance of physical treatment processes within stormwater treatment systems (Dierschke, 2014).

The regression relationships observed at both study sites are presented in Figure 21.

The Raemerich site demonstrated a strong positive correlation between TSS and COD, with a Pearson correlation coefficient of $r = 0.85$ and an R^2 value of 0.73 (Figure 21a). This indicates that approximately 73% of COD variability could be explained by variations in suspended solids concentrations. The regression equation obtained for the site was:

$$COD = 61.19 + 0.161(TSS)$$

The strong positive relationship demonstrates that increases in suspended solids were directly associated with elevated COD concentrations.

The relatively steep regression slope indicates that rising particulate loads were accompanied by proportionally higher organic pollutant concentrations, confirming that COD dynamics at Raemerich were strongly governed by particulate transport processes.

This behaviour indicates that organic pollution at Raemerich was predominantly particle-associated, with suspended solids functioning as major carriers of oxygen-demanding substances. Such dynamics are consistent with stormwater studies reporting that particulate fractions frequently dominate pollutant transport during runoff events due to the mobilisation of accumulated sediments and organic residues during rainfall events (Hathaway et al., 2012). The clustering of low-TSS and low-COD samples alongside several extreme high-TSS/high-COD events further suggest episodic first-flush mobilisation, where pollutant build-up is rapidly washed into the treatment system during storm initiation (Meyer et al., 2011).

Several extreme TSS events were associated with comparatively lower COD concentrations, indicating that under intense storm conditions dilution effects, variable particle composition, or episodic sediment pulses may partially alter pollutant concentration behaviour. Nevertheless, the relatively high intercept value (61.19 mg/L) indicates that a baseline organic load remained present even under lower TSS conditions, implying that dissolved or fine colloidal organic fractions also contributed to COD concentrations. Although particulate transport clearly dominated, non-particulate organic fractions were therefore not negligible.

The overall strength of the regression confirms that particulate pathways represented the principal control on COD dynamics at Raemerich. This behaviour is consistent with previous stormwater research demonstrating that suspended solids are primary drivers of organic pollutant transport in urban runoff systems (Schmitt et al., 2015). Likewise, Lieske et al. (2021) identified suspended particles as dominant vectors for COD-associated pollution transport in urban runoff environments (Lieske et al., 2021).

Overall, the Raemerich results indicate that COD dynamics were predominantly governed by particulate-phase pollutant mobilisation, reinforcing the importance of sedimentation, particulate filtration, and solids retention processes as primary treatment mechanisms.

At Steinfort, a positive but comparatively weaker relationship between TSS and COD was observed, with an R^2 value of 0.58 (Figure 21b). Although the correlation remained significant, the broader dispersion of data points indicates greater variability in the relationship between suspended solids and organic pollution.

Compared with Raemerich, the lower regression slope indicates that increases in TSS resulted in comparatively smaller increases in COD concentrations, suggesting a weaker dependence of

COD on particulate transport. This behaviour indicates that dissolved or weakly particle-associated organic fractions contributed more substantially to total COD concentrations at Steinfort. The greater scatter observed in the regression likely reflects variable hydrological conditions, dilution effects, and heterogeneous pollutant inputs associated with mixed urban runoff sources.

These findings are consistent with observations from mixed-source stormwater systems, where COD is frequently influenced by both particulate and dissolved transport pathways rather than exclusively sediment-bound (Fletcher et al., 2015; Y.-Y. Yang & Lusk, 2018). Consequently, although TSS remained an important contributor to COD variability, it represented a less reliable single predictor of COD concentrations than at Raemerich.

Despite this weaker relationship, elevated TSS events still corresponded with increased COD concentrations, confirming that suspended solids continued to function as important pollutant carriers. However, compared with Raemerich, COD dynamics at Steinfort appear to reflect a more complex pollutant partitioning behaviour involving both particulate retention and dissolved organic removal mechanisms. As a result, pollutant control within the Steinfort CW may require a more integrated treatment approach combining physical retention processes with biological degradation mechanisms capable of targeting dissolved organic fractions.

The comparative analysis demonstrates that the TSS-COD relationship was substantially stronger at Raemerich than at Steinfort, indicating a clearer particulate dominance of COD transport at Raemerich. The higher R^2 value and steeper regression slope observed at Raemerich suggest that COD concentrations were more directly governed by suspended solids mobilisation, whereas Steinfort exhibited greater variability and weaker dependence on particulate transport.

From a treatment design perspective, the stronger particulate dependence observed at Raemerich suggests greater reliance on solids capture efficiency, whereas the comparatively weaker relationship at Steinfort indicates that treatment performance may depend more strongly on combined physical and biological processes capable of addressing both particulate and dissolved pollutant fractions.

These contrasting TSS-COD dynamics demonstrate that stormwater treatment performance cannot be interpreted solely through pollutant concentration magnitudes, but must also consider pollutant partitioning behaviour, which fundamentally influences treatment selection, removal efficiency, and regulatory compliance.

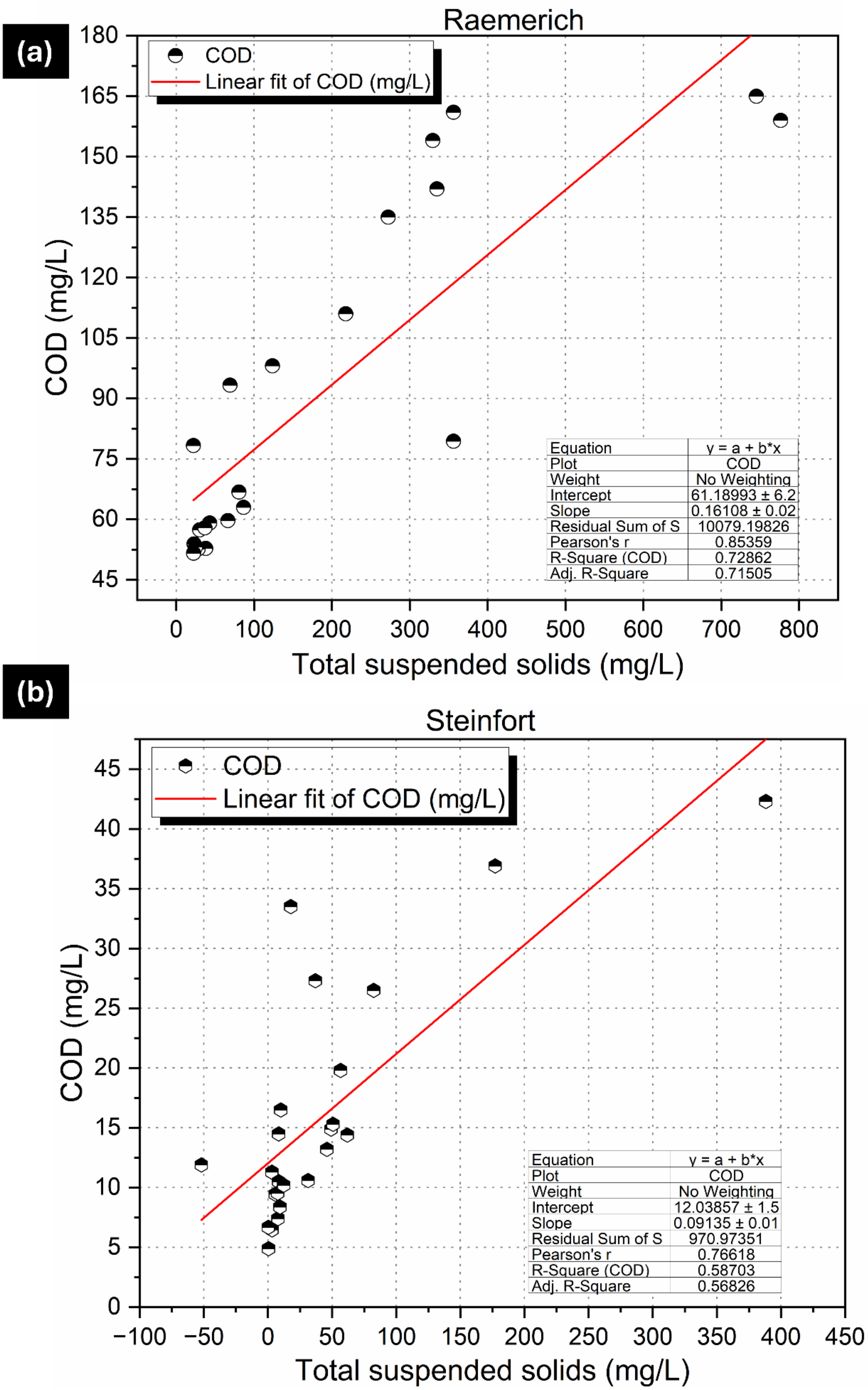


Figure 21. *Correlation between TSS and COD concentrations measured during monitoring campaigns at the Raemerich and Steinfort CWs. Figure 21**(a)**: Raemerich. Figure 21**(b)**: Steinfort.*

4.6 Inorganic Ion Dynamics

Assessing dissolved inorganic ions in stormwater runoff is essential for understanding pollutant loading patterns, identifying dominant anthropogenic sources, and evaluating treatment efficiency within CWs. Major ions such as Na^+, Cl^-, SO_4^{2-}, calcium (Ca^{2+}), potassium (K^+), and magnesium (Mg^{2+}) predominantly remain in dissolved form, making them more persistent than particulate-associated pollutants and more difficult to remove through conventional sedimentation processes (Galfi et al., 2017). Their concentration profiles therefore provide important insight into pollutant origin, runoff severity, and treatment performance.

The inorganic ion profiles measured at both sites are presented in Figure 22.

Raemerich exhibited exceptionally high dissolved inorganic pollutant concentrations, indicating severe anthropogenic loading conditions. The measured Na^+ concentrations ranged between approximately 474 and 3969 mg/L, while Cl^- concentrations ranged between approximately 706 and 5139 mg/L, clearly exceeding typical urban stormwater values reported for traffic-dominated catchments (Göbel et al., 2007).

Cl^- concentrations peaked at approximately 5139 mg/L, confirming intense de-icing and traffic-related influences. SO_4^{2-} concentrations, reaching values above 3348 mg/L, were particularly elevated and suggest that pollutant sources extended beyond conventional roadway runoff to include industrial discharges, fossil fuel emissions, and infrastructure-related deposition.

Previous stormwater and CW studies have similarly linked elevated Cl^- and SO_4^{2-} loads to intensive road salting, industrial discharge, fossil fuel combustion, and urban infrastructure weathering (Göbel et al., 2007; Mundahl & Howard, 2025).

This interpretation is further supported by the Raemerich catchment composition, where approximately 50% of the area is dominated by road infrastructure and around 25% by urban-industrial surfaces. The predominance of transportation infrastructure strongly explains Na^+ and Cl^- enrichment, while industrial and urban surfaces likely contributed SO_4^{2-}, calcium, potassium, and magnesium through infrastructure weathering, atmospheric deposition, emissions, and industrial activities.

The observed Na^+ trends closely mirrored Cl^- behaviour, reinforcing road salt application as a dominant source. Despite these elevated concentrations, the CW achieved measurable attenuation. SO_4^{2-} concentrations declined from approximately 3348 mg/L to approximately

1610 mg/L, corresponding to a reduction greater than 50%, while Cl^- decreased from approximately 5139 mg/L to approximately 461 mg/L.

SO_4^{2-} reduction likely resulted from combined dilution, adsorption to substrate surfaces, plant uptake, and microbially mediated SO_4^{2-} reduction occurring under anaerobic wetland conditions. In contrast, Cl^- remained comparatively persistent because of its conservative dissolved behaviour and limited sedimentation or biological transformation potential, which is consistent with previous CW studies (Choi et al., 2021).

Substrate filtration, hydraulic retention, microbial biofilms, and rhizosphere interactions collectively contributed to pollutant moderation, although pollutant overload conditions limited complete removal. Overall, Raemerich primarily functioned as a peak-load attenuation system operating under severe anthropogenic pressure.

In contrast to Raemerich, Steinfort exhibited substantially lower inorganic pollutant concentrations and more moderate anthropogenic influence. Although concentrations remained elevated relative to pure rainwater conditions, they were considerably lower than those observed under extreme roadway contamination scenarios.

Cl^- concentrations generally ranged between approximately 19 and 173 mg/L, while SO_4^{2-} concentrations ranged between approximately 80 and 173 mg/L, reflecting lower traffic density and less intensive pollutant loading.

The Steinfort catchment was characterised by a more heterogeneous land-use composition including construction, manufacturing, commercial, retail, and technical service sectors. These mixed urban activities likely generated broader but less concentrated pollutant inputs than those observed at Raemerich. Construction and manufacturing activities may have contributed calcium, SO_4^{2-}, and magnesium through cement dust, building materials, and infrastructure weathering, whereas automotive and commercial activities likely contributed moderate Na^+ and Cl^- enrichment.

A notable feature of the Steinfort system was the progressive decline in inorganic ion concentrations across treatment stages, indicating cumulative attenuation through sedimentation, filtration, plant-root interactions, substrate adsorption, and microbial processing. Vegetation likely enhanced treatment performance by improving rhizosphere oxygen transfer, promoting ion uptake, and supporting microbial communities responsible for biogeochemical transformations (Wang et al., 2018; C. Yang et al., 2022). Compared with Raemerich, Steinfort therefore demonstrated more stable pollutant moderation, lower residual concentrations, and improved operational consistency due to reduced influent burden and more balanced CW functioning. Comparison of both systems demonstrates that CW treatment efficiency for dissolved in OPs is strongly influenced by influent source intensity, surrounding land use, and system component interactions.

Raemerich reflected pollutant-overload conditions associated with intensive road infrastructure and urban-industrial land cover, where treatment primarily reduced extreme concentration peaks, but residual ion concentrations remained high. Steinfort, by contrast, reflected more diversified commercial and industrial land use with lower pollutant severity, allowing more stable and effective long-term attenuation.

Across both systems, inorganic pollutant attenuation depended on integrated physical, chemical, and biological processes. Hydraulic retention promoted dilution and settling, substrates provided adsorption and ion-exchange sites, vegetation enhanced rhizosphere oxygenation and ion uptake, and microbial communities facilitated sulphur cycling and nutrient transformation.

