MULTISOURCE

Monitoring Final Report

Deliverable 1.2

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EXECUTIVE SUMMARY

This Deliverable 1.2 “Monitoring Final Report” aims to provide an overview of the main results achieved by the different monitoring activities carried by the MULTISOURCE WP1–ENTS pilots. This report is a brief summary of the main findings and highlights of each pilot. It also provides a reflection on common achievements and challenges encountered during the monitoring work of the ENTS Pilots. This report is not intended to provide the full description of all the results obtained by each pilot. Extensive description of each pilot and respective results are published separately, or in preparation to be published in the coming months, in international peer-reviewed journals. Major scientific outputs are listed per pilot.

In brief, all pilots were monitored for at least 1 full year, the majority (5 out of the 7 pilots) for at least 2 full years covering different seasons and/or relevant local operation conditions. Results show overall good performance for pollutants abatement or rainwater or stormwater control, and systems that meet local regulation for their primary design criteria. MULTISOURCE enabled exploring their capacity to provide water for reuse, enhancement of treatment capacity or monitoring of co-benefits.

In detail,

Pilot 1: France - INRAE - Rhizosph’air pilot treating raw domestic wastewater met discharge regulations, explored the impact of aeration on the hydraulic behaviour of the system, different aeration strategies to reach high total nitrogen (TN) removal efficiencies as well as different aeration control strategies to optimize TN removal. Co-benefits monitored include educational and energetic indicators.

Pilot 2: USA - MSU – Vertical flow wetland, treating high-strength wastewater, tested operational parameters for optimization of chemical oxygen demand (COD) and TN removal, including denitrification and nitrification in the different stages of the system. Besides demonstrating the compliance with treatment performance, the system was used to monitor greenhouse gases (GHG) emissions.

Pilot 3: Belgium - Rietland - Phytoparking treating pre-treated wastewater was demonstrated to perform well as a decentralized system, meeting the discharge requirements of the Flemish legislation. The pilot was tested for automation of the aeration via online sensors. Co-benefits monitored include energetic indicators, other pollutants removal such as vehicle fluids and water reuse potential.

Pilot 4: Italy - IRIDRA – Hybrid treatment wetland treating combined sewage overflow (CSO) demonstrated the feasibility of the technology for the targeted design pollutants total suspended solids (TSS), COD, biochemical oxygen demand (BOD_5) and ammonium ($N\text{-}NH_4$). Optimization of the supply of air was explored, but there is still space to further push the system. Co-benefits monitored include educational and cost indicators, as well as biodiversity.

Pilot 5: Spain - ICRA - Greenwall treating greywater was effectively demonstrated to supply treated water for toilet flushing complying with European and Spanish regulations. During the monitoring period, the pilot was tested for the maintenance of planted surface area. The monitored co-benefits include stakeholder engagement, increment of green area, biodiversity and carbon sequestration.

Pilot 6: NIVA/Oslo Municipality - Raingarden treating road runoff demonstrated that the pilot could retain tire wear particles and organic micropollutants. Online sensors were deployed with success. Co-benefits monitored included environmental and socio-economic indicators as well as disservices.

Pilot 7: Germany - UFZ - Green roof rainwater was never thought as a treatment system contrary to all other MULTISOURCE pilots. Nevertheless, it was important to assess the water quality of the overflows due to their potential for reuse. By focusing on stormwater and irrigation water, demand data and models were provided to assist dimensioning and modelling of green roof systems. Co-benefit monitoring included a large array of indicators covering building management and protection, health and social impacts, air quality and pollutant reduction, climate adaptation and mitigation, water resources management, and ecosystem services.

MULTISOURCE datasets include a broad range of pollutants and indicators for each system. These datasets are being prepared to be made available in Zenodo's via the project community page, together with the different published outputs of the project.

Challenges during the project for Pilot 1: France - INRAE - Rhizosph'air pilot included down periods due to the adaptation of the research infrastructure to accommodate new pilots for new projects. Pilot 2: USA - MSU – Vertical flow wetland pilot challenge is the short window of operation of the ski resort that feeds it, together with the adverse operating conditions that imply snow removal every sampling event. Pilot 3: Belgium - Rietland – Phytoparking showcases how a technical system needs to be adapted to meet local constrains due to archaeological heritage and adaptation of existing infrastructure. Pilot 4: Italy - IRIDRA – Hybrid treatment wetland denotes the importance of the compromise of the local stakeholders to support sampling efforts, as well the installation and maintenance of online sensors. Pilot 5: Spain - ICRA - Greenwall had large delays due to the IPR attempt on the WetWall design, meaning that the pilot monitored was another type of green wall originally built for the finished HOUSEFUL project, and MULTISOURCE ensured continuity of the monitoring activities. Pilot 6: NIVA/Oslo Municipality – Raingarden monitored was a mitigation pilot, due to the bankruptcy of the entrepreneur responsible for the original pilot. The project revealed that, besides the raingarden itself, the integrated hydraulic design of the road and watershed is critical for the successful function of the raingarden. Moreover, the system was not ideal for calculating removal efficiencies, as outlet samples were not representative due to the infiltration nature of the raingarden. Pilot 7: Germany - UFZ - Green roof largest challenge was its design to favour biodiversity and retain stormwater, not being primarily focused on water harvesting, which limited the number of samples available.

Overall challenges for the future implementation of nature-based solutions were also identified and discussed with the different local stakeholders. Main general concerns relate to operation strategies tailored for urban areas, need for disinfection of effluents to meet European regulations for water reuse, invasive species and biodiversity control, existing regulations and general practice for urban areas which may hinder implementation of nature-based solutions as decentralised treatment options, and the fact that NBS can be land-intensive. A highly relevant barrier noted was ownership of the projects and/or of the technical systems and ensuring continuous and reliable operation on a client ground.

All in all, the monitoring work of MULTISOURCE was achieved according to the expectations raised at the beginning of the project and according to the monitoring plans laid down. No case study was comparable, results are pilot and case specific. However, this enabled very detailed assessments of their performance and providing remarkable examples of tailored optimization and local stakeholder assessment.

1 MULTISOURCE ENTS Pilots

WP1– ENTS pilots conveys all piloting activities, including demonstration and optimization of the pilots through T1.1: Pilot monitoring, including real-time monitoring options (M1 – M40); T1.2: Participatory methods for quantification of co-benefits (M10 – M40); and T1.3: Pilot evaluation (M36 – M48). MULTISOURCE has a total of seven pilots, six in European countries and one in the USA, each comprising an innovative technical nature-based solution and addressing a specific urban water type. Deliverable 1.2 is a brief summary of the main findings and highlights of each pilot, as well as provides a reflection on common achievements and challenges encountered during the monitoring work of the ENTS pilots. Thus, this report sums outcomes of MULTISOURCE WP1 Task 1.1 and Task 1.2. More specifically, it addresses the first objective of WP1 *"Test and demonstrate of the pilots, by monitoring and collecting data for a broad range of operational and pollutant endpoints"*, as well as objective 2 "Develop and test participatory methods – including ICT/digital tools - quantification of co-benefits provided by each pilot".

1.1 Overview of the common work carried

Since the beginning of the MULTISOURCE project, all partners involved in the pilot activities aligned the individual R&D goals by developing the monitoring plan (M1.1). Regular WP1 meetings were held to discuss pilot status, problems and mitigation measures, share experiences with online sensors and digital monitoring tools, as well as to work on the co-benefits monitoring work (M1.2/D1.1), produce the overview of monitoring data (M1.3 and M1.4), as well as the pilot optimization plan (M1.5). The last months of 2024 have been dedicated to data processing, preparation of scientific papers and this report (D1.2).

During 2021, partners focused in developing the monitoring plans, as well as getting the pilots ready for monitoring. Depending on the pilot, this implied construction or maintenance. Since January 2022, the first monitoring work started, and during 2022, 2023 and 2024 the different pilots gathered their data. Problems with starting the monitoring work have occurred and were detailed in the first MULTISOURCE periodical technical report (RP1). Mitigation plans were put in place and, since then, no further deviations occurred and the work has been carried out as planned to address project objectives in all geographical locations and covering the proposed water management challenges. By mid 2024, most MULTISOURCE pilots had been monitored for a 2-years period (Table 1.1). Results of such monitoring work is further detailed in this report, organized as one chapter per pilot. A final chapter summarizes common results, achievements and challenges experienced.

Table 1.1 Timeline of the MULTISOURCE monitoring efforts.

Pilot	Start date	Stop date
Pilot 1: France - INRAE - Rhizosph'air pilot treating raw domestic wastewater	November 2022	August 2024
Pilot 2: USA - MSU – Vertical flow wetland treating high-strength wastewater	January 2022	April 2024
Pilot 3: Belgium - Rietland - Phytoparking treating pre-treated wastewater	May 2022	November 2023
Pilot 4: Italy - IRIDRA – Hybrid treatment wetland treating CSO	June 2022	July 2024
Pilot 5: Spain - ICRA - Greenwall treating greywater	May 2023	May 2025
Pilot 6: NIVA/Oslo Municipality - Raingarden treating road runoff	October 2022	September 2024
Pilot 7: Germany - UFZ - Green roof rainwater	April 2022	August 2023

2 Pilot 1: France - INRAE - Rhizosph’air pilot treating raw domestic wastewater

2.1 Pilot 1 description

The pilot-scale treatment wetland (TW) studied is part of the REFLET research platform (https://eng-reversaal.lyon-grenoble.hub.inrae.fr/equipment-platforms/reflet), located in Craponne, France. The pilot system (Figure 2.1) had one month of start-up before starting the sampling campaign. Its commission started in January 2019 and has been operated since then. At total, the pilot covers an area of 20 ^{m2} (8 × 2.5 m). It replicates Rhizosph’air® system, which comprises a single-stage French vertical flow (VF) TW, receiving raw wastewater directly on the surface of the filter, above an aerated horizontal flow (HF) TW. This arrangement enables the TW system to provide combined primary and secondary wastewater treatment. The TW receives wastewater from around 4 m^3/d (26 PE), collected by a combined sewer from the upstream sewage basin produced by the community.

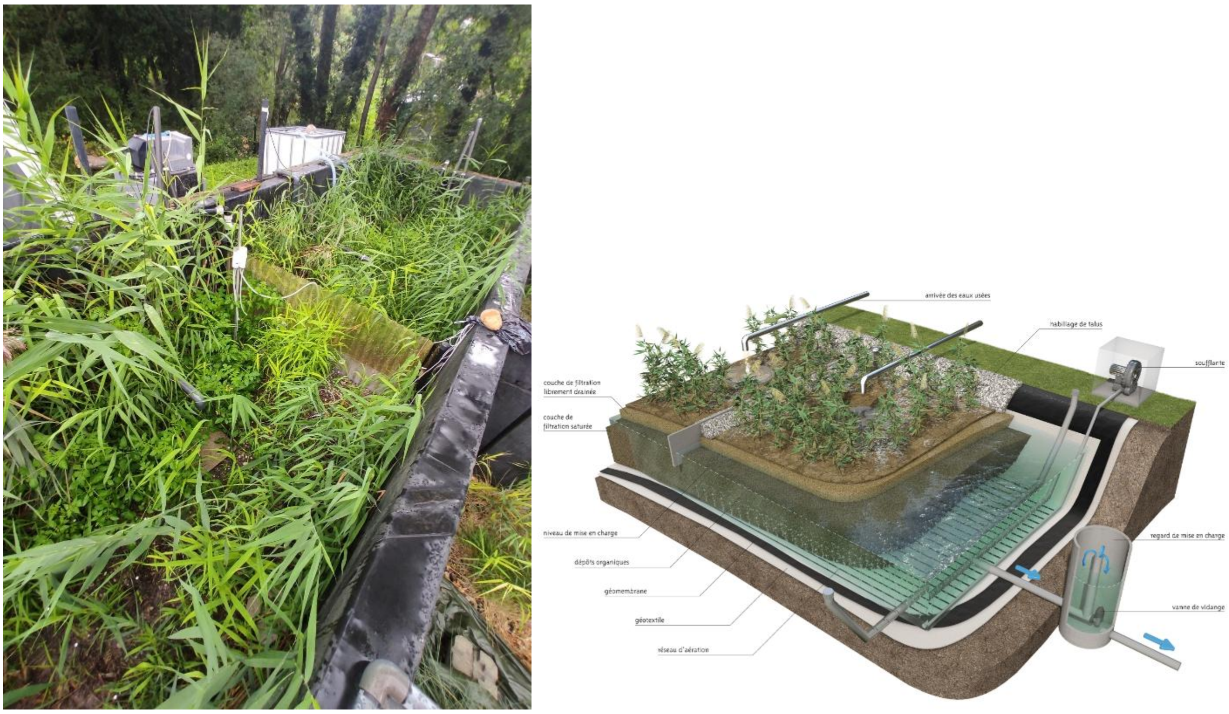


Figure 2.1. Rhizosph’air pilot at INRAE Platform

The TW is planted with *Phragmites australis* and the upper layer is divided into two filters (10 m^2 each) by a PVC plate embedded up to the level of the filtration (0.2 m depth) and transition layers (0.15 m depth – see Figure 2.2 left). This division allows for alternating feeding/resting phases of the filters (3.5 days each) to ensure mineralization of the organic deposit layer. The TW is fed by batches, and the filter that actively receives wastewater is referred to as the "primary filter" (PF), while the filter at rest is referred as the "secondary filter" (SF). The drainage system of the pilot system is designed such that during the feeding phase of the PF, the outflow is directed to the outlet of the SF, which is achieved through the opening and closing of associated electro-valves, as depicted in Figure 2.3.

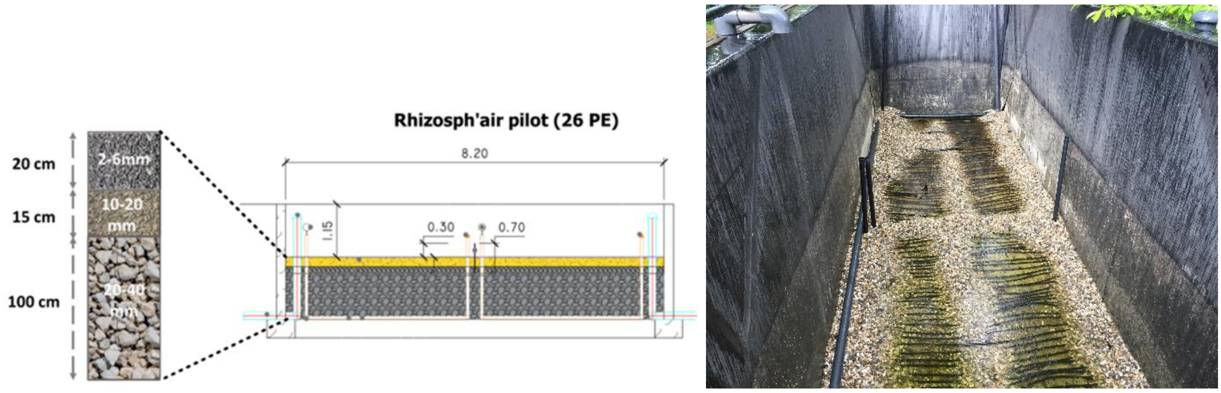


Figure 2.2. Material layers (left) and aeration driplines (right) of the pilot.