However, conservative ions such as Cl^- and Na^+ remained more resistant to removal than reactive ions such as SO_4^{2-}. Consequently, stormwater CW performance depends not only on wetland design but also on source control, vegetation selection, microbial processes, and catchment land-use management.

Effective management of road salts, transport emissions, and industrial discharges, combined with optimised CW design, is therefore essential for improving long-term inorganic pollutant removal efficiency in urban stormwater systems.

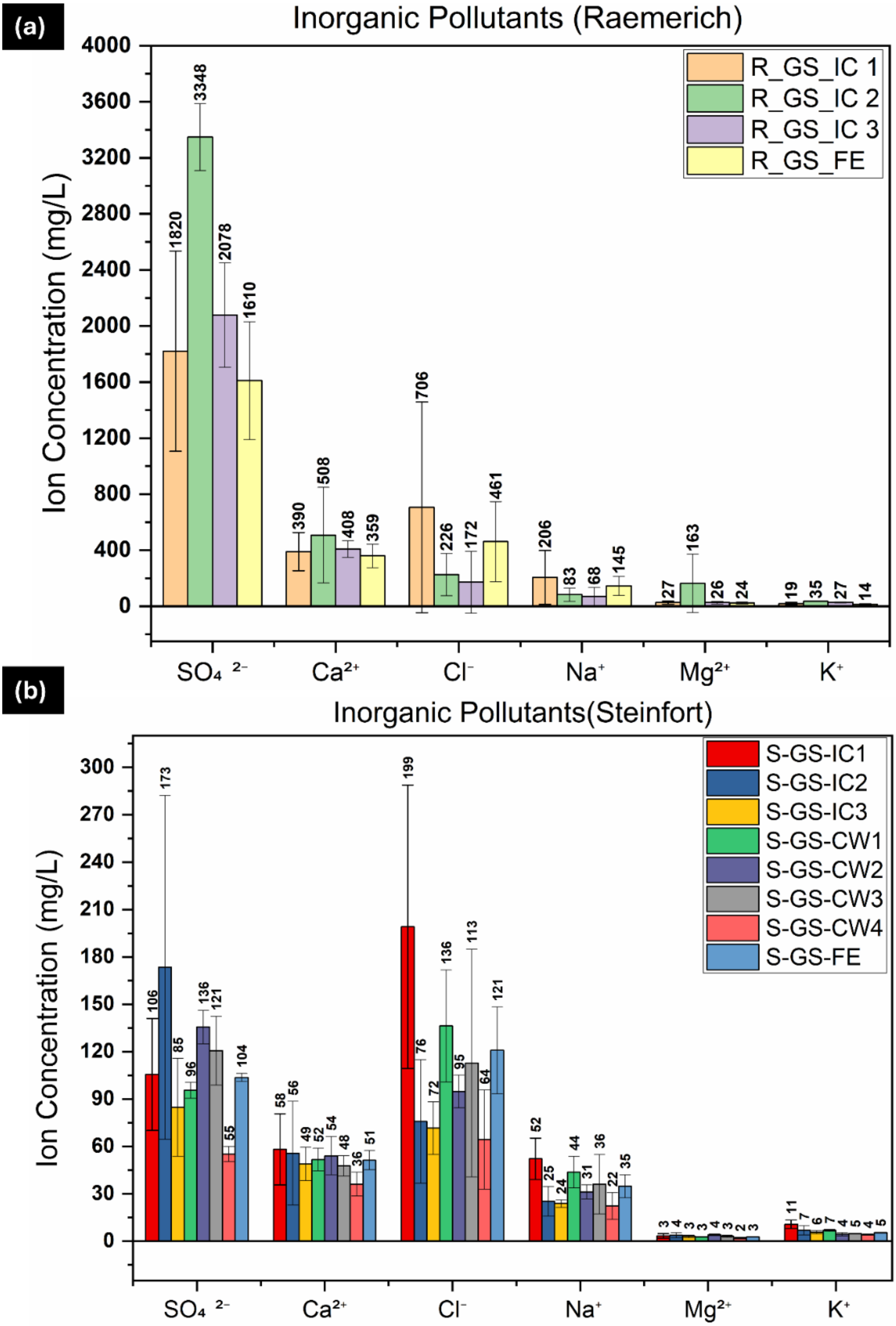


Figure 22. *Ion concentrations measured during monitoring campaigns at the Raemerich and Steinfort CWs. Figure 22**(a)**: Raemerich. Figure 22**(b)**: Steinfort.*

4.7 Pollutant Removal Efficiency of Constructed Wetlands

The Raemerich CW received highly variable stormwater inflows characterized by elevated organic and particulate pollutant concentrations. Substantial increases in pollutant concentrations were observed within the AS samples during the monitored runoff events. Despite these variable inflow conditions, the CW demonstrated considerable attenuation of pollutant concentrations before final discharge.

4.7.1 COD Dynamics and Organic Matter Attenuation

- **Raemerich CW**

COD concentrations at Raemerich showed strong event-driven variability associated with rapid runoff generation and first-flush mobilisation processes (Figure 23). While GS concentrations remained comparatively moderate, AS concentrations increased substantially during rainfall events and reached peak values between approximately 98 and 165 mg/L. The pronounced increase within the AS compartments reflects rapid mobilisation of particulate-associated organic matter from the motorway catchment during the early runoff phase.

Despite elevated influent concentrations, FE concentrations remained substantially lower, generally between approximately 28 and 49 mg/L, corresponding to estimated COD removal efficiencies of approximately 60-80%. The progressive reduction in COD concentrations throughout the treatment train indicates effective attenuation of organic pollutant fractions during water passage through the CWs.

The observed COD reduction was likely controlled by a combination of physical retention and biological transformation processes. Sedimentation and filtration of particulate-associated organic matter likely represented the dominant initial removal mechanisms, particularly during high-flow conditions characterised by elevated suspended solid concentrations. In parallel, microbial degradation within vegetated and oxygenated CW likely contributed to further transformation of biodegradable organic fractions. The previously discussed DO dynamics support the occurrence of oxygen-consuming biodegradation processes during hydraulic residence within the CW units. Similar interactions between hydraulic retention, oxygen availability, and organic matter degradation have been described for stormwater CWs by Lucas et al. (Lucas et al., 2014).The strong correspondence between COD and TSS dynamics at Raemerich further suggests that a substantial proportion of the transported organic load was associated with suspended particulate matter. Consequently, efficient particulate retention within the CW likely contributed directly to the observed COD attenuation behaviour.

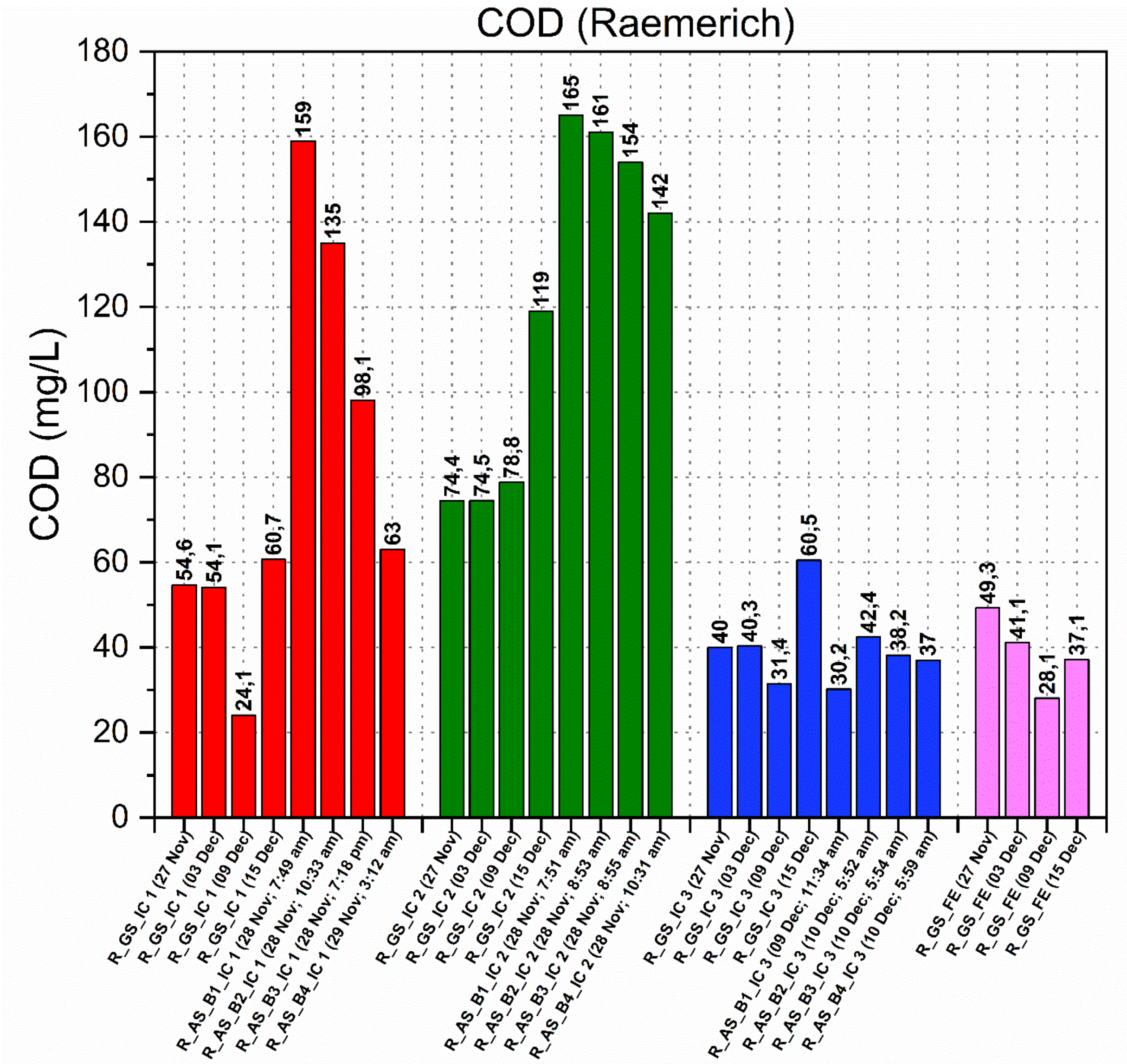


Figure 23. *COD concentrations measured throughout the Raemerich CW treatment system during monitored rainfall events, including GS, AS, intermediate CW compartments, and FE samples (Where GS: Grab sample; AS: Autosampler; FE: Final effluent).*

- **Steinfort CW**

Compared with Raemerich, COD concentrations at Steinfort remained substantially lower and exhibited reduced temporal variability throughout the monitored rainfall events (Figure 24). GS concentrations generally ranged between approximately 6 and 35 mg/L, while AS concentrations remained mostly below 35 mg/L. The absence of pronounced concentration peaks indicates comparatively buffered runoff conditions and reduced hydraulic shock loading within the catchment.

FE concentrations remained consistently low, generally between approximately 7 and 10 mg/L, corresponding to estimated COD removal efficiencies of approximately 40-75%. Although removal efficiencies were slightly lower than those estimated at Raemerich, the Steinfort CW maintained considerably more stable effluent concentrations throughout the monitored campaigns.

The comparatively moderate COD dynamics suggest that dissolved organic fractions contributed more substantially to total organic loading at Steinfort than at Raemerich. Consequently, COD attenuation was likely controlled not only by particulate retention but also by microbial degradation and longer hydraulic residence within the staged CW configuration. The sequential treatment compartments and downstream pond zone likely promoted hydraulic buffering, reduced flow velocities, and more stable redox conditions, thereby supporting progressive organic matter transformation during water passage through the system.

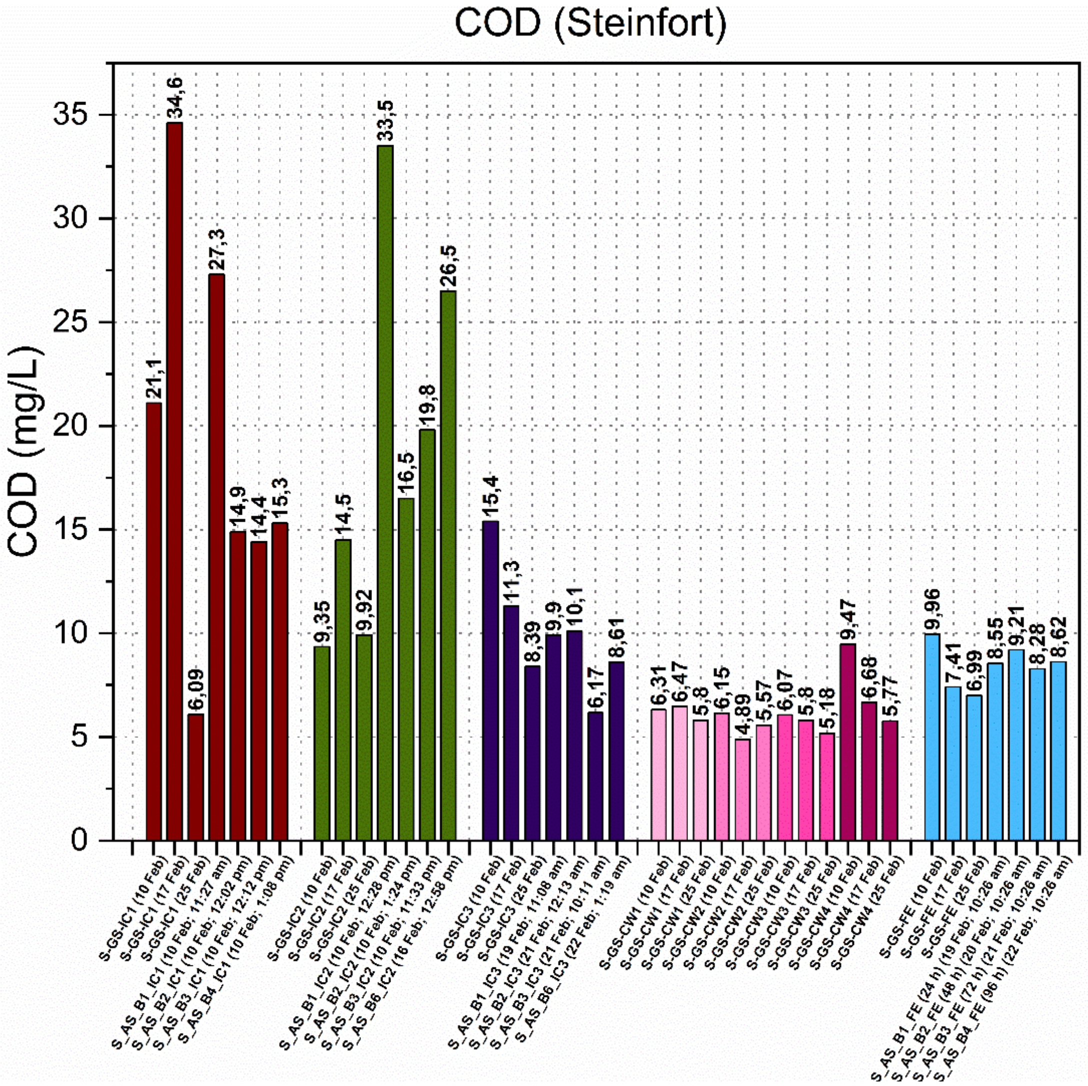


Figure 24. *COD concentrations measured throughout the Steinfort CW treatment system during monitored rainfall events, including GS, AS, intermediate CW compartments, and FE samples (Where GS: Grab sample; AS: Autosampler; FE: Final effluent).*

Overall, the COD results demonstrate that both CWs effectively attenuated organic pollution under event-based runoff conditions, although the dominant controlling mechanisms differed according to catchment characteristics and pollutant phase composition. Raemerich was dominated by highly dynamic particulate-associated organic transport, whereas Steinfort exhibited more hydraulically buffered and progressive organic matter attenuation behaviour.