The saturation layer (1 m depth) is shared between the two parallel filters. Aeration of the system is accomplished by employing 120 driplines positioned at the bottom of the saturation layer (60 diffusers/m^2 – see Figure 2.2 right). The aeration process is facilitated by two side channel blowers (Becker SV 5.90/1). The estimated supply airflow rate for each blower is approximately 15 m^3/h (equivalent to 1.5 m^3/h/m^2). It is worth noting that no gas flow meter or temperature sensor was installed and therefore, the airflow rate estimation is based on these specifications.

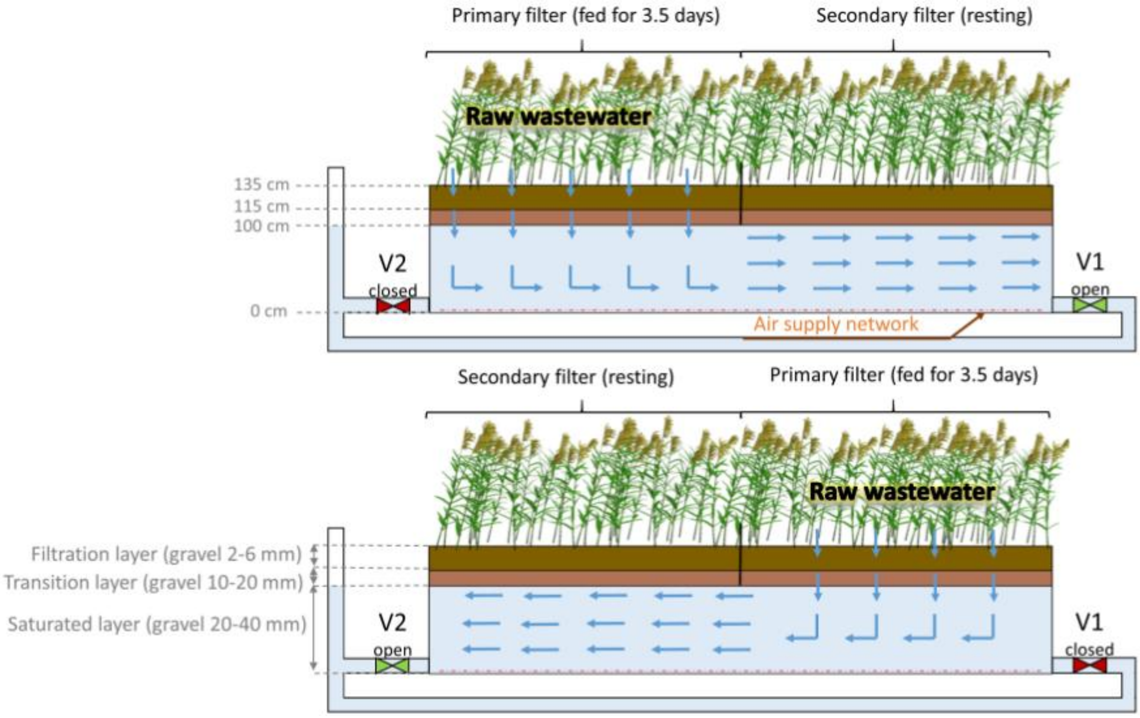


Figure 2.3. Hydraulic operating scheme of the hybrid aerated vertical/horizontal flow TW pilot.

2.2 Overview of the monitoring work

The pilot started running in 2019 and monitoring activities were carried until 2020, when the pilot was stopped for technical works on the research platform. Pilots were monitored for MULTISOURCE in 2022 for hydraulic characterization and have been continuously running from March 2023 for water quality assessment. Different aeration strategies were applied to assess the impact of aeration on treatment performances to reach water reuse objectives. The overview of the monitoring work is summarized in Table 2.1 below.

Table 2.1 Monitoring overview for Pilot 1: France - INRAE - Rhizosph'air pilot treating raw domestic WW.

Endpoint	Sensor or samples	Sampling point	Monitoring period	Sampling frequency	Number of data points available[1]
Flow	Sensor	Influent, effluent	March 2023-August 2024	Every 5min	-
Temperature	Sensor	Influent, effluent, inside	March 2023-August 2024	Every 5min	-
pH	Sensor	inside	March 2023-August 2024	Every 5min	-
Redox	Sensor	Inside, effluent	March 2023-August 2024	Every 5min	-
Ammonium (N-NH4), nitrate (N-NO3)	Sensor	Influent, effluent, inside	March 2023-August 2024	Every 5min	-
Dissolved oxygen (DO)	Sensor	inside	March 2023-August 2024	Every 5min	-
COD	Composite samples	Influent, Effluent	March 2023-August 2024	Weekly	40 for inlet and outlet
All nitrogen species	Composite samples	Influent, Effluent	March 2023-August 2024	Weekly	40 for inlet and outlet
Total phosphorous (TP)	Composite samples	Influent, Effluent	March 2023-August 2024	Weekly	20 for inlet and outlet
Microplastics	Composite samples	Influent, Effluent	March 2023-August 2024	Monthly	5
Metals	Composite samples	Influent, Effluent	March 2023-August 2024	Every three months	2
Organic micropollutants	Composite samples	Influent, Effluent	March 2023-August 2024	Weekly	20 for inlet and outlet
Educational visits	-	Overall REFLET platform including the Rhizopsh'air pilot	May 2022 to August 2024	According to received request > 40 visitors	7 visits with diverse participation types (PhDs and Postdocs during MULTISOURCE summer school, researchers, Lyon municipality, funding agency, private companies, and students)
Electricity consumption		Rhizosph'air pilor	Spring 2024		Electricity consumption measurement per m^3 of water treated
Questionnaire about ecosystem services			October 2024	Once at the National EPNAC technical event (79 people)	Questionnaire on possible ecosystem services provided by decentralized approach with NBS and impact on professional activities related to urban water management (different stakeholders from water agencies, ministry, departmental technical

					support for sanitation and research)

[1] by August 2024.

The monitoring of the pilot was planned to address different objectives:

- Evaluating the impact of aeration on the hydraulics of the system.
- Test different aeration strategies to reach high TN removal efficiencies, and evaluate the removal performances for other type of pollutants (including emerging contaminants).
- Explore different aeration control strategies to optimize TN removal.

Impact of aeration on hydraulics of the pilot.