4.7.2 TSS Dynamics and Particulate Retention

- **Raemerich CW**

TSS concentrations at Raemerich exhibited extremely pronounced event-driven variability consistent with intense first-flush mobilisation from the motorway catchment (Figure 25). Peak AS concentrations reached approximately 512, 745, and 776 mg/L during monitored runoff events, whereas FE concentrations remained consistently low, generally between approximately 2 and 7 mg/L. These results correspond to estimated TSS removal efficiencies frequently exceeding 95% and approaching approximately 99% during several events.

The observed attenuation behaviour indicates highly efficient retention of fine suspended particles within the CW system despite severe hydraulic loading conditions. Because the analysed TSS fraction primarily represented particles <63 µm, the results are particularly relevant within the DWA-A 102 framework, where AFS63 is regarded as a critical transport fraction for stormwater-associated contaminants (Baum et al., 2018; Dierschke, 2014).

The strong reduction of suspended solids suggests that physical retention mechanisms dominated treatment performance at Raemerich. Collection pond in Raemerich before CW may have likely promoted gravitational settling of fine particles during the recession phase of runoff events. Furthermore, vegetated zones and substrate filtration likely enhanced particulate trapping and reduced remobilisation under variable hydraulic conditions.

The simultaneous attenuation of both TSS and COD further supports the strong coupling between particulate transport and organic pollutant dynamics within the motorway runoff system. The results indicate that a substantial fraction of the transported organic pollution was associated with suspended particulate matter rather than dissolved organic fractions alone.

Despite the highly dynamic inflow conditions, FE concentrations remained consistently low throughout the monitored campaigns, indicating stable particulate retention capacity within the treatment system.

Similar high suspended solid removal efficiencies under event-based stormwater loading have been reported in previous CW investigations (Lucas et al., 2014).

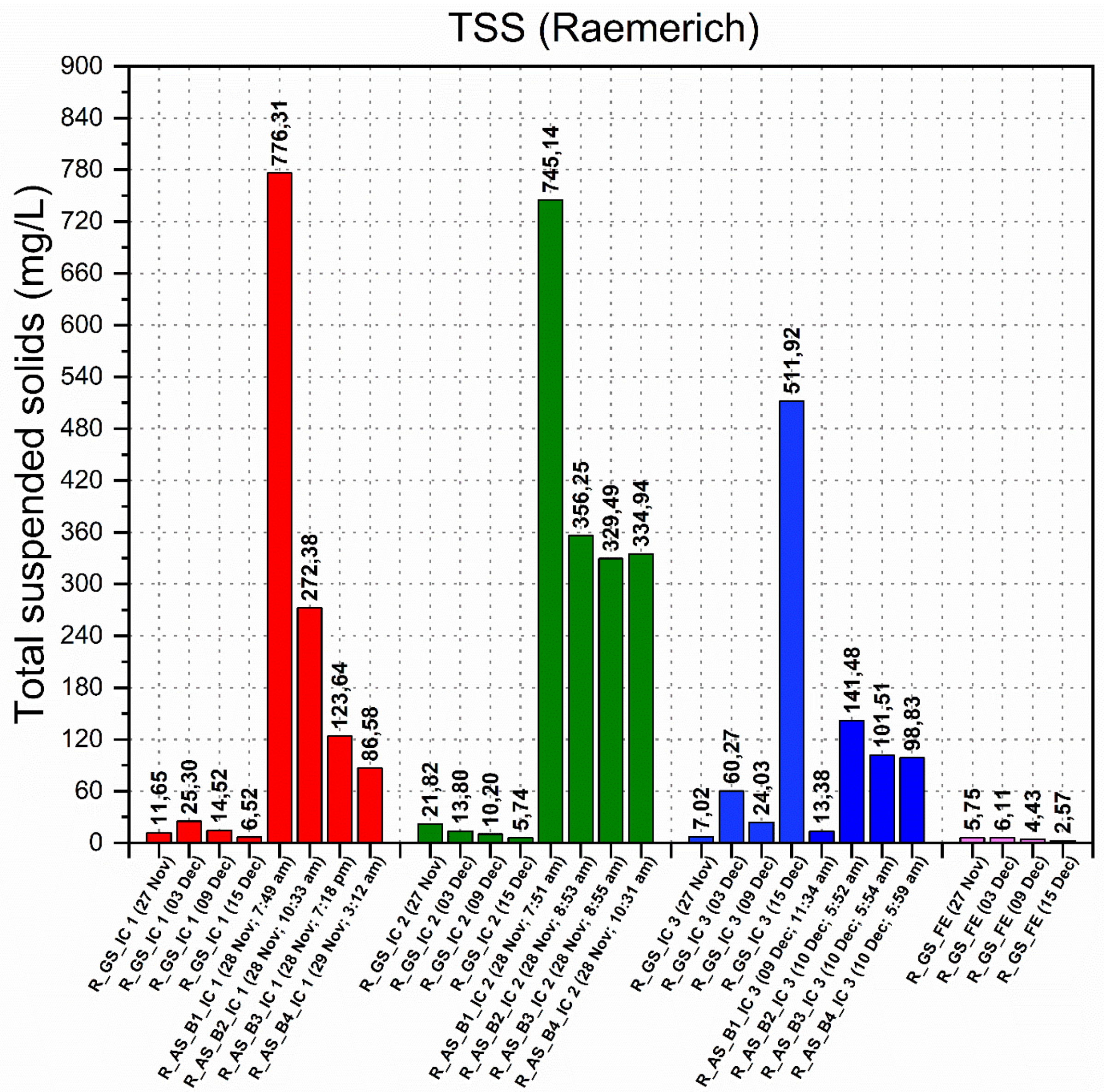


Figure 25. *TSS concentrations measured throughout the Raemerich CW treatment system during monitored rainfall events, including GS, AS, intermediate CW compartments, and FE samples (Where GS: Grab sample; AS: Autosampler; FE: Final effluent).*

- **Steinfort CW**

Compared with Raemerich, TSS concentrations at Steinfort remained substantially lower and exhibited considerably reduced temporal variability throughout the monitored rainfall events (Figure 26). Peak AS concentrations reached approximately 50, 62, and 82 mg/L, while FE concentrations generally remained between approximately 5 and 16 mg/L. Estimated TSS removal efficiencies ranged approximately between 70% and 95%.

The comparatively moderate TSS concentrations suggest lower particulate mobilisation intensity and reduced hydraulic disturbance within the mixed urban catchment. In contrast to the abrupt first-flush behaviour observed at Raemerich, particulate transport at Steinfort appeared more progressively distributed throughout the rainfall events.

The staged hydraulic configuration likely played a major role in stabilising particulate attenuation behaviour. Sequential treatment compartments and pond likely increased hydraulic residence time, reduced turbulence, and promoted continuous sedimentation during runoff events. Consequently, particulate transport remained comparatively buffered despite variable inflow conditions.

Although TSS attenuation remained highly effective, the weaker relationship between TSS and COD previously observed at Steinfort suggests that dissolved organic fractions contributed more substantially to overall COD concentrations than at Raemerich. This indicates that particulate retention alone cannot fully explain organic pollutant attenuation within the Steinfort system.

Overall, both CWs demonstrated strong particulate retention capacity under real rainfall conditions. However, the dominant transport behaviour differed substantially between sites. Raemerich was characterised by highly dynamic first-flush mobilisation associated with motorway runoff, whereas Steinfort exhibited more hydraulically buffered and progressive particulate attenuation behaviour.

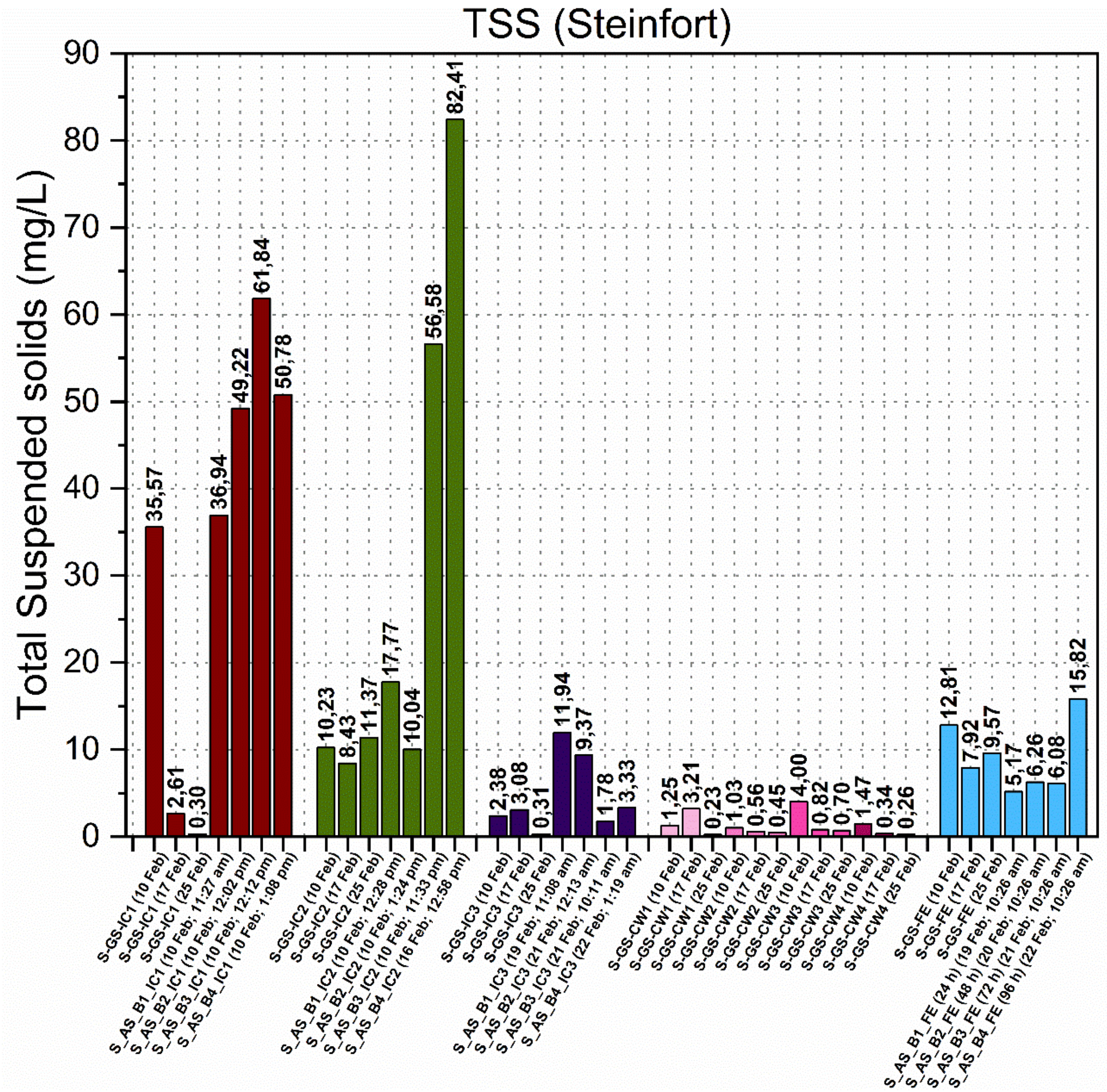


Figure 26. *TSS concentrations measured throughout the Steinfort CW treatment system during monitored rainfall events, including GS, AS, intermediate CW compartments, and FE samples (Where GS: Grab sample; AS: Autosampler; FE: Final effluent).*

4.7.3 Carbon Fractions and Dissolved Inorganic Species

The carbon fraction and inorganic ion results further demonstrated clear differences between particulate-associated and dissolved pollutant behaviour within both CWs. While moderate attenuation was observed for organic carbon fractions, dissolved IC and inorganic ions generally exhibited comparatively conservative transport behaviour during water passage through the treatment systems.

- **Organic Carbon Fractions**

At Raemerich, elevated TOC concentrations within the AS compartments frequently exceeded approximately 40-60 mg/L during monitored rainfall events, whereas FE concentrations remained substantially lower. Estimated TOC removal efficiencies generally ranged between approximately 40% and 70%, indicating moderate-to-strong attenuation of organic carbon throughout the treatment train.

The comparatively strong TOC attenuation likely reflects the dominant contribution of particulate-associated organic matter within motorway runoff. Sedimentation and retention of suspended particles therefore likely represented a major removal pathway for organic carbon within the CW system. Additional attenuation likely resulted from microbial degradation processes occurring during hydraulic residence within vegetated treatment compartments.

In contrast, IC concentrations remained comparatively stable throughout the treatment train and exhibited only limited reductions between influent and FE samples. This behaviour indicates relatively conservative transport of dissolved IC species within the CW system. Similar behaviour of dissolved carbon fractions has been reported in previous CW studies investigating urban stormwater treatment processes (Sanciolo et al., 2023).

At Steinfort, both TOC and IC concentrations remained substantially lower and more stable than those observed at Raemerich. TOC concentrations generally remained below approximately 5 mg/L throughout most monitored events, while IC represented the dominant carbon fraction. Estimated TOC removal efficiencies generally ranged between approximately 30% and 60%.

The comparatively weaker TOC attenuation at Steinfort likely reflects lower organic loading intensity together with a reduced contribution of particulate-associated organic matter within the catchment runoff. Nevertheless, the relatively stable FE concentrations indicate sustained treatment performance throughout the monitored rainfall campaigns.

- **Inorganic Ions**

The inorganic ion results demonstrated substantially lower attenuation efficiencies for dissolved mineral species than for particulate-associated pollutants. At Raemerich, elevated SO_4^{2-}, Ca^{2+}, and Cl^- concentrations reflected the strongly mineralised motorway runoff conditions. Although moderate concentration reductions were observed throughout the treatment train, substantial ion concentrations persisted within the FE compartment, indicating limited permanent retention of dissolved species.

The partial attenuation observed for Cl^- and SO_4^{2-} likely resulted primarily from hydraulic dilution, temporary retention within pore water, and partial association with fine suspended particles rather than from permanent physicochemical removal processes.

At Steinfort, inorganic ion concentrations remained comparatively low and stable throughout the monitored events. Moderate attenuation was observed for Cl^- and Na^+, whereas SO_4^{2-} and Ca^{2+} exhibited largely conservative behaviour during transport through the CW system. Similar conservative transport of dissolved ions under variable stormwater conditions has been reported previously for urban runoff CWs (Walaszek et al., 2018).

Compared with the strong attenuation observed for TSS and particulate-associated organic matter, the relatively limited removal of dissolved inorganic species highlights the importance of pollutant phase partitioning in controlling CW treatment efficiency. Particulate-bound pollutants can be effectively retained through sedimentation and filtration processes, whereas dissolved mineral species generally remain highly mobile during stormwater transport (Ofiera, 2025).

4.7.4 Comparative Evaluation of Treatment Behaviour

The comparison between Raemerich and Steinfort demonstrates the strong influence of catchment characteristics, hydraulic response, and pollutant phase composition on CW treatment behaviour.

Raemerich exhibited highly dynamic pollutant mobilisation associated with intense motorway runoff and pronounced first-flush processes. Extremely elevated TSS and COD concentrations during rainfall onset indicate rapid mobilisation of particulate-associated pollutants under high hydraulic loading conditions. Nevertheless, the CW maintained very low FE concentrations, demonstrating highly efficient particulate retention and substantial attenuation of associated organic pollution despite severe inflow variability.

In contrast, Steinfort exhibited lower and more hydraulically buffered pollutant concentrations throughout the monitored events. The staged hydraulic configuration promoted comparatively stable treatment conditions, progressive attenuation behaviour, and reduced concentration variability during water passage through the system. However, the comparatively weaker relationship between TSS and COD suggests a larger contribution of dissolved organic fractions within the mixed urban runoff.

Overall, both CWs demonstrated considerably stronger removal efficiencies for particulate-associated pollutants than for dissolved inorganic species. TSS and particulate-bound organic fractions were efficiently attenuated through sedimentation, filtration, and hydraulic retention processes, whereas IC and dissolved mineral ions exhibited comparatively conservative transport behaviour throughout the treatment systems. Similar differences between particulate and dissolved pollutant attenuation have been reported in previous stormwater CW studies investigating urban runoff treatment performance (Mohammed A. B. Bosnina, 2021; Walaszek et al., 2018)

The results therefore highlight the critical role of hydraulic configuration, particulate retention, and pollutant phase partitioning in controlling stormwater treatment efficiency within CWs under real rainfall conditions.

4.8 Comparison with Environmental Standards and Regulatory Frameworks

The interpretation of stormwater treatment performance within a regulatory framework remains complex because neither Luxembourg nor current European legislation defines universal discharge limits for all conventional stormwater pollutants investigated in this study. Instead, European water protection policy is primarily governed through the WFD, which focuses on the prevention of water-body deterioration and the achievement of good ecological and chemical status at the receiving-water scale rather than through fixed end-of-pipe stormwater discharge thresholds (« DIRECTIVE 2000/60/EC », s. d.).

Within this framework, the assessment of stormwater impacts relies mainly on river basin management approaches, environmental quality objectives, and pressure reduction strategies. Consequently, parameters such as COD, TSS/AFS63, Cl^-, and SO_4^{2-} cannot systematically be evaluated against a single legally binding discharge standard for stormwater systems in Luxembourg. The Luxembourg implementation of the WFD similarly prioritises long-term protection of receiving waters and reduction of diffuse pollutant pressures rather than universal stormwater effluent thresholds.

To address this limitation, the present study combines different levels of reference frameworks:

the ecological protection objectives established by the WFD,

technical SM guidance such as DWA-A 102,

and selected proxy values derived from urban wastewater treatment regulations where scientifically relevant.

This layered comparison approach reflects the current regulatory reality of diffuse urban SM across Europe and provides a technically robust basis for interpreting the observed treatment performance of CW under real operating conditions. The DWA-A 102 framework specifically emphasises emission-related stormwater assessment and the importance of AFS63 due to their role as vectors for pollutant transport (*Arbeitsblatt DWA-A 102-2/BWK-A 3-2*, 2022; Dierschke, 2014).

Table 7. *Comparative interpretation of monitored pollutant attenuation with relevant technical and regulatory reference frameworks.*

Parameter	Site	Removal efficiency	Relevant reference framework	Interpretation
COD	Raemerich	~75%	UWWTD proxy; WFD objectives	Comparable to proxy urban wastewater benchmarks
COD	Steinfort	~75-80%	UWWTD proxy; WFD objectives	High organic matter attenuation observed
TSS / AFS63	Raemerich	~98%	DWA-A 102	Significant particulate removal
TSS / AFS63	Steinfort	~80%	DWA-A 102	Outlet concentrations substantially reduced
Cl^-	Raemerich	~91%	WFD receiving-water protection approach	Elevated residual concentrations remained
SO_4^{2-}	Raemerich	>50%	WFD receiving-water protection approach	Partial attenuation observed
Cl^-	Steinfort	Progressive decline observed	WFD framework	No direct stormwater benchmark available
SO_4^{2-}	Steinfort	Progressive decline observed	WFD framework	No direct stormwater benchmark available

The results demonstrate that the investigated CW achieved substantial attenuation of particulate and organic pollution indicators, particularly for TSS/AFS63 and COD.

The very high particulate removal observed at Raemerich is consistent with previous studies highlighting the strong capacity of CW to retain suspended solids and associated pollutants through sedimentation, filtration and adsorption processes (Lucas et al., 2014; Venditti et al., 2024)

The strong attenuation of fine suspended solids is particularly relevant within the DWA-A 102 framework because fine particles below 63 µm are recognised as major carriers of adsorbed pollutants in urban runoff (*Arbeitsblatt DWA-A 102-2/BWK-A 3-2*, 2022; Dierschke, 2014)

Similarly, the observed reduction in COD concentrations suggests effective removal of particulate and biodegradable organic matter within the CWs. Comparable removal efficiencies have been widely reported for stormwater treatment wetlands and other nature-based SM systems (Lucas et al., 2014).

However, the results also indicate that elevated residual concentrations of Cl^- and SO_4^{2-} remained at the Raemerich site despite substantial attenuation during treatment. This behaviour reflects the conservative nature of dissolved ions, which are generally less effectively removed by conventional wetland processes than particle-bound pollutants (Maniquiz-Redillas et al., 2022).

The findings therefore highlight an important distinction between particulate stormwater pollution and dissolved inorganic contamination. While CW demonstrated high efficiency for particulate-bound pollutants and organic matter, dissolved ions associated with road runoff, winter salting practices or industrial influences may require complementary treatment approaches or source-control measures. Similar limitations have been identified in previous SM studies (Brunhoferova, 2022; Lucas et al., 2014).

The presented benchmarks should therefore not be interpreted as strict legal compliance thresholds, but rather as comparative technical references used to contextualise the observed treatment behaviour of the investigated CWs within the broader European water protection framework.

4.9 Implications for Sustainable Stormwater Management in Luxembourg

The results of this study demonstrate the potential of CWs as NBS for sustainable stormwater management under Luxembourgish conditions. The monitored systems showed the capacity to attenuate suspended solids, organic matter, and associated pollutants under real operating conditions, highlighting their relevance for improving urban runoff management in increasingly urbanised catchments.

4.9.1 Implications for Urban Runoff Management

The contrasting behaviour observed between Raemerich and Steinfort demonstrates the strong influence of catchment characteristics and hydraulic design on treatment performance. Systems receiving highly impervious motorway runoff experienced stronger first-flush effects and higher pollutant loading, whereas staged hydraulic configurations promoted more stable hydraulic behaviour and pollutant attenuation. These findings indicate that future stormwater management strategies should integrate hydraulic buffering and retention-based treatment approaches to improve resilience against rainfall-driven pollutant transport.

4.9.2 Relevance Under Climate Change and Urbanisation

The findings are particularly relevant in Luxembourg, where increasing urbanisation and climate-related rainfall variability are expected to intensify pressure on urban drainage systems and receiving water (Bonciarelli et al., 2025; Venditti et al., 2022). By temporarily storing runoff and reducing hydraulic peaks, CWs may contribute to flood mitigation and reduce stress on conventional drainage infrastructure during high-intensity rainfall events. Nature-based systems therefore represent an important adaptation strategy for improving urban hydrological resilience under future climatic conditions.

4.9.3 Regulatory and Policy Implications

The study additionally supports the growing importance of integrated stormwater management within European environmental policy. The revised UWWTD (*Directive (EU) 2024/3019*, 2024) recognises urban runoff and wet-weather discharges as significant pollution sources and promotes sustainable mitigation strategies within urban water management planning.

In this context, CWs represent a relevant management approach because they combine hydraulic retention, pollutant attenuation, and ecological functionality while operating with relatively low energy requirements compared with conventional treatment technologies (Kadlec & Wallace, 2009; Lucas et al., 2014).

4.9.4 Ecological and Sustainability Benefits

Beyond pollutant removal, CWs may provide additional ecosystem services including habitat creation, biodiversity support, and landscape integration. Such multifunctional benefits are increasingly recognised within sustainable urban planning approaches and support the transition toward more environmentally integrated water management systems (Simperler et al., 2020). Previous studies from the Greater Region have similarly demonstrated the importance of CWs for micropollutant mitigation and regional water management planning (Venditti et al., 2022).

4.9.5 Overall Implications

Overall, the findings support the integration of CWs into future stormwater management strategies in Luxembourg. Their implementation may contribute simultaneously to pollution control, climate adaptation, regulatory compliance, and enhancement of urban ecological resilience under future environmental pressures.

5 Conclusions and Recommendations

5.1 Overall Conclusions

This thesis investigated the performance of two CWs treating urban stormwater runoff under Luxembourgish conditions through event-based monitoring of hydraulic and water quality parameters. The monitoring campaigns demonstrated that stormwater pollutant transport is highly dynamic and strongly influenced by rainfall intensity, antecedent dry periods, runoff characteristics, and catchment-specific conditions. Significant temporal variations were observed throughout the monitored rainfall events, particularly during the initial runoff phases, where elevated concentrations of suspended solids and associated pollutants frequently occurred, confirming the importance of first-flush dynamics within urban stormwater systems.

The results further highlighted clear differences between the investigated catchments and demonstrated the strong influence of land use and runoff origin on pollutant behaviour. The motorway-related catchment generally exhibited more pronounced particulate pollution patterns and higher concentrations of suspended solids and associated contaminants compared to the mixed urban catchment. These observations suggest that traffic-related runoff processes, including tyre wear, road surface abrasion, and the accumulation of particulate material during dry periods, likely contributed to the higher pollutant mobilisation observed during rainfall events. Overall, this demonstrates that catchment characteristics play a fundamental role in determining stormwater quality and treatment requirements.

The investigated CWs demonstrated satisfactory treatment performance under real operating conditions, particularly regarding the retention of suspended solids and particulate-associated pollutants. The results indicate that sedimentation and filtration were the dominant treatment mechanisms within the monitored systems, enabling efficient removal of particulate matter during stormwater treatment. However, several dissolved parameters displayed more variable behaviour throughout the monitored events and were not consistently reduced to the same extent as particulate fractions. These findings highlight the complexity of stormwater treatment processes and confirm that pollutant behaviour cannot always be fully represented through particulate indicators alone.

Particular attention was given to the role of AFS63 due to its increasing relevance within emission-based stormwater management approaches such as DWA-A 102. The monitoring results confirmed the suitability of AFS63 for characterising fine particulate pollution and assessing sediment-bound pollutant transport within urban runoff systems. At the same time, the behaviour of dissolved parameters suggests that exclusive reliance on particulate-oriented indicators may not fully capture the complexity of pollutant dynamics under highly variable stormwater conditions. In this context, the thesis highlights the importance of integrated monitoring approaches combining hydraulic observations, particulate indicators, and complementary physicochemical analyses for a more representative assessment of stormwater treatment performance.

From a broader perspective, this thesis provides valuable field-based insight into the behaviour and treatment of urban stormwater runoff within Luxembourgish catchments. The results support the potential of CWs as NBS capable of contributing to sustainable stormwater management and pollutant mitigation under increasingly variable hydrological conditions. At the same time, the findings demonstrate the importance of event-based monitoring and site-specific assessment approaches for improving the understanding of pollutant transport processes and supporting the future development of more adapted stormwater management strategies in Luxembourg.

5.2 Research Questions and Hypotheses Revisited

The monitoring campaigns conducted at the Raemerich and Steinfort CWs provided valuable insights into the behaviour of stormwater pollutants during real rainfall events and into the treatment performance of CW under dynamic hydraulic conditions. The obtained results allow the initial research questions and hypotheses of this study to be revisited and critically evaluated.

RQ1: Evolution of AFS63 and MaPs during storm events

The first research question investigated how concentrations and loads of AFS63 and selected MaPs evolve during storm events in small Luxembourgish catchments. The results demonstrated strong temporal variability in pollutant concentrations throughout rainfall events, particularly during the initial runoff phases. Elevated concentrations of AFS63 and COD were frequently observed at the beginning of rainfall events, especially at the Raemerich motorway catchment, indicating the mobilisation of accumulated particulate and OPs from impervious surfaces. In contrast, NH_4^+ and orthophosphate generally showed low concentrations and limited event-driven variability.