In order to evaluate the influence of aeration on the hydraulics, experiments with six different aeration strategies were conducted (Figure 2.2). The first four experimental conditions maintained the same aeration duration for both filters, starting from 24 hours per day and decreasing to 9h/d, 6h/d, and no aeration. In the last two experimental conditions, aeration was differentiated between primary and secondary filters, with 9h1 aerating for 9h per day in the primary filter (filter fed) and no aeration in the secondary filter. The last condition, 9h2, was the opposite of 9h1.

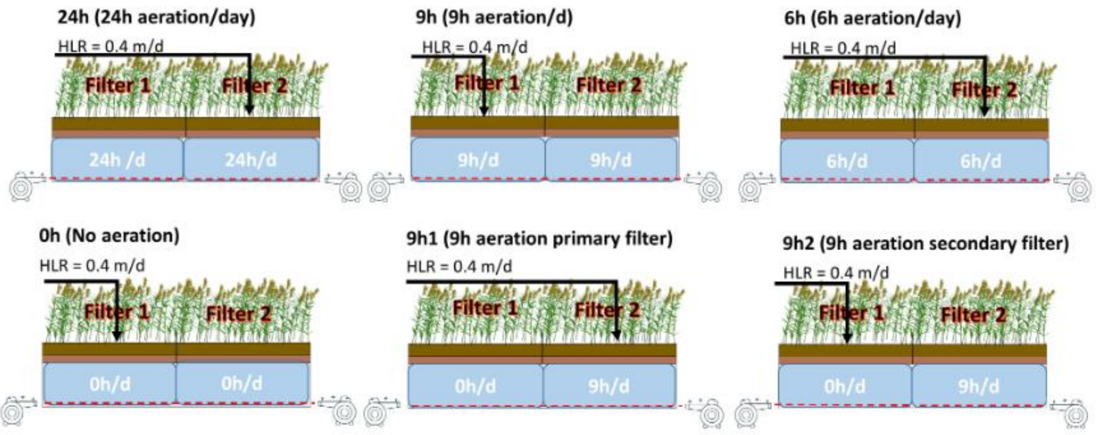


Figure 2.2. Aeration strategy for each experimental condition for the pilot system.

In all conditions involving 9h and 6h aeration per day, the aeration was divided into 8 cycles equally distributed over the day. The hydraulic loading rate on the primary filter remained fixed throughout the experiment at 0.4 m/d, with a total 10 batches per day and no filter alternation done over the course of each tracer test.

For each aeration set-up a tracer test has been conducted. It involved the introduction of a non-reactive and soluble tracer at the system's inlet to subsequently analyse its response at the outlet. amino-G acid has been used at it exhibits minimal sorption to wetland soils and sediments typically associated with wetland environments. Another tracer, salt, was employed to assess the system's internal hydraulic behaviour. This selection was driven by the need to use a tracer that could change the resistivity of the water for another parallel experiment. However, it was important to place a conductivity meter at the outlet to compare the results with amino-G acid to guarantee the replicability and the possibility of validating internal measurements.

Test different aeration strategies to reach high TN removal efficiencies, and evaluate the performances for other type of pollutants.

The pilot operation was monitored using a combination of continuously online sensors and laboratory analysis. Eight sensors were strategically installed along the filter, with measurements recorded at a 5-minute time step (Figure 2.3). Three of these sensors were dedicated to monitoring NH4-N and NO3-N concentrations (WTW, FDO 700IQ), positioned at the inlet, centre and outlet of the pilot. The remaining sensors were oxygen sensors (WTW, VARION 700IQ), distributed within horizontal and vertical piezometers located inside the pilot.

The laboratory analysis occurred once per week, sampling the inlet and outlet through 24-hour composite samples. Each week, the filter was sampled alternated (different inlet and outlet).

The pilot was operated under different regimes (Figure 2.3). Aeration was based on time ("T" condition) for the first five experiments, e.g., hours of aeration per day spread across number of aeration cycles. Initially, a low hydraulic loading rate (HLR, 0.15 m/d) with the longest aeration time (9 h) was tested as C1 condition to favour plant establishment as well as good aerobic performances: T-9h-0.15. The aim of this condition was to not overload the system since the beginning and fasten nitrifying bacteria growth in winter. Then, the aeration time and number of aeration cycles were decreased (C2: T-3h-0.15). To better identify the treatment capacity of the system, the HLR was gradually increased (C3: T-3h-0.25 and C4: T-3h-0.35), and the pollutant load was increased by adding ammonia to the influent (C5: T-3h-0.35-NH4). Since the influent comes from a combined sewer and, consequently, the inlet ammonium concentration was low, ammonium addition (the goal was to reach around 80 mg NH_4-N/L) allowed to test the capacity of the system for higher wastewater concentrations (C5, C6 and C7 conditions).

To increase denitrification, the timing of the aeration was coordinated with pulse feeding on the PF ("F" condition), optimizing the use of the available carbon in raw wastewater. Additionally, the aeration was decreased on the SF (C6: F-3.3h-1.7h-0.35-NH4). For the last condition (C7: F-2.5h-0h-0.35-NH4) aeration was decreased on the PF (2.5 h) and completely stopped on SF (0 h) to favor denitrification. In these cases, aeration was set to start 40 minutes before the batch and stop after 20 minutes for C6 and 15 minutes for C7 (time needed to degrade the oxygen inside the filter and remain in an anoxic environment).

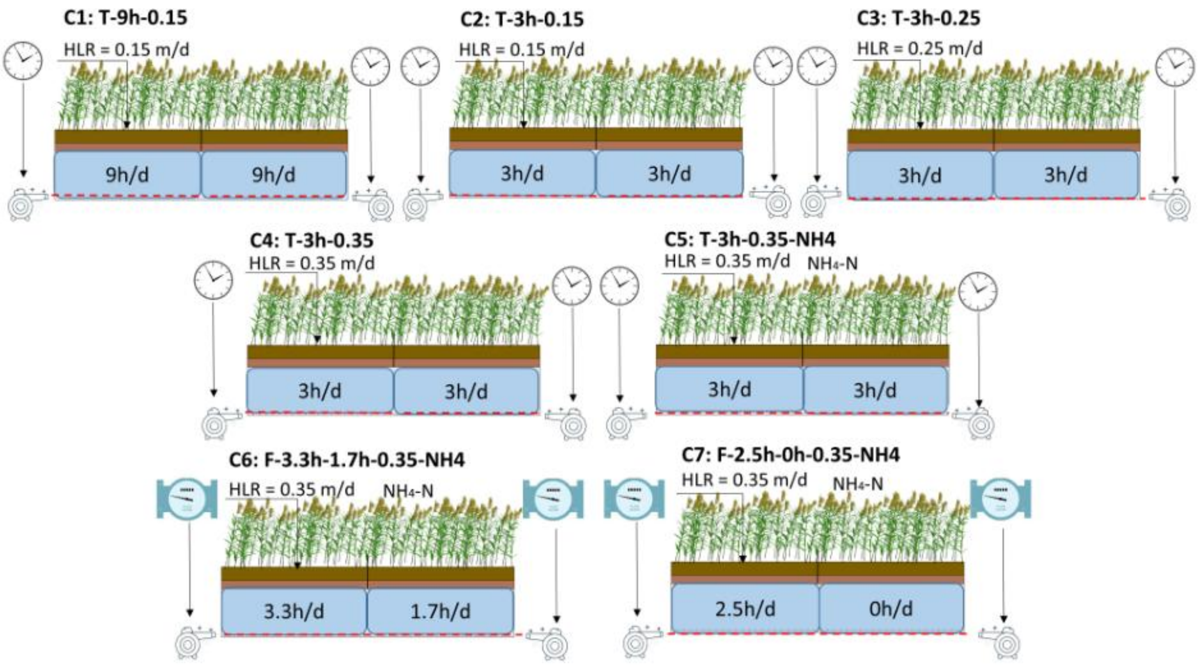


Figure 2.3. Parameters for each experimental condition.

Explore different aeration control strategies to optimize TN removal

The aeration strategy was based on the previous experiment, which demonstrated the effectiveness of synchronizing aeration for the primary filter with feeding times. The aeration started 1.5 hours prior to each batch and lasted for 48 minutes, resulting in 10 aeration cycles per day. In contrast, the secondary filter was aerated on a time-based schedule, with each cycle occurring every five hours for a duration of 36 minutes (five cycles per day). Figure 2.4 illustrates the aeration cycles for the primary and secondary filters. This aeration strategy commenced in July 2023 and remained active until February 2024. The primary objective of this aeration strategy was to use the primary filter to facilitate the nitrification and denitrification processes. The strategy is based on two key elements: first, aeration process transfers oxygen to the liquid phase, enabling the oxidation of ammonium to nitrate before the next batch arrives. As the nitrification process consumes oxygen, the environment tends to become anoxic. Second, this anoxic environment, coupled with an input of organic carbon during the next batch, will encourage the reduction of nitrates and nitrites via the denitrification process. The secondary filter is used to polish the remaining pollutant concentration as a secondary treatment process.

During this experimental phase specific biomass sampling has been done to analyse bacterial communities.

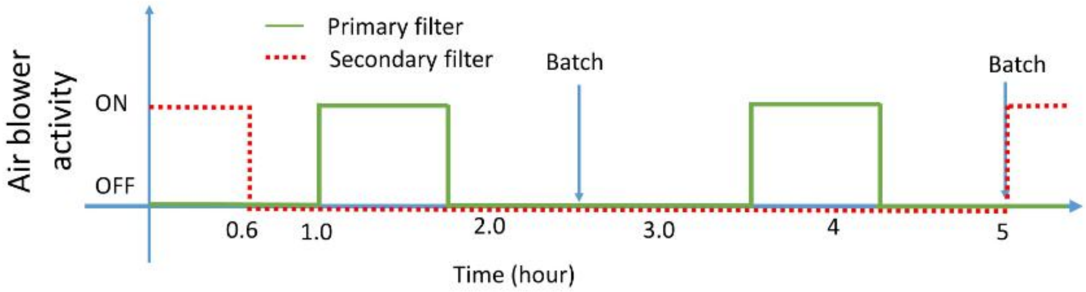


Figure 2.4. Aeration strategy for last experimental phase.

2.3 Main technical results

Impact of aeration on hydraulics of the pilot

Tracer studies showed that aeration of the primary filter is of high importance to minimize preferential pathways by mixing the water in the filter. The longer aeration duration prevents the formation of dead zones. The hydraulic performance and, as consequence, the system performance, could be affected in case of reduction of aeration duration. Thus, for an optimal setting, it is recommended to aerate at least 6h per day (in different sequences) in accordance as well with oxygen needs for biological degradation. Tracer study done on a larger scale similar system, with similar aeration strategy, showed that results obtained on the pilot can be up scaled for different system capacities.

Test different aeration strategies to reach high TN removal efficiencies, and evaluate the performances for other type of pollutants

The different aeration strategies tested are presented in Table 2.2.

Table 2.2 Experimental conditions parameters.

Experimental conditions	C1	C2	C3	C4	C5	C6	C7
Ammonium addition	no	no	no	no	yes	yes	yes
Aeration based on timer (T) or feeding (F)	T	T	T	T	T	F	F

Aeration on the primary filter	Number of cycles/day	6	4	4	4	4	10	10
	Operation (min per cycle)	90	45	45	45	45	20	15
	Stop (min per cycle)	150	315	315	315	315	130	135
Aeration on the secondary filter	Number of cycles/day	6	4	4	4	4	10	0
	Operation (min per cycle)	90	45	45	45	45	10	0
	Stop (min per cycle)	150	315	315	315	315	140	0
Hydraulic loading rate	m/day	0.15	0.15	0.25	0.35	0.35	0.35	0.35
Sampling period	start	19/Jan	19/May	19/Jul	19/Oct	20/May	21/Jun	21/Aug
	end	19/May	19/Jul	19/Oct	20/Jan	20/Sep	21/Aug	21/Oct
Duration (days)		129	73	84	113	119	41	62
Number of samples		10	7	9	3	8	6	7

Table 2.3 presents the treatment performance for the experimental conditions employing the aeration strategies based on time (“T”). Overall, the system demonstrated high performance in removing carbon and solids pollution regardless the experimental conditions, with an average outlet concentrations of less than 29 mg COD/L and 4 mg TSS/L. These results highlight the filtration capacity provided by the TW. These results also highlight the effectiveness and stability of the Rhizosph’air® in removing carbon and solids from raw wastewater.

Regarding ammonium removal, the nitrification process was nearly complete, regardless of the total aeration duration per day (C1: 9 h/d or C2, C3, C4: 3 h/d). However, when ammonium was added to the influent raw wastewater (C5: T-3h-0.35-NH4), removal efficiency decreased to 89.2 ± 12.5%, indicating that nitrification had reached its maximum. To further enhance ammonium removal, the possible strategies are to increase the number of aeration cycles per day, the duration of aeration for each cycle or to automate the aeration using online sensors.

Regarding TN removal, in the case of condition C1 (T-9h-0.075), the issue was excessive oxygenation within the filter. While decreasing aeration or increasing oxygen demand (increased load) denitrification (and TN removal) improved until reaching TN efficiency around 70 % in condition 5 where TN removal is mainly limited by a lack of carbon in the secondary filter for denitrification.

Regarding the optimization of carbon for denitrification, table 2.4 shows the results with a aeration aligned with batch feeding time (aeration based on flow). It is noteworthy that NH4-N concentrations at the outlet were 20 times higher for condition C7 (F-2.5h-0h-0.175-NH4) than for condition C6 (F-3.3h-1.7h-0.175-NH4). However, condition C7 also exhibited the lowest NO3-N outlet concentration among all experimental conditions (8.70 ± 4.40mg NO3-N/L), consequently resulting in the highest TN removal. This condition demonstrated its capability to effectively treat TN loads that were nearly twice as high as those of the other experimental conditions. Despite the extended anoxic periods, denitrification was again hindered by organic carbon limitation. The C/N ratios for C6 and C7 averaged 1.9 and 1.3, respectively. Thus, the carbon source from the batch was not sufficient to meet the denitrification requirement, causing nitrate accumulation.

Table 2.3 Inlet and outlet concentrations and removal efficiencies for each condition, considering temperature inside the filter, COD, TSS, TN, NH4-N and NO3-N, where Avg = average, Std dev = standard deviation and n= number of observations.