These findings confirm that stormwater pollutant dynamics are strongly governed by hydrological response and catchment characteristics.

Overall, the results support Hypothesis H1, confirming a pronounced first-flush effect primarily associated with particulate and organic pollutant transport.

RQ2: Pollutant reduction efficiency of CWs under storm events

The second research question examined the extent to which CWs reduce AFS63 and MaPs loads under real stormwater conditions, particularly during events characterised by first-flush behaviour. The inlet measurements captured clear event-driven increases in TSS, AFS63 and COD, confirming strong pollutant mobilisation during rainfall. In contrast, effluent concentrations were generally lower, indicating that both CWs were able to attenuate pollutant peaks prior to discharge.

This attenuation was more consistent for AFS63 and particulate-associated pollution than for dissolved parameters, reflecting the dominant role of sedimentation and filtration processes within the systems. However, differences in sampling methods (automated inlet sampling versus grab sampling at the outlet) must be considered when interpreting direct comparisons.

Overall, Hypothesis H2 is largely supported for particulate-bound pollutants such as AFS63 and COD, while dissolved pollutant behaviour shows more limited and variable removal.

RQ3: Influence of rainfall and hydraulic conditions on treatment performance

The third research question assessed how rainfall characteristics and hydraulic loading conditions influence CW removal efficiency during storm events. The results showed that rainfall intensity and inflow dynamics strongly affected pollutant behaviour in both systems. High-intensity rainfall events triggered sharp increases in TSS, AFS63 and COD, particularly at Raemerich, where strong first-flush dynamics and highly variable inlet concentrations were observed.

These conditions likely reduced HRT and increased short-term hydraulic stress. Despite this, both CWs maintained substantial attenuation of particulate and OPs during all monitored events. Raemerich showed highly event-driven behaviour with extreme inlet peaks but also high removal efficiencies for particulate pollutants (TSS >95%, COD up to ~80%). In contrast, Steinfort exhibited more stable inflow conditions and smoother pollutant attenuation patterns.

These results suggest that hydraulic buffering and staged flow conditions contributed to treatment stability under variable stormwater conditions.

Therefore, Hypothesis H3 is partially supported: while high hydraulic loading can reduce short-term stability, both CWs still maintained effective treatment performance for particulate-associated pollutants.

<u>RQ4: Compliance with emission-based benchmarks (AFS63 and MaPs)</u>

The fourth research question evaluated whether treated stormwater discharges comply with emission-based benchmarks defined under DWA-A 102-2 for AFS63 and national reference targets for MaPs reduction in Luxembourg. The results showed strong attenuation of particulate-associated pollutants throughout the monitoring period, particularly for TSS and AFS63-related fractions.

Both CWs demonstrated high efficiency in reducing sediment-bound pollutant loads prior to discharge. However, dissolved parameters and inorganic ions showed more conservative behaviour and lower removal efficiencies, highlighting phase-dependent treatment limitations.

Overall, the findings indicate that CWs are particularly effective for controlling particulate-associated stormwater pollution under real operating conditions.

Thus, Hypothesis H4 is supported, confirming that CWs can contribute to compliance with emission-based stormwater management objectives in Luxembourg.

<u>Overall synthesis</u>

Collectively, the results demonstrate that stormwater pollutant behaviour is highly event-driven and strongly influenced by catchment characteristics, rainfall intensity, and hydraulic conditions. CW showed robust performance in attenuating particulate and organic pollution, particularly during high-intensity storm events, while dissolved pollutants exhibited more variable behaviour.

These findings reinforce the importance of integrated, event-based monitoring approaches and highlight the relevance of distinguishing between particulate and dissolved pollutant fractions when evaluating stormwater treatment systems. The study further supports the applicability of CWs as NBS for sustainable urban stormwater management under Luxembourgish conditions.

5.3 Limitations and Uncertainties

Although this thesis provides relevant field-based evidence on the behaviour and performance of CWs for stormwater treatment in Luxembourg, several limitations should be considered when interpreting the results:

- **Limited monitoring period:**

  The monitoring campaigns were based on a limited number of rainfall events and therefore represent specific hydrological and seasonal conditions rather than long-term system behaviour. Since stormwater processes are highly event-dependent, additional monitoring covering a wider range of rainfall intensities, antecedent dry periods, and seasonal conditions would improve dataset representativeness and robustness.

- **Sampling strategy and efficiency interpretation:**

  Inlet dynamics were primarily captured through AS, whereas FE conditions were assessed using grab samples. This approach allowed identification of pollutant mobilisation and attenuation trends during rainfall events; however, it does not represent a direct real-time comparison of identical water parcels entering and leaving the systems. Therefore, reported removal efficiencies should be interpreted as concentration-based performance indicators rather than full mass-balance estimates.

- **Lack of process-level resolution:**

  The study focused on overall system performance without quantifying the individual contributions of internal removal mechanisms such as sedimentation, filtration, adsorption, microbial degradation, and plant uptake. This is particularly relevant given the observed stronger retention of particulate-associated pollutants compared to dissolved parameters, indicating that pollutant phase partitioning strongly influences treatment performance.

- **Exclusion of long-term operational processes:**

  Long-term processes such as sediment accumulation, substrate ageing, vegetation development, clogging risk, and potential remobilisation of retained pollutants were not assessed. These factors may significantly influence hydraulic behaviour and treatment efficiency over time, particularly under variable stormwater loading conditions such as those observed at the Raemerich site.

- **<u>Indicator limitations (AFS63):</u>**

  While AFS63 proved to be a useful indicator for fine particulate pollution and sediment-bound contaminant transport, results show that stormwater pollution cannot be fully characterised using particulate indicators alone. Dissolved parameters and inorganic ions exhibited more variable and conservative behaviour, highlighting the need for integrated assessment approaches combining particulate and dissolved-phase indicators.

5.4 Recommendations for Future Research and Practical Implementation

Future research should extend the monitoring of CWs under a wider range of rainfall and seasonal conditions. Longer monitoring periods would allow a more robust evaluation of treatment stability, first-flush behaviour, and hydraulic performance under both moderate and extreme storm events. This is particularly important for Luxembourg, where small and reactive catchments can generate rapid runoff responses and highly variable pollutant loads.

Further investigations should also integrate concentration-based monitoring with flow measurements to enable the calculation of pollutant loads and mass-based removal efficiencies. This would allow a more precise evaluation of CW performance during storm events and improve comparability with emission-based assessment approaches. Future monitoring should aim to better synchronise inlet and outlet sampling so that pollutant attenuation can be assessed more directly along the treatment pathway.

The findings of this thesis also confirm that AFS63 should remain an important indicator for stormwater assessment, but not as a standalone parameter. Future monitoring strategies should integrate AFS63 with COD, carbon fractions, conductivity, and selected inorganic ions. Such an integrated approach would provide a more realistic understanding of both particulate-associated and dissolved pollutant behaviour. This is particularly relevant given that the monitored CWs showed strong retention of particulate pollutants, while several dissolved parameters were less consistently removed.

From an operational perspective, future research should focus on sediment accumulation, substrate condition, and long-term maintenance requirements. Since the investigated CWs retained large amounts of suspended solids, particularly at Raemerich, regular assessment of sediment storage and clogging risk will be essential to maintain hydraulic capacity and treatment performance. Accordingly, maintenance strategies should be considered as an integral part of CW performance evaluation rather than as an independent operational aspect.

For practical implementation in Luxembourg, the results support the wider application of CWs as sustainable stormwater treatment systems, particularly for controlling sediment-bound pollution and first-flush-related particulate loads. However, the findings also demonstrate that site-specific design and monitoring are essential. CWs should therefore not be evaluated solely on AFS63 removal efficiency, but also on their capacity to buffer hydraulic peaks, retain particulate pollution, and limit the discharge of dissolved pollutants under real rainfall conditions.

Overall, the main practical recommendation is that stormwater management strategies in Luxembourg should adopt CWs as part of an integrated, site-specific, and monitoring-based approach. The investigated systems demonstrated that CWs can provide effective stormwater treatment under real operating conditions, especially for particulate-associated pollution. At the same time, the variable behaviour of dissolved parameters highlights that future regulatory and design frameworks should avoid relying on a single proxy indicator alone. This represents one of the central contributions of this thesis: CWs are technically relevant for stormwater treatment in Luxembourg, but their performance assessment should extend beyond AFS63 and reflect the combined behaviour of particulate and dissolved pollutant fractions.

6 References

Arbeitsblatt DWA-A 102-2/BWK-A 3-2. (2022).

Baum, P., Benisch, J., Blumenstaat, F., Dierschke, M., Dittmer, U., Gelhardt, L., Gruber, G., Grüner, S., Heinz, E., Hofer, T., Kemper, M., Leutnant, D., Nickel, J. P., & Graz, T. (2018). AFS63 -Harmonisierungsbedarf und Empfehlun- gen für die labortechnische Bestimmung des neuen Parameters. . . *Juni*.

Biswal, B. K., & Balasubramanian, R. (2022). Constructed Wetlands for Reclamation and Reuse of Wastewater and Urban Stormwater : A Review. *Frontiers in Environmental Science*, *10*, 836289. https://doi.org/10.3389/fenvs.2022.836289

Bonciarelli, L., Orlandi, F., Muscas, D., & Fornaciari, M. (2025). Sustainable Stormwater Management and Bioretention : An Overview of Reviews of the Last 10 Years. *Land*, *14*(4), 736. https://doi.org/10.3390/land14040736

Brunhoferova, H. (2022). *Mechanisms of Micropollutant Elimination in Vertical Flow Constructed Wetlands* [Unilu - University of Luxembourg, Luxembourg, Luxembourg]. https://orbilu.uni.lu/handle/10993/52773

Choi, H., Geronimo, F. K. F., Jeon, M., & Kim, L.-H. (2021). Investigation of the Factors Affecting the Treatment Performance of a Stormwater Horizontal Subsurface Flow Constructed Wetland Treating Road and Parking Lot Runoff. *Water*, *13*(9), 1242. https://doi.org/10.3390/w13091242

Decezaro, S. T., Wolff, D. B., Pelissari, C., Ramírez, R. J. M. G., Formentini, T. A., Goerck, J., Rodrigues, L. F., & Sezerino, P. H. (2019). Influence of hydraulic loading rate and recirculation on oxygen transfer in a vertical flow constructed wetland. *Science of The Total Environment*, *668*, 988-995. https://doi.org/10.1016/j.scitotenv.2019.03.057

Dierschke, M. (2014). *Methodischer Ansatz zur Quantifizierung von Feinpartikeln (PM63) in Niederschlagsabflüssen in Abhängigkeit von der Herkunftsfläche*. file:///C:/Users/beiro/OneDrive%20-%20Universite%20de%20Liege/Bureaublad/Patrick-Beiros/Thesis/sources/UNI/_Dierschke+2014+Dissertation++Quantifizierung+von+Feinpartikeln+(PM63)+in+Niederschlagsabfl%C3%BCssen.pdf

DIRECTIVE 2000/60/EC. (s. d.). In *Core EU Legislation* (p. 423-426). Macmillan Education UK. https://doi.org/10.1007/978-1-137-54482-7_44

Directive (EU) 2024/3019. (2024).

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more -The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, *12*(7), 525-542. https://doi.org/10.1080/1573062X.2014.916314

Galfi, H., Österlund, H., Marsalek, J., & Viklander, M. (2017). Mineral and Anthropogenic Indicator Inorganics in Urban Stormwater and Snowmelt Runoff : Sources and Mobility Patterns. *Water, Air, & Soil Pollution*, *228*(7), 263. https://doi.org/10.1007/s11270-017-3438-x

Göbel, P., Dierkes, C., & Coldewey, W. G. (2007). Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology*, *91*(1-2), 26-42. https://doi.org/10.1016/j.jconhyd.2006.08.008

Hathaway, J. M., Tucker, R. S., Spooner, J. M., & Hunt, W. F. (2012). A Traditional Analysis of the First Flush Effect for Nutrients in Stormwater Runoff from Two Small Urban Catchments. *Water, Air, & Soil Pollution*, *223*(9), 5903-5915. https://doi.org/10.1007/s11270-012-1327-x

Jones, K., Borgert, J., Van Dam, E., Liess, A., & Sjöstedt, J. (2025). Depth and water residence time shape dissolved organic matter removal in constructed wetlands. *Journal of Environmental Management*, *396*, 128064. https://doi.org/10.1016/j.jenvman.2025.128064

Kadlec, R. H., & Wallace, S. D. (2009). *Treatment wetlands* (2nd ed). CRC press.

Lieske, C., Leutnant, D., & Uhl, M. (2021). Assessing the TSS Removal Efficiency of Decentralized Stormwater Treatment Systems by Long-Term In-Situ Monitoring. *Water*, *13*(7), 908. https://doi.org/10.3390/w13070908

Lucas, R., Earl, E. R., Babatunde, A. O., & Bockelmann-Evans, B. N. (2014). Constructed wetlands for stormwater management in the UK : A concise review. *Civil Engineering and Environmental Systems*, *32*(3), 251-268. https://doi.org/10.1080/10286608.2014.958472

Maniquiz-Redillas, M., Robles, M. E., Cruz, G., Reyes, N. J., & Kim, L.-H. (2022). First Flush Stormwater Runoff in Urban Catchments : A Bibliometric and Comprehensive Review. *Hydrology*, *9*(4), 63. https://doi.org/10.3390/hydrology9040063

Martin, C., Ruperd, Y., & Legret, M. (2007). Urban stormwater drainage management : The development of a multicriteria decision aid approach for best management practices. *European Journal of Operational Research*, *181*(1), 338-349. https://doi.org/10.1016/j.ejor.2006.06.019

Meyer, B., Pailler, J.-Y., Guignard, C., Hoffmann, L., & Krein, A. (2011). Concentrations of dissolved herbicides and pharmaceuticals in a small river in Luxembourg. *Environmental Monitoring and Assessment*, *180*(1-4), 127-146. https://doi.org/10.1007/s10661-010-1777-9

Mittal, Y., Dash, S., Srivastava, P., Mishra, P. M., Aminabhavi, T. M., & Yadav, A. K. (2022). Azo dye containing wastewater treatment in earthen membrane based unplanted two chambered constructed wetlands-microbial fuel cells : A new design for enhanced performance. *Chemical Engineering Journal*, *427*, 131856.