C1: T-9h-0.15 (Temperature inside the filter: 8.4 ± 2.5°C)									
	In			Out			Concentration percent removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n
COD (mg/L)	325	384 ± 197	10	21	24 ± 6	10	93%	92 ± 4%	10
TSS (mg/L)	244	289 ± 146	10	<2	<2±0	10	99%	99 ± 1%	10
TN (mg/L)	36.1	33.9 ± 7.7	10	35.7	34.4 ± 5.7	10	5.5%	5.0 ± 12.7%	7
NH_4-N (mg/L)	34.7	32.3 ± 9.3	10	0.10	0.23 ± 0.48	10	99.7%	99.2 ± 1.7%	10
NO_3-N (mg/L)	0.83	1.33 ± 1.79	10	35.6	34.0 ± 5.9	10	-	-	-
C2: T-3h-0.15 (Temperature inside the filter: 17.2 ± 2.7°C)									
	In			Out			Concentration percent removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n
Temperature (°C)									
COD (mg/L)	642	723 ± 202.0	7	25	26 ± 2	7	96 %	96 ± 1 %	7
TSS (mg/L)	570	585 ± 146	7	<2	<2 ± 1	7	99.6 %	99.6± 0.2 %	7
TN (mg/L)	51.7	55.8 ± 19.4	7	24.1	26.4 ± 5.7	7	45.1 %	47.2 ± 19.6 %	7
NH_4-N (mg/L)	45.5	43.0 ± 8.5	7	0.02	0.23 ± 0.31	7	99.9 %	99.5 ± 0.7 %	7
NO_3-N (mg/L)	0.51	0.71 ± 0.43	7	22.6	25.3 ± 6.2	7	-	-	
C3: T-3h-0.25 (Temperature inside the filter: 19.9 ± 1.4°C)									
	In			Out			Concentration percent removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n
Temperature (°C)									
COD (mg/L)	554	545 ± 212	8	25	24 ± 4	8	96 %	95 ± 3 %	8
TSS (mg/L)	380	434 ± 275	8	<2	<2±0	8	99.5 %	99.4± 0.3 %	8
TN (mg/L)	35.3	41.1 ± 21.9	6	16.8	17.1 ± 1.8	5	66.4 %	62.6 ± 17.7 %	4
NH_4-N (mg/L)	38.3	36.2 ± 16.2	8	0.47	0.65 ± 0.62	8	98.4 %	97.6 ± 3.0 %	8
NO_3-N (mg/L)	0.49	0.75 ± 0.71	8	16.2	16.0 ± 2.4	7	-	-	-
C4: T-3h-0.35 (Temperature inside the filter: 12.0 ± 3.2°C)									
	In			Out			Concentration percent removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n
Temperature (°C)									
COD (mg/L)	274	280 ± 112	3	<20	<20 ± 1	3	93 %	92 ± 4 %	3
TSS (mg/L)	176	179 ± 91	3	<2	<2±0	3	99 %	99 ± 1 %	3
TN (mg/L)	35.9	29.8 ± 12.2	3	15.4	15.0 ± 1.1	3	56.0 %	42.8 ± 25.7 %	3
NH_4-N (mg/L)	23.3	23.9 ±11.1	3	0.24	0.65 ± 0.91	3	98.2 %	97.8 ± 2.4 %	3
NO_3-N (mg/L)	0.74	1.17 ± 0.9	3	13.6	13.6 ± 0.2	3	-	-	-
C5: T-3h-0.35-NH4 (Temperature inside the filter: 19.8 ± 1.7°C)									
	In			Out			Concentration percent removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n

Temperature (°C)									
COD (mg/L)	772	789 ± 242	6	28	29 ± 6	6	97 %	96 ± 1 %	6
TSS (mg/L)	446	494 ± 145	6	3.7	3.9 ± 1.1	6	99 %	99 ± 0.3 %	6
TN (mg/L)	106.4	108.2 ± 18.1	6	28.1	29.9 ± 11.1	6	75.2 %	71.2 ± 12.8 %	6
NH_4-N (mg/L)	83.8	86.9 ± 19.0	6	6.09	8.17 ± 8.92	6	93.7 %	89.2 ± 12.5 %	6
NO_3-N (mg/L)	0.45	0.48 ± 0.33	6	18.0	17.6 ± 4.9	6	-	-	-

Table 2.4 Inlet and outlet concentrations and concentration removals for each condition, considering temperature inside the filter, COD, TSS, TN, NH4-N and NO3-N, where Avg = average, Std dev = standard deviation and n= number of observations.

C6: F-3.3h-1.7h-0.35-NH4 (Temperature inside the filter: 19.5 ± 0.5°C)									
	In			Out			Concentration removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n
COD (mg/L)	286	252 ± 136	6	21	23 ± 4	6	91 %	87 ± 10 %	6
TSS (mg/L)	201	189 ± 113	6	<2.0	<2.0 ± 0.0	6	99 %	98 ± 2 %	6
TN (mg/L)	53.3	59.6 ± 42.8	6	31.5	35.3 ± 12.0	6	38.2 %	24.7 ± 9.2 %	5
NH_4-N (mg/L)	52.7	47.1 ± 20.9	6	0.08	1.35 ± 3.01	6	99.6 %	98.0 ± 4.4 %	5
NO_3-N (mg/L)	0.45	0.68 ± 0.55	6	30.5	30.3 ± 3.1	6	-	-	-
C7: F-2.5h-0h-0.35-NH4 (Temperature inside the filter: 20.2 ± 0.5°C)									
	In			Out			Concentration removal (%)		
	Median	Avg + Std dev	n	Median	Avg + Std dev	n	Median	Avg + Std dev	n
COD (mg/L)	595	548 ± 137	7	40	34 ± 13	7	94 %	94 ± 2 %	7
TSS (mg/L)	367	384 ± 85	7	7	7 ± 1	7	98 %	98 ± 0%	7
TN (mg/L)	98.0	91.8 ± 41.6	7	29.6	27.0 ± 10.2	7	70.5 %	70.7 ± 5.3 %	6
NH_4-N (mg/L)	97.3	91.3 ± 41.4	7	19.5	18.3 ± 7.1	7	80.5 %	80.0 ± 5.3 %	6
NO_3-N (mg/L)	0.45	0.38 ± 0.16	7	9.76	8.70 ± 4.40	7	-	-	-

Explore different aeration control strategies to optimize TN removal

This phase explored an optimized aeration strategy and the associated limitations in terms of TN removal as well as the ways to control aeration by online sensors.

Table 2.5 shows the overall system performance for a dataset corresponding to normal and high organic loadings. The figure demonstrates the variations in concentrations and removal efficiencies for COD, TSS, NH4-N, and TN. The results for COD and TSS indicate that the treatment process is highly efficient, regardless of the inlet concentration. The concentration removal efficiencies are 96 ± 1% and 97 ± 1% for COD and 99 ± 1% and 99 ± 1% for TSS for normal and high organic loadings, respectively. Regarding nitrogen, the normal organic loading results indicate robust performance, with NH4-N concentration removal of 90 ± 9 %. The TN had a lower performance than other parameters, with 81 ± 6%, yet still reaching a reasonably lower outlet concentration of 13.7 ± 5.8 mg/L. The aeration strategy employed in the current study to better use organic carbon for the denitrification process had a superior performance for all the parameters, including NH4-N and TN, compared to the seven strategies evaluated in previous phase.

The results showed that aeration control on flow rates is of relevance but can lead to limited removal efficiencies if inlet concentrations vary a lot. Consequently, an automatic control based on online sensor have been explored. The sensors tested concern pH, redox potential, temperature, dissolved oxygen as well as ammonia and nitrates. Different locations have been tested from inlet/outlet to internal measurement in the primary and secondary filters. The experiments (results not shown) identified several bending points, including the "DO bend," the "ORP plateau," and the "nitrate knee," which represent the end of the nitrification or denitrification processes. However, the bending points did not appear consistently, and the concentrations at the bending points varied. Finally, the feasibility of using linear predictive models was investigated. However, the input variables exhibited issues with non-linear relationships. Therefore, it is recommended that future predictive modelling approaches consider these challenges.

Table 2.5 Inlet and outlet concentrations and concentration removal for normal and high organic loads, for COD, TSS, TN, NH4-N and NO3-N. Avg = average and Std dev = standard deviation.

Parameter		In		Out		Concentration removal (%)	
		Median	Avg + Std dev	Median	Avg + Std dev	Median	Avg + Std dev
Normal organic loading	COD (mg/L)	819	805 ± 222	< 21	28 ± 10	96%	96 ± 1%
	TSS (mg/L)	204	253 ± 124	< 2	3 ± 2	99%	99 ± 1%
	NH_4-N (mg/L)	65.0	61.0 ± 22.4	3.7	6.0 ± 6.7	94.0%	90.3 ± 8.6%
	NO_3-N (mg/L)	< 0.5	< 0.6 ± 0.6	5.9	7.4 ± 6.1	-	-
	TN (mg/L)	78.9	74.8 ± 22.4	12.9	13.7 ± 6.4	80.0%	81.4 ± 5.8%
High organic loading	COD (mg/L)	1060	1080 ± 271	< 36	35 ± 9	96%	97 ± 1%
	TSS (mg/L)	420	372 ± 147	< 2	4 ± 3	99%	99 ± 1%
	NH_4-N (mg/L)	118.0	134.3 ± 37.4	13.5	20.7 ± 14.9	87.0%	85.6 ± 7.8%
	NO_3-N (mg/L)	< 0.5	< 0.5 ± 0.0	3.1	5.9 ± 5.9	-	-
	TN (mg/L)	142.5	158.2 ± 38.7	26.4	27.2 ± 12.0	82.0%	83.0 ± 5.3%

2.4 Main co-benefits results

Co-benefits have been evaluated based on the three following topics:

- Educational visits have been conducted on the research platform dedicated to NBS for wastewater treatment to disseminate the interest in using NBS in urban area. More than 40 people from different skills (PhDs and Postdocs during MULTISOURCE summer school, researchers, Lyon municipality, funding agency, private companies and students). The platform is an interesting tool to improve acceptance by water professionals and make them confident in the results that come from the pilots.
- Electricity consumption has been measured. Based on the optimized aeration strategy for TN removal and taking into account an upscaling factor (the ratio power/treatment capacity is not linear, and the pilot is quite small), the system consumes around 1.5 kWh/kg of treated BOD_5 (1.8 for 500 PE, 1.3 for 1000 PE and 1 for 4,000 PE) and around 0.5 kWh per cubic meter of treated

water (0.7 for 500 PE, 0.5 for 1,000 PE and 0.4 for 4,000 PE). It is around 2 to 3 times lower than activated sludge typical consumption values for comparison.

- Potential benefits and constraints in developing decentralized wastewater management in urban areas by NBS have been evaluated by a questionnaire to water professionals (from water agencies, ministry of environment and departmental services for wastewater treatment). 79 persons answered the questionnaire (62 % of male and 38 % of female) with 71% being between 35 and 54 years old. 63 % of the persons works in departmental services in charge of wastewater treatment, 11 % from departmental water services (local representative of the ministry) and 9 % from water agencies and 5 % from municipalities.
    - Among the potential environmental co-benefits of decentralized approach with NBS, main of the examples given were agreed or totally agreed by the respondents. From the most agreed to the less agreed we can note increasing green spaces (85 %), preserve biodiversity (77 %), contribute to flood mitigation (77 %), increase water reuse (76 %), thermal regulation (73 %), promote pollination (71 %), carbon storage (68 %), reduce energy consumption (61 %), increase air quality (57%) and improve acoustic comfort (53 %). Open answers related to environmental co-benefits were linked to improving the living environment, increasing user awareness or increase urban water management resiliency and decreasing the cost of water management.
    - Regarding socio-cultural benefits, from the most agreed to the less agreed we can note an improvement of urban aesthetic (90 %), easier environmental education (78 %), improve health and well-being (76 %), favour citizen involvement (72 %), increase the quality of recreational areas (70 %), easier social cohesion (60 %), reduce costs (60 %) and contribute to local employment (50 %). In the open answer appeared as well important role for social links and gender equilibrium.
    - Regarding drawbacks of such an approach the main one agreed by respondents was related to appearance of unwanted species (50 %), promotes allergies (41 %), smells (31 %), increase water cost (31 %), threats to health safety (27 %) and heritage threats (21 %). Globally, open answers show low worries about such an approach except issues regarding footprint, complicated to implement on existing urban area and questions about the management of green areas. It seems relevant to focus on training staff and address the challenge of multi-stakeholder dialogue.
    - When raising the question of benefits for their work, it appears that it will allow to questioning current practices, increase the levels of action, involve citizen in decision and favour treated water reuse. In term of drawbacks for their work, many answers said that there is no problem and other raised the question of increasing administrative authorization (more infrastructures), the necessity of coordination between more actors, and training professions regarding new approaches for decision-makers and managers alike.

2.5 Challenges and barriers

The main challenges regarding the implementation of Rhizosph’air pilot in urban areas for domestic wastewater treatment can be listed as follow:

- The necessity in adapting aeration strategy to ensure TN removal when facing high loads variation. The aeration strategy based on inflow does not take into account possible inflow concentration variation, which can be high when designing low-capacity systems (10- 50 PE). Further research would be necessary to better assess the limits of the system in such conditions.
- The necessity to implement an additional treatment step at the end to finish disinfection in the case of water reuse for irrigation with European class A and B.

- Address the question of possible contact with wastewater by citizen when implemented in urban area. It is not a strong technical issue but requires maybe additional footprint.
- As for other NBS technologies for decentralized approaches in urban areas, adapt regulations so that the decentralized approaches can be favoured compared to centralized approaches.

2.6 Main outcomes

International Peer reviewed Publications

Miyazaki, C.K., Morvannou, A., Higelin, E., Nivala, J., Molle, P., 2023. Aeration strategies and total nitrogen removal in a hybrid aerated treatment wetland. *Blue-Green Systems* 5, 321–335. https://doi.org/10.2166/bgs.2023.045

Miyazaki, C.K., Morvannou, A., Petitjean, A., Nivala, J., Molle, P., 2024. Hydraulic characterization of a hybrid aerated vertical and horizontal treatment wetland. *Ecological engineering*, 206, 107301. https://doi.org/10.1016/j.ecoleng.2024.107301

Conference Presentations

Miyazaki, C.K., Delgado-Gonzalez, L., Morvannou, A., Molle, P. 2022. Hydraulic characterization in a hybrid vertical/horizontal treatment wetland with forced aeration. *IWA 17th International Conference on Wetland Systems for Water Pollution Control*. Lyon, France. (Poster presentation).

Miyazaki, C.K., Nivala, J., Morvannou, A., Clément, R., Molle, P. 2023. Hydraulic characterization in a hybrid vertical/horizontal treatment wetland with forced aeration. *WETPOL*. Bruges, Belgium. (Oral presentation).