Mohammed A. B. Bosnina. (2021). *Characterising and modelling pollutant dynamics in urban stormwater constructed wetlands.* [PhD]. School of Engineering, Cardiff University Cardiff, Wales, UK.

Mundahl, N. D., & Howard, J. (2025). Stormwater Management and Late-Winter Chloride Runoff into an Urban Lake in Minnesota, USA. *Hydrology*, *12*(4), 76. https://doi.org/10.3390/hydrology12040076

Nivala, J., Wallace, S., Headley, T., Kassa, K., Brix, H., Van Afferden, M., & Müller, R. (2013). Oxygen transfer and consumption in subsurface flow treatment wetlands. *Ecological Engineering*, *61*, 544-554. https://doi.org/10.1016/j.ecoleng.2012.08.028

Ofiera, L. (2025). *Modified constructed wetlands for the elimination of organic and inorganic trace compounds from municipal wastewater* [Dissertation].

Pradhanang, S. M., & Jahan, K. (2021). Structural Stormwater Best Management Practices and Watershed Management. In *Clean Water and Sanitation* (p. 1-13). Springer, Cham. https://doi.org/10.1007/978-3-319-70061-8_178-1

Prodanoff, J. H. A. (s. d.). *AVALIAÇÃO DA POLUIÇÃO DIFUSA GERADA POR ENXURRADAS EM MEIO URBANO.*

Rizzo, A., Tondera, K., Pálfy, T. G., Dittmer, U., Meyer, D., Schreiber, C., Zacharias, N., Ruppelt, J. P., Esser, D., Molle, P., Troesch, S., & Masi, F. (2020). Constructed wetlands for combined sewer overflow treatment : A state-of-the-art review. *Science of The Total Environment*, *727*, 138618. https://doi.org/10.1016/j.scitotenv.2020.138618

Sanciolo, P., Sharma, A. K., Navaratna, D., & Muthukumaran, S. (2023). Stormwater Treatment Using Natural and Engineered Options in an Urban Growth Area : A Case

Study in the West of Melbourne. *Water*, *15*(23), 4047. https://doi.org/10.3390/w15234047

Sandoval, S., Bertrand-Krajewski, J.-L., Caradot, N., Hofer, T., & Gruber, G. (2018). Performance and uncertainties of TSS stormwater sampling strategies from online time series. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, *78*(5-6), 1407-1416. https://doi.org/10.2166/wst.2018.415

Santos, J., Rodrigues, S., Magalhães, M., Rodrigues, K., Pereira, L., & Marinho, G. (2024). A state-of-the-art review (2019–2023) on constructed wetlands for greywater treatment and reuse. *Environmental Challenges*, *16*, 100973. https://doi.org/10.1016/j.envc.2024.100973

Schmitt, N., Wanko, A., Laurent, J., Bois, P., Molle, P., & Mosé, R. (2015). Constructed wetlands treating stormwater from separate sewer networks in a residential Strasbourg urban catchment area : Micropollutant removal and fate. *Journal of Environmental Chemical Engineering*, *3*(4), 2816-2824. https://doi.org/10.1016/j.jece.2015.10.008

Simperler, L., Ertl, T., & Matzinger, A. (2020). Spatial Compatibility of Implementing Nature-Based Solutions for Reducing Urban Heat Islands and Stormwater Pollution. *Sustainability*, *12*(15), 5967. https://doi.org/10.3390/su12155967

Søberg, L. C., Al-Rubaei, A. M., Viklander, M., & Blecken, G.-T. (2020). Phosphorus and TSS Removal by Stormwater Bioretention : Effects of Temperature, Salt, and a Submerged Zone and Their Interactions. *Water, Air, & Soil Pollution*, *231*(6), 270. https://doi.org/10.1007/s11270-020-04646-3

Tsihrintzis, V. A., & Hamid, R. (1997). *Modeling and Management of Urban Stormwater Runoff Quality : A Review*.

Venditti, S., Kiesch, A., Brunhoferova, H., Schlienz, M., Knerr, H., Dittmer, U., & Hansen, J. (2022). Assessing the impact of micropollutant mitigation measures using vertical flow constructed wetlands for municipal wastewater catchments in the greater region : A reference case for rural areas. *Water Science and Technology*, *86*(1), 128-141. https://doi.org/10.2166/wst.2022.191

Venditti, S., Salmeron, I., Tafalla, P. N., Hobus, I., Kolisch, G., & Hansen, J. (2024). Biochar from recovered cellulose as new admixture in constructed wetlands for micropollutant removal : A circular approach. *Science of The Total Environment*, *927*, 172055. https://doi.org/10.1016/j.scitotenv.2024.172055

Vymazal, J. (2010). Constructed Wetlands for Wastewater Treatment. *Water*, *2*(3), 530-549. https://doi.org/10.3390/w2030530

Walaszek, M., Bois, P., Laurent, J., Lenormand, E., & Wanko, A. (2018). Urban stormwater treatment by a constructed wetland : Seasonality impacts on hydraulic efficiency, physico-chemical behavior and heavy metal occurrence. *Science of The Total Environment*, *637-638*, 443-454. https://doi.org/10.1016/j.scitotenv.2018.04.325

Wang, Q., Hu, Y., Xie, H., & Yang, Z. (2018). Constructed Wetlands : A Review on the Role of Radial Oxygen Loss in the Rhizosphere by Macrophytes. *Water*, *10*(6), 678. https://doi.org/10.3390/w10060678

Yang, C., Zhang, X., Tang, Y., Jiang, Y., Xie, S., Zhang, Y., & Qin, Y. (2022). Selection and optimization of the substrate in constructed wetland : A review. *Journal of Water Process Engineering*, *49*, 103140.

Yang, Y.-Y., & Lusk, M. G. (2018). Nutrients in Urban Stormwater Runoff : Current State of the Science and Potential Mitigation Options. *Current Pollution Reports*, *4*(2), 112-127. https://doi.org/10.1007/s40726-018-0087-7

Zhao, F., Zhang, X., Xu, Z., Feng, C., Pan, W., Lu, L., & Luo, W. (2024). Review of hydraulic conditions optimization for constructed wetlands. *Journal of Environmental Management*, *370*, 122377. https://doi.org/10.1016/j.jenvman.2024.122377

Zheng, Z., Shi, B., McCarthy, D., Deletic, A., Le-Clech, P., Khan, S., Fletcher, T. D., Hancock, M., & Zhang, K. (2025). Organic micropollutant removal in stormwater : A review of treatment performance. *Environmental Science: Water Research & Technology*, *11*(10), 2274-2294. https://doi.org/10.1039/D5EW00306G

7 Appendices

7.1 Sampling Locations and Field Photographs

<u>Locations Raemerich:</u> Field Photography's

Locations Steinfort: Field Photography’s

7.2 Raw Data Tables and Laboratory Result

Excel Raemerich:

Datas-Thesis-Patrick-Beiros-2025-26.xlsx

Campaign	Dry day (grab samples) at 10:30am 27-11-2025			
Sample ID	GRS-IC1	GRS-IC2	GRS-IC3	GRS-EFF
COD (mg/L)	54.6	74.4	40	49.3
TOC (mg/L)	18.56	38.08	13.07	15.57
TC (mg/L)	78.21	166.2	56.29	72.42
IC (mg/L)	59.65	128.1	43.22	56.85
TN (mg/L)	1.55	1.59	1.68	0.9673
Conductivity (µS/cm)	4.32	3.13	2.22	2.58
Redox (mV)	202	100	154	71
pH	7.73	7.64	8.69	7.7
T (°C)	na	na	na	na
DO (mg/L)	6.92	6.58	7.06	4.04
TSS (mg/L)	11.65	21.82	7.02	5.75
Weight before (mg)	5206.8	4144.1	4156.7	4153.1
Weight after (mg)	5214.9	4160.2	4161.7	4157.8
Volume (mL)	695	738	712	817
IC data				
	A___C	A___C	A___C	A___C
F^- Li^+	1.44___na	1.08___0.08	1.43___na	0.82___na
Cl^- Na^+	1712.9___454.2	158.94___60.0	70.18___35.5	686.3___187.2
NO_2^- NH_4^+	7.64___na	na___na	na___na	na___na
Br^- K^+	na___21.88	na___35.79	na___28.08	na___19.35
NO_3^- Mg^{2+}	3.80___29.4	0.34___61.59	8.39___33.9	1.97___29.91
PO_4^{3-} Ca^{2+}	na___392.6	na___645.80	na___461.4	na___403.75
SO_4^{2-}	1966.1	3314.7	2541.7	2001.4
Autosampler trigger condition				
Date				
Trigger time				
Water level increase (mm)				
Precipitation (mm) (Rain)				

Campaign	Dry day (grab samples) at 10:30am 03-12-2025 & Autosampler from 28-11 - 30-11-2025															
Sample ID	GRS-IC1	GRS-IC2	GRS-IC3	GRS-EFF	IC1-B1-AS	IC1-B2-AS	IC1-B3-AS	IC1-B4-AS	IC1-B5-AS	IC1-B6-AS	IC2-B1-AS	IC2-B2-AS	IC2-B3-AS	IC2-B4-AS	IC2-B5-AS	IC2-B6-AS
COD (mg/L)	54.1	74.5(HR)	40.3	41.1	159	135	98.1	63	52.8	79.4	165	161	>154	142	111	66.8
TOC (mg/L)	15.93	37.28	12.09	13.46	21.96	20.56	19.05	12.54	13	17.87	23.06	18.65	17.85	18.48	19.82	14.88
TC (mg/L)	70.28	159.9	50.48	64.76	73.98	78.38	74.95	53.01	55.38	66.03	83.3	67.07	66.31	69.89	72.48	60.39
IC (mg/L)	54.35	122.6	38.39	51.31	52.02	57.82	55.9	40.47	42.38	48.16	60.24	48.42	48.45	50.91	52.66	45.51
TN (mg/L)	1.47	1.74	1.98	0.7916	2.03	1.59	1.59	1.27	1.3	1.34	2.09	1.91	1.91	2.08	1.6	1.17
Conductivity (µS/cm)	3020	3420	2670	2740	8090	5040	4560	3560	3640	3670	6670	4800	4910	4950	4100	3380
Redox (mV)	179	78	112	63	107	136	139	137	131	132	128	132	136	143	147	145
pH	7.87	7.53	8.7	7.81	8.23	8.08	8.07	8.15	8.16	8.2	8.14	8.16	8.16	8.17	8.18	8.1
T (°C)	na	na	na	na	na	na	16.8	16.6	17	17.1	17.7	16.8	16.6	16.8	17	17.8
DO (mg/L)	6.77	5.81	6.65	4.8	6.91	6.67	6.89	6.47	6.66	6.69	6.93	7.12	7.02	6.93	6.17	6.99
TSS (mg/L)	25.30	13.80	60.27	6.11	776.31	272.38	123.64	86.58	37.94	356.25	745.14	356.25	329.49	334.94	217.84	80.69
Weight before (mg)	4165.5	5201.9	5247.2	5186.4	5223.9	4137.6	4169.1	5203.8	5205.4	5191.3	5202.3	5191.3	4185.7	4153.9	5211.7	4158.7
Weight after (mg)	4182.2	5211.7	5291.8	5189.4	5417.2	4223.4	4223.5	5242.5	5229.3	5305.3	5440	5305.3	4288.5	4265.1	5292.3	4205.5
Volume (mL)	660	710	740	491	249	315	440	447	630	320	319	320	312	332	370	580
IC data																
	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C
F^- Li^+	1.35___na	1.30___na	1.30___na	0.80___na	na___na	na___na	1.15___na	0.85___na	0.85___na	0.85___na	1.25___na	0.90___na	0.75___na	0.95___na	0.80___na	0.75___na
Cl^- Na^+	848___259.45	453.60___153.80	502.25___167.80	714.15___214.00	5662.10___1485.10	2374.00___678.25	2267.80___649.75	1585.45___454.35	1592.95___474.15	1315.15___399.20	3964.15___1074.35	2066.45___683.45	2257.50___639.40	2518.75___715.10	1615.70___482.80	1241.00___381.85
NO_2^- NH_4^+	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na
Br^- K^+	na___24.80	na___35.005	na___24.80	na___15.85	na___13.10	na___17.80	na___17.45	na___8.65	na___9.35	na___11.75	na___21.35	na___12.00	na___9.80	na___13.40	na___11.30	na___5.15
NO_3^- Mg^{2+}	5.85___32.05	na___474.75	9.90___30.10	1.15___31.20	na___33.65	2.10___35.025	2.65___34.10	na___16.75	na___18.55	na___23.70	na___40.55	na___22.60	na___20.75	na___23.25	na___22.60	na___19.05
PO_4^{3-} Ca^{2+}	na___482.05	na___na	na___456.25	na___446.25	na___429.95	na___458.25	na___443.35	na___248.90	na___260.85	na___318.40	na___500.15	na___297.85	na___270.50	na___312.80	na___288.05	na___256.05
SO_4^{2-}	2177.85	3531	2198.1	1870.2	1423.3	1935.75	1842	985.85	988.1	1256.45	2000.7	1108.7	966.9	1157.65	1089.35	974.35
Autosampler trigger condition																
Date					28/11/2025	28/11/2025	28/11/2025	29/11/2025	29/11/2025	30/11/2025	28/11/2025	28/11/2025	28/11/2025	28/11/2025	28/11/2025	28/11/2025
Trigger time					7:49am	10:33am	19:18pm	3:12am	8:17am	1:48am	7:51am	8:53am	8:55am	10:31am	5:53pm	10:04pm
Water level increase (mm)					14.5	4	24.6	3.2	7	13.7	30.1	14.5	15.8	19.8	15.5	15.5
Precipitation (mm) (Rain)					0.4	0.2	1.2	0.2	0.2	0.6	0.4	0.4	0.4	0.2	0.2	0.4

Sample ID	IC2-B7-AS	IC2-B8-AS	IC2-B9-AS	IC2-B10-AS	IC2-B11-AS	IC2-B12-AS	IC2-B13-AS	IC2-B14-AS	IC2-B15-AS	IC2-B16-AS
COD (mg/L)	59.7	59.1	52.7	53.9	57.4	57.9	93.3	53.1	51.6	78.3
TOC (mg/L)	14.27	16.28	14.56	15.28	14.86	15.05	18.68	12.84	13.99	13.4
TC (mg/L)	60.01	64.02	60.96	62.02	61.55	60.6	69.54	55.97	57.33	57.62
IC (mg/L)	45.74	47.79	45.7	46.73	46.69	45.55	50.86	43.13	43.73	44.92
TN (mg/L)	1.23	1.3	1.27	1.26	1.28	1.24	1.27	0.9639	0.8945	0.9278
Conductivity (µS/cm)	3510	3710	3690	3750	3360	3380	2860	2780	2650	2680
Redox (mV)	149	146	154	153	154	158	156	154	150	151
pH	8.11	8.07	8.11	8.13	8.11	8.12	8.13	8.06	8.02	8.06
T (°C)	17.8	17.6	18	18.5	18.3	18.4	18.8	18.7	18.9	19.5
DO (mg/L)	6.78	7.13	6.5	6.6	7.33	6.82	6.92	6.83	6.43	6.45
TSS (mg/L)	66.50	43.18	28.32	23.03	30.25	37.02	69.15	24.83	22.36	22.24
Weight before (mg)	5233	4173	3428.8	4198.6	5221.2	5202.8	5186.8	4155.3	5210.2	4156.1
Weight after (mg)	5272.9	4201.5	3448.2	4214.7	5240.8	5223.9	5231.4	4170.1	5226.3	4169
Volume (mL)	600	660	685	699	648	570	645	596	720	580
IC data										
	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C
F^- Li^+	0.80___na	0.80___na	0.70___na	0.70___na	0.80___na	0.80___na	0.90___na	0.75___na	0.80___na	0.80___na
Cl^- Na^+	1308.60___396.25	1440.35___429.30	1429.80___430.60	1454.70___435.85	1217.30___371.65	1245.65___380.85	812.30___259.90	869.05___275.90	819.35___262.65	834.15___266.65
NO_2^- NH_4^+	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na	na___na
Br^- K^+	na___8.90	na___9.95	na___9.00	na___10.25	na___9.10	na___9.40	na___12.30	na___8.00	na___5.60	na___9.00
NO_3^- Mg^{2+}	na___19.65	1.51___20.60	2.05___19.50	1.85___20.10	1.20___19.35	na___19.10	1.35___20.85	1.00___17.05	na___17.70	na___17.75
PO_4^{3-} Ca^{2+}	na___262.70	na___272.50	na___259.70	na___269.65	na___255.15	na___254.95	na___284.00	na___240.05	na___241.05	na___240.85
SO_4^{2-}	1002.05	1032.7	980.85	1000.6	962.95	966.35	1105.75	885.5	915.8	905.75
Autosampler trigger condition										
Date	28/11/2025	29/11/2025	29/11/2025	29/11/2025	29/11/2025	29/11/2025	30/11/2025	30/11/2025	30/11/2025	30/11/2025
Trigger time	10:07pm	2:48am	4:08am	5:21am	8:14am	9:18am	1:49am	6:26am	6:32am	6:34am
Water level increase (mm)	15	14.1	15.2	17.3	16.1	15.3	27.1	15.3	14.8	14.8
Precipitation (mm) (Rain)	0.4	0.2	0.2	0.1	0.1	0.2	0.6	0.1	0.1	0.1

Campaign	Campaign Dry day at 10:30am 9-12-2025			
Sample ID	GRS-IC1	GRS-IC2	GRS-IC3	GRS-EFF
COD (mg/L)	24.1	78.8	31.4	28.1
TOC (mg/L)	7.06	21.9	11.17	8.93
TC (mg/L)	36.16	114.5	31.74	46.27
IC (mg/L)	29.1	93.16	20.57	37.29
TN (mg/L)	0.7108	1.42	1.94	0.6042
Conductivity (µS/cm)	1322	2850	1759	1780
Redox (mV)	242	81	120	123
pH	8.67	7.45	9.33	7.89
T (°C)	17.9	17.9	18	18.1
DO (mg/L)	6.69	5.6	6.99	3.89
TSS (mg/L)	14.52	10.20	24.03	4.43
Weight before (mg)	4167.4	4149.9	4161.3	5210.3
Weight after (mg)	4176.4	4156.1	4176.8	5213
Volume (mL)	620	608	645	609
IC data				
	A___C	A___C	A___C	A___C
F^- Li^+	0.8970___na	1.1235___na	1.9360___na	0.8945___na
Cl^- Na^+	108.46___47.09	143.51___57.16	58.75___37.39	309.29___115.43
NO_2^- NH_4^+	na___na	na___na	na___na	na___na
Br^- K^+	na___7.0950	na___33.0465	na___32.3935	na___8.5115
NO_3^- Mg^{2+}	1.7320___9.99	2.0180___47.38	11.2990___14.1490	1.2245___14.9915
PO_4^{3-} Ca^{2+}	na___196.19	na___649.73	na___346.78	na___259.46
SO_4^{2-}	775.75	3022.65	1702.15	1061.05
Autosampler trigger condition				
Date				
Trigger time				
Water level increase (mm)				
Precipitation (mm) (Rain)				

Campaign	Campaign Dry day at 10:15am 15-12-2025 & Autosampler from 09-12 - 10-12-2025									
Sample ID	GRS-IC1	GRS-IC2	GRS-IC3	GRS-EFF	IC3-B1-AS	IC3-B3-AS	IC3-B4-AS	IC3-B5-AS	IC3-B6-AS	IC3-B12-AS
COD (mg/L)	60.7	119	60.5	37.1	30.2	42.4	38.2	37	50.2	53.3
TOC (mg/L)	19.23	33.65	11.23	11.65	9.53	9.06	8.5	8.77	9.76	8.4
TC (mg/L)	85.2	152.5	42.12	55.97	32.01	31.97	31.21	31.83	28.25	32.57
IC (mg/L)	65.97	118.9	30.89	44.32	22.48	22.9	22.71	23.06	18.49	24.17
TN (mg/L)	1.45	1.57	2.63	0.868	1.45	1.37	1.42	1.41	0.9937	1.7
Conductivity (µS/cm)	2510	3080	1936	1898	1479	1388	1383	1401	1421	1351
Redox (mV)	202	158	140	168	156	163	159	158	161	161
pH	7.8	7.61	9.11	7.98	8.86	8.81	8.9	8.91	8.88	8.87
T (°C)	12.5	12.6	13.3	14	13.4	12.7	12.7	13.9	14.5	15.9
DO (mg/L)	7.49	6.51	8.11	6.9	8.12	8.69	8.43	8.06	7.73	7.96
TSS (mg/L)	6.52	5.74	511.92	2.57	13.38	141.48	101.51	98.83	138.91	266.31
Weight before (mg)	4165.1	4148.8	4164.1	5208	5224.7	5185.2	5246.8	5202.6	4162.6	5237
Weight after (mg)	4169.7	4153.2	4318.7	5209.1	5234.2	5269.1	5294	5261.9	4203.3	5361.9
Volume (mL)	705	767	302	428	710	593	465	600	293	469
IC data										
	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C	A___C
F^- Li^+	1.21___na	1.2890___na	1.4125___na	0.9340___na	1.2780___na	2.0735___na	1.384___na	1.4785___na	0.7855___na	1.293___na
Cl^- Na^+	155.11___61.93	148.99___59.22	55.18___32.41	136___63.97	68.7220___36.2230	126.0180___63.1565	88.6730___46.1785	93.478___48.6895	50.63___25.8395	67.2825___36.577
NO_2^- NH_4^+	na___na	na___na	na___na	na___na	0.2575___na	na___na	na___na	0.7430___na	na___na	0.6690___na
Br^- K^+	na___24.15	na___34.76	na___23.25	na___13.31	na___20.3220	na___26.2270	na___18.5380	na___20.3330	na___9.1590	na___15.5020
NO_3^- Mg^{2+}	4.1645___34.57	0.7010___67.63	12.3580___25.58	3.6680___20.63	6.6475___10.6420	10.7700___15.1320	7.8725___10.5360	8.5180___11.7975	4.1850___8.9575	6.3405___9.9330
PO_4^{3-} Ca^{2+}	na___489.24	na___735.45	na___368.32	na___326.25	na___261.1555	na___339.9990	na___250.6220	na___274.3040	na___170.7975	na___230.5920
SO_4^{2-}	2360.13	3522.35	1868.5	1508.2	1236.7	1654	1178.3	1305.2	764.95	1052.5
Autosampler trigger condition										
Date					09/12/2025	10/12/2025	10/12/2025	10/12/2025	10/12/2025	10/12/2025
Trigger time					11:34am	5:52am	5:54am	5:59am	6:47am	4:02pm
Water level increase (mm)					42.2	46.3	44.8	44.8	44.7	44.7
Precipitation (mm) (Rain)					0.3	0.4	0.4	0.4	0.3	0.2

Excel Steinfort:

Datas-Thesis-Patrick-Beiros-2025-26.xlsx

Campaign	Dry day (grab samples) at 10:30am 10-02-2026							
Sample ID	STR-GS-I1	STR-GS-I2	STR-GS-I3	STR-GS-CW1	STR-GS-CW2	STR-GS-CW3	STR-GS-CW4	STR-GS-FE
COD (mg/L)	21.1	9.35	15.4	6.31	6.15	6.07	9.47	9.96
TOC (mg/L)	6.11	4.16	4.02	3.59	3.94	2.48	3.83	2.55
TC (mg/L)	15.42	14.6	14.6	22.9	19.68	22.47	22.95	18.66
IC (mg/L)	9.31	10.7	10.58	19.3	15.73	19.99	19.12	16.09
TN (mg/L)	2.96	1.15	1.07	1.24	0.78	0.28	0.24	0.41
Conductivity (µS/cm)	586	298	385	672	595	691	469	617
Redox (mV)	214	206	85	19	31	-19	-46	54
pH	9.79	8.19	8.21	7.95	7.85	7.61	7.56	8.42
T (°C)	14.9	15.1	15	15.2	15	15.4	15.5	15.9
DO (mg/L)	7.41	7.11	8.54	4.63	4.28	5.59	3.6	7.18
TSS (mg/L)	35.57	10.23	2.38	1.25	1.03	4.00	1.47	12.81
Weight before (mg)	4170.2	3425.8	4185.7	5222.9	5198.4	5187.1	4151.2	5197.3
Weight after (mg)	4195.1	3431.2	4187.2	5223.8	5199.2	5189.3	4152.3	5206.2
Volume (mL)	700	528	630	720	778	550	750	695
IC data	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C
F^- Li^+	0.4488__na	0.2242__na	0.1655__na	0.5004__na	0.4072__na	0.3881__na	0.2421__na	0.4121__na
Cl^- Na^+	98.3549__37.2264	31.5080__14.7036	57.2754__22.3905	174.9379__50.7951	104.9622__31.9255	195.8176__57.4498	92.9387__30.8215	146.2211__42.4790
NO_2^- NH_4^+	0.3068__na	0.1743__na	na__na	na__na	na__na	na__na	na__na	na__na
Br^- K^+	na__7.5525	0.2174__2.2182	na__4.5505	na__7.4879	na__3.5341	na__4.6383	na__4.5140	na__5.6278
NO_3^- Mg^{2+}	14.2189__1.6473	4.7188__2.0178	3.4580__2.1723	5.7838__2.8001	3.8321__4.4584	na__3.6525	na__2.4731	2.1654__2.6696
PO_4^{3-} Ca^{2+}	na__42.2269	na__32.3990	na__36.6637	na__59.8434	na__64.8541	na__54.3452	na__44.5770	na__58.0147
SO_4^{2-}	65.83	53.36	49.02	97.82	139.82	95.79	60.45	102.27
Autosampler trigger condition								
Date								
Trigger time								
Water level increase (mm)								

Campaign	Dry day (grab samples) at 10:30am 17-02-2026 & Autosampler from 10-02-26 _ 16-02-26													
Sample ID	STR-GS-I1	STR-GS-I2	STR-GS-I3	STR-GS-CW1	STR-GS-CW2	STR-GS-CW3	STR-GS-CW4	STR-GS-FE	AS-IC1-B1	AS-IC1-B2	AS-IC1-B3	AS-IC1-B4	AS-IC1-B5	AS-IC1-B6
COD (mg/L)	34.6	14.5	11.3	6.47	4.89	5.8	6.68	7.41	27.3	14.9	14.4	15.3	11.9	10.5
TOC (mg/L)	2.64	4.41	3.42	2.39	2.08	2.67	2.83	2.55	8.16	2.82	2.52	4.16	2.63	2.91
TC (mg/L)	24.1	21.76	25.96	18.44	16.07	15.25	18.07	19.71	23.07	13.49	13	12.29	18.11	17.38
IC (mg/L)	21.46	17.35	22.54	16.05	13.99	12.58	15.24	17.16	14.91	10.66	10.49	8.76	15.49	14.47
TN (mg/L)	3.20	3.79	1.41	1.33	1.08	0.94	0.20	0.70	3.55	1.90	2.19	1.78	2.75	3.90
Conductivity (µS/cm)	766	658	489	501	453	346	327	481	544	470	378	324	537	612
Redox (mV)	173	171	210	196	194	202	302	191	247	178	318	182	183	210
pH	9.96	9.43	8.7	8.28	8.02	7.66	7.65	8.18	8.36	8.37	8.62	8.82	8.73	8.67
T (°C)	15.9	16.7	17.3	17.3	18.3	18.3	18.1	18.2	18.2	18.7	19.2	18	17.8	18
DO (mg/L)	7.73	7.64	8.12	6.09	5.74	6.52	5.8	8.09	7.7	8.51	7.93	8.28	8.64	6.49
TSS (mg/L)	2.61	8.43	3.08	3.21	0.56	0.82	0.34	7.92	36.94	49.22	61.84	50.78	50.45	8.45
Weight before (mg)	4147.4	5203.4	5187.1	3431.1	4160.9	5115	5198.8	4198.4	4140.8	5226.8	4196.3	4189.2	4116	4141.6
Weight after (mg)	4149.2	5207.7	5188.7	3433.3	4161.3	5115.5	5199	4204.1	4163.7	5251.9	4219.8	4215.1	4144	4146.5
Volume (mL)	690	510	520	685	718	612	582	720	620	510	380	510	555	580
IC data	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C
F^- Li^+	1.0468__na	0.8244__na	0.6216__na	0.6302__na	0.5558__na	0.3799__na	0.2888__na	0.6173__na	0.5485__na	0.6216__na	0.4825__na	0.4739__na	0.6935__na	0.4982__na
Cl^- Na^+	228.3429__57.6495	105.2340__32.2462	90.0040__26.4583	128.4255__36.5530	95.1280__35.1530	76.8456__28.4908	69.0855__22.1163	124.6382__33.9391	168.3521__46.2108	146.5157__34.7800	129.1714__33.6830	90.2321__25.6601	145.8932__37.1829	208.3320__53.8578
NO_2^- NH_4^+	na__na	3.6073__na	na__na	na__na	na__na	0.2518__na	na__na	na__na	0.6096__na	0.3982__na	0.5333__na	0.5168__na	0.2275__na	0.1132__na
Br^- K^+	na__12.1493	na__10.4013	na__6.2258	na__6.1112	na__4.0697	na__4.4322	na__3.8809	na__5.2745	na__3.8016	na__5.5315	na__4.8114	na__4.0717	na__8.2542	na__5.6775
NO_3^- Mg^{2+}	21.3258__4.4095	17.3922__3.9384	8.3908__3.3622	8.9897__2.2714	6.9230__4.2198	5.6028__2.4723	0.1642__1.5635	3.8694__2.7389	25.0333__2.2763	12.1788__1.8535	14.2387__1.5415	10.5320__0.8314	18.0882__2.7053	27.0365__2.4149
PO_4^{3-} Ca^{2+}	na__74.0683	na__78.8917	na__54.9964	na__46.3588	na__40.8405	na__41.2614	na__30.3627	na__49.5140	na__44.6955	na__43.8462	na__36.7649	na__27.0779	na__50.4929	na__51.5275
SO_4^{2-}	133.88	265.59	103.9	98.93	123.57	136.33	53.42	106.71	74.88	90.11	66.81	46.08	103.07	82.85
Autosampler trigger condition														
Date									10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026
Trigger time									11:27 AM	12:02 PM	12:12 PM	1:08 PM	1:42 PM	3:47 PM
Water level increase (mm)									15.7	17.5	21.2	16.7	23	13.4
Precipitation (mm) (Rain)									0.3	0.6	0.6	0.1	0.1	0.1