Miyazaki, C.K., Morvannou, A., Petitjean, A., Nivala, J., Molle, P. 2024. Optimization of total nitrogen removal in a hybrid aerated treatment wetland. *IWA 18th International Conference on Wetland Systems for Water Pollution Control*. Martinique, France. (Oral presentation).

Silveira, D.D., Miyazaki, C.K., Sorgato, A.C., Lapolli, F.R., Morvannou, A., Kela, P., Nivala, J., Molle, P. 2024. Microbial insights in a hybrid aerated treatment wetland for total nitrogen removal. *IWA 18th Conference on Wetland Systems for Water Pollution Control*. Martinique, France. (Oral presentation).

Kisielius, V., Miyazaki, C.K., Morvannou, A., Nivala, J., Molle, P., Carvalho, P.N. 2024. A hybrid aerated treatment wetland for removal of water contaminants and micropollutants. *IWA 18th Conference on Wetland Systems for Water Pollution Control*. Martinique, France. (Oral presentation).

3 Pilot 2: USA - MSU – Vertical flow wetland treating high-strength wastewater

3.1 Pilot 2 description

The US pilot is specifically tailored for the treatment of high-strength domestic wastewater in a sub-freezing winter climate and is housed at the Bridger Bowl Ski Area, situated at 45.040 degrees North latitude and an elevation of 1,960 meters. The Bridger Bowl Ski Area receives approximately 9 m of annual snowfall and snow may be present as early as October and may not melt until May. The pilot was constructed in 2012 and planted in 2013. Since construction, it has been monitored, and operational parameters have been tested for optimization of COD and total N removal.

The pilot system receives clarified but high-strength wastewater from a septic tank during the ski season, from December to April, which is characterized by water temperatures in the range of 2-4 °C in the TW and TSS approximately 75 mg L^{-1}. The wastewater is generated in the ski resort lodges, which house toilet facilities and kitchens. Thus, the waste is more highly concentrated than domestic wastewater due to the lack of dilution from shower and laundry facilities. Influent COD to the system is generally between 600-900 mg COD L^{-1} and influent total nitrogen is typically between 150-200 mg N L^{-1}.

The pilot is a two-stage sub-surface vertical flow system with two parallel cells at each stage (Figure 3.1 and 3.2). Each cell has a surface area of 23,8 m^2 (95m^2 system total) and nominal depth of 1 m. The effluent of the second stage is recycled and independently applied to the first stage to facilitate complete nitrogen removal. The first stage contains a treatment layer consisting of fine gravel media (d50 ≈ 5 mm) in the top 0.9 m of the bed. The second stage consists of a treatment layer of coarse sand (d50 ≈ 0,6 mm). Both stages contain coarser drainage layers consisting of medium gravel and small cobble at the bottom of the cells and the second stage is overlain by a gravel cover for frost protection. Both stages were planted with two wetland plant species native to the northwestern United States, *Carex utriculata* (beaked sedge) and *Schoenoplectus acutus* (hardstem bulrush).

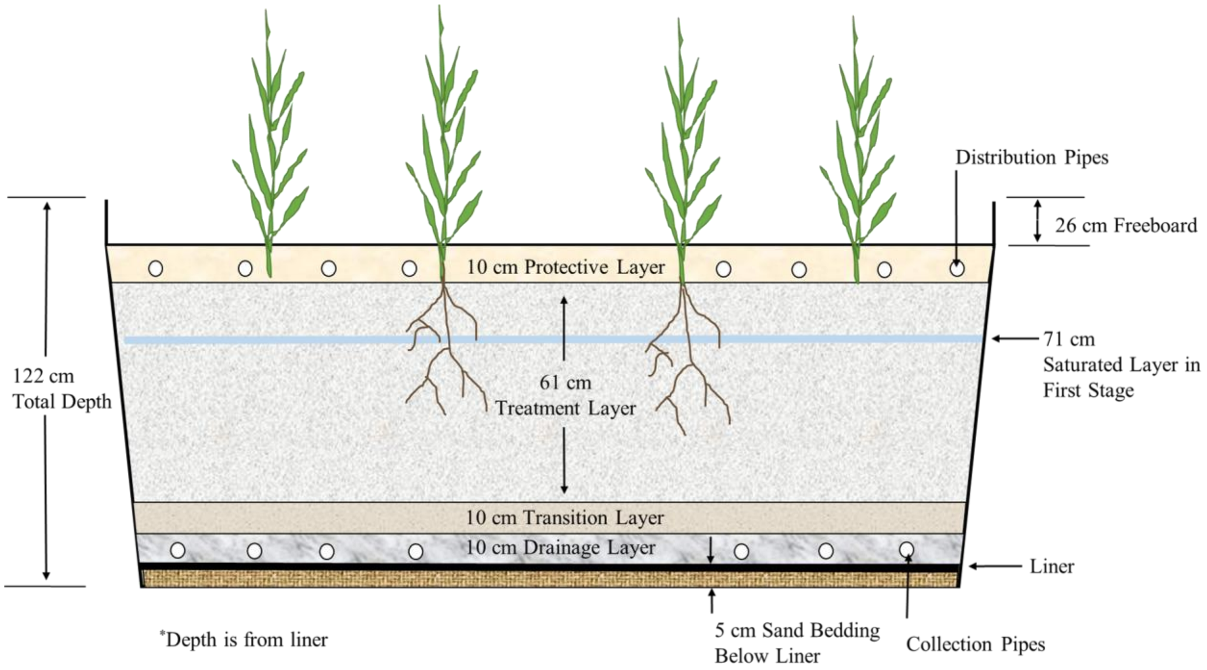


Figure 3.1. Transverse cross section of a TW cell.

Major differences between the first and second stage cells are 1) media material for the treatment layer is gravel in the first stage and sand in the second and 2) only the first stage is maintained partially saturated.

This project has received funding from the European Union's Horizon H2020 innovation action programme under grant agreement 101003527.

The first stage receives influent from the septic tank and recycled effluent from the second stage, which are dosed independently of each other. The first stage drains into a transfer tank of 3.8 m^3 capacity and the influent to the second stage is taken from this tank. The two parallel cells in each stage can be dosed independently due to installation of ball valves upstream of both stages in 2023, allowing for real-time comparisons of mass loading, recycle ratio and dosing schedules.

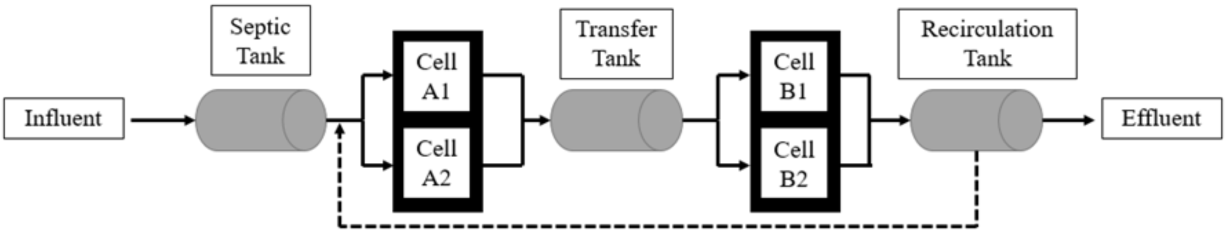