Campaign												
Sample ID	AS-IC1-B7	AS-IC1-B8	AS-IC1-B9	AS-IC1-B10	AS-IC1-B11	AS-IC1-B12	AS-IC2-B1	AS-IC2-B2	AS-IC2-B3	AS-IC2-B6	AS-IC2-B7	AS-IC2-B8
COD (mg/L)	8.37	10.6	9.45	13.2	9.55	10.2	33.5	16.5	19.8	26.5	36.9	42.3
TOC (mg/L)	2.46	2.63	2.67	2.69	2.59	2.71	9.24	4.21	2.69	3.88	2.17	3.21
TC (mg/L)	16.89	16.2	16.58	14.45	14.72	15.74	22.98	17.48	18.07	11.63	9.828	10.74
IC (mg/L)	14.42	13.57	13.91	11.75	11.68	13.03	13.74	13.27	15.39	7.75	7.658	7.536
TN (mg/L)	3.71	2.76	4.19	2.77	3.27	4.13	0.97	0.99	1.37	0.80	0.72	0.69
Conductivity (µS/cm)	570	291	666	472	547	690	382	360	492	231	197.8	190
Redox (mV)	170	193	261	181	184	193	235	221	233	212	220	210
pH	8.85	8.74	8.7	8.74	8.71	8.74	8.02	8.24	8.36	8.64	8.76	8.84
T (°C)	18.3	18.4	18	18.4	17.5	17.2	18.5	18.6	18.6	18.5	18.8	18.8
DO (mg/L)	7.53	8.1	7.5	7.63	8.35	8.07	7.4	7.81	7.63	7.85	7.7	7.32
TSS (mg/L)	9.43	31.38	5.74	46.02	7.59	12.22	17.77	10.04	56.58	82.41	177.24	251.18
Weight before (mg)	3357.8	4160.6	4158.1	4170.2	4138.9	4157.6	5211.3	5201.8	5199.1	5196.2	5180	5224.7
Weight after (mg)	3362.8	4178.8	4161.2	4196.8	4143	4164.2	5220.7	5207.1	5227.9	5240.7	5205.7	5267.4
Volume (mL)	530	580	540	578	540	540	529	528	509	540	145	170
IC data	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C
F^- Li^+	0.7159__na	0.9051__na	0.5447__na	0.7431__na	0.4174__na	0.5101__na	0.3812__na	0.3867__na	0.4311__na	0.2019__na	0.1846__na	0.2029__na
Cl^- Na^+	222.6807__54.4365	228.1979__49.2203	244.6476__57.8606	192.5098__43.2042	191.8348__46.8149	240.9490__55.6467	74.1323__23.1527	73.6332__22.0008	100.2832__26.9901	39.9574__15.2065	34.6919__13.3992	32.5891__13.0493
NO_2^- NH_4^+	0.8805__na	1.1620__na	1.0382__na	0.3376__na	0.5872__na	1.0490__na	na__na	na__na	0.3774__na	0.5864__na	0.6736__na	0.4337__na
Br^- K^+	na__7.8924	na__9.1063	na__5.4227	na__7.3350	na__4.8151	na__5.2482	na__3.1320	na__2.8291	na__3.4104	na__1.8023	na__1.3579	na__1.3004
NO_3^- Mg^{2+}	24.8192__2.2854	18.1128__2.3855	29.2026__2.4284	16.3036__2.4848	21.3696__1.7818	27.7305__2.1380	4.8724__2.5982	5.9405__2.3561	7.6091__2.7582	3.5802__0.7687	3.0991__0.5831	3.1253__0.5396
PO_4^{3-} Ca^{2+}	na__54.5886	na__63.1979	na__54.6725	na__53.8165	na__43.4354	na__52.2804	na__39.5958	na__38.3828	na__45.1610	na__20.3526	na__18.5164	na__18.1739
SO_4^{2-}	95.65	144.69	81.76	113.88	66.7	73.4	82.97	79.45	85.99	43.74	38.33	35.64
Autosampler trigger condition												
Date	10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026	10/02/2026	16/02/2026	16/02/2026	16/02/2026
Trigger time	4:01 PM	4:29 PM	6:13 PM	6:37 PM	7:19 PM	8:26 PM	12:28 PM	1:24 PM	11:33 PM	12:58 PM	1:01 PM	1:06 PM
Water level increase (mm)	24.4	16.7	21.4	16.6	13.4	18.1	24.4	25.8	38.1	57.5	388	696
Precipitation (mm) (Rain)	0.2	0.2	0.2	0.3	0.3	0.3	0.6	0.1	0.1	0.1	0.8	0.8

Campaign	Dry day (grab samples) at 10:30am 25-02-2026 & Autosampler from 19-02-2026 to 25-02-2026							
Sample ID	STR-GS-I1	STR-GS-I2	STR-GS-I3	STR-GS-CW1	STR-GS-CW2	STR-GS-CW3	STR-GS-CW4	STR-GS-FE
COD (mg/L)	6.09	9.92	8.39	5.80	5.57	5.18	5.77	6.99
TOC (mg/L)	3.51	2.86	3.01	2.14	2.24	2.41	3.04	2.69
TC (mg/L)	24.26	26.38	27.95	23.17	21.69	19.82	22.83	19.59
IC (mg/L)	20.75	23.52	24.95	21.02	19.46	17.41	19.78	16.9
TN (mg/L)	3.13	2.35	1.19	1.25	1.18	0.28	0.17	0.69
Conductivity (µS/cm)	788	787	457	486	492	418	288	446
Redox (mV)	188	191	197	142	167	105	-10	99
pH	9.57	8.04	8.24	8.26	7.93	7.6	7.61	8.34
T (°C)	17.4	16.9	16.4	16.3	16.3	17	16.5	16.9
DO (mg/L)	11.46	7.10	7.00	5.10	4.20	3.56	2.18	8.75
TSS (mg/L)	0.30	11.37	0.31	0.23	0.45	0.70	0.26	9.57
Weight before (mg)	4142.2	5202.7	5184.8	3415.2	4170.4	5221.2	5198.3	4203.2
Weight after (mg)	4142.4	5209.1	5185	3415.4	4170.7	5221.7	5198.5	4209.4
Volume (mL)	673	563	637	885	670	710	760	648
IC data	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C
F^- Li^+	1.1219__na	0.9670__na	0.5389__na	0.5381__na	0.5826__na	0.5669__na	0.3854__na	0.5243__na
Cl^- Na^+	270.4588__61.6064	90.7550__28.7155	67.4191__22.4407	105.3698__-1.0981	84.1916__26.4074	65.6153__22.2431	30.6900__13.9439	91.6703__27.7669
NO_2^- NH_4^+	0.7227__na	1.3379__na	na__na	na__na	na__na	1.0068__na	0.0551__na	na__na
Br^- K^+	na__12.2627	na__7.8613	na__6.1883	na__6.8135	na__5.5556	na__4.9867	na__4.0442	na__5.2136
NO_3^- Mg^{2+}	21.0464__3.9833	12.5769__5.2009	7.4581__3.5663	8.0703__2.7294	7.0703__3.4403	1.0068__2.8208	0.0551__1.6998	4.2841__2.5205
PO_4^{3-} Ca^{2+}	na__na	na__na	na__54.8586	na__48.7635	na__56.4878	na__47.4818	na__33.2829	na__46.2393
SO_4^{2-}	117.02	201.32	101.33	89.75	143.33	129.7	51.25	102
Autosampler trigger condition								
Date								
Trigger time								
Water level increase (mm)								
Precipitation (mm) (Rain)								

Campaign												
Sample ID	AS-IC3-B1	AS-IC3-B2	AS-IC3-B3	AS-IC3-B4	AS-IC3-B5	AS-IC3-B6	AS-FE-B1-24	AS-FE-B2-48	AS-FE-B3-72	AS-FE-B4-96	AS-FE-B5-120	AS-FE-B6-144
COD (mg/L)	9.90	10.10	6.17	8.61	7.63	9.82	12.90	8.55	9.21	8.28	8.62	9.24
TOC (mg/L)	3.67	3.07	2.43	3.02	4.49	3.47	4.75	3.3	3.03	3.12	3.32	3.79
TC (mg/L)	19.32	17.14	16.19	22.25	20.77	19.38	21.35	19.84	19.6	19.62	19.85	20.25
IC (mg/L)	15.64	14.07	13.76	19	16.28	15.91	16.6	16.53	16.57	16.5	16.53	16.46
TN (mg/L)	0.90	0.96	0.72	1.06	0.76	0.70	0.73	0.70	0.77	0.69	0.68	0.69
Conductivity (µS/cm)	307	314	274	401	293	275	494	489	489	482	462	445
Redox (mV)	125	146	147	158	157	196	158	149	152	142	145	148
pH	8.51	8.44	8.46	8.42	8.66	8.65	8.43	8.37	8.4	8.42	8.37	8.38
T (°C)	17.9	17.6	17.3	17.6	17.4	17.5	17.8	18.2	17.8	17.8	18.1	18.9
DO (mg/L)	6.76	7.01	6.98	7.14	7.15	7.04	7.36	7.15	7.80	7.63	7.36	6.97
TSS (mg/L)	11.94	9.37	1.78	3.33	2.58	1.25	5.17	6.26	6.08	15.82	16.87	21.76
Weight before (mg)	4143.7	5226.2	4205.5	4191.2	4164	4142.4	3348.8	4164.9	4164.5	4165.5	4141.5	4162.1
Weight after (mg)	4151.4	5232.4	4206.7	4193.4	4165.6	4143.2	3351.8	4169	4168.5	4176.1	4152.8	4176.9
Volume (mL)	645	662	674	660	620	640	580	655	658	670	670	680
IC data	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C	A__C
F^- Li^+	0.3686__na	0.3185__na	0.3174__na	0.3610__na	0.3532__na	0.3527__na	0.5856__na	0.6295__na	0.6022__na	0.5242__na	0.6198__na	0.4678__na
Cl^- Na^+	49.2884__17.3422	60.6521__19.3633	44.8384__15.7279	67.0862__21.1213	40.5756__14.7508	35.4013__13.4685	120.5611__33.0726	119.0041__33.3462	118.1236__33.0961	113.9926__31.8286	105.7350__30.1868	95.3124__28.1552
NO_2^- NH_4^+	0.1594__na	na__na	na__na	na__na	0.2291__na	na__na	na__na	na__na	na__na	na__na	na__na	na__na
Br^- K^+	na__3.6425	na__3.5865	na__3.2374	na__5.2416	na__3.8059	na__3.5648	na__5.1754	na__5.1941	na__4.9583	na__4.9264	na__4.8545	na__5.0282
NO_3^- Mg^{2+}	5.2084__1.7828	6.0067__1.7379	4.8710__1.4931	6.7775__2.7428	4.3156__1.8996	3.9292__1.7952	4.2769__2.7635	4.5766__2.7324	5.0815__2.6411	4.2013__2.7348	3.8016__2.6476	3.8291__2.5293
PO_4^{3-} Ca^{2+}	na__33.0775	na__31.3686	na__28.8682	na__45.5801	na__33.5971	na__31.5591	na__49.5588	na__48.8246	na__48.3690	na__47.8068	na__47.1039	na__45.9364
SO_4^{2-}	52.02	49.66	44.99	84.03	50.56	45.93	108.45	106.86	109.58	107.02	103.01	101.45
Autosampler trigger condition												
Date	19/02/2026	21/02/2026	21/06/2026	22/02/2026	22/02/2026	22/02/2026	19/02/2026	20/02/2026	21/02/2026	22/02/2026	23/02/2026	24/02/2026
Trigger time	11:08 AM	12:13 AM	10:11 AM	1:19 AM	3:41 AM	6:11 PM	10:26 AM	10:26 AM	10:26 AM	10:26 AM	10:26 AM	10:26 AM
Water level increase (mm)	93.5	96.7	84.7	81.7	66.2	90.2	/	/	/	/	/	/
Precipitation (mm) (Rain)	0.4	0.2	0.7	0.8	0.3	0.8	0.3	0.1	0.7	0.2	0.1	0.1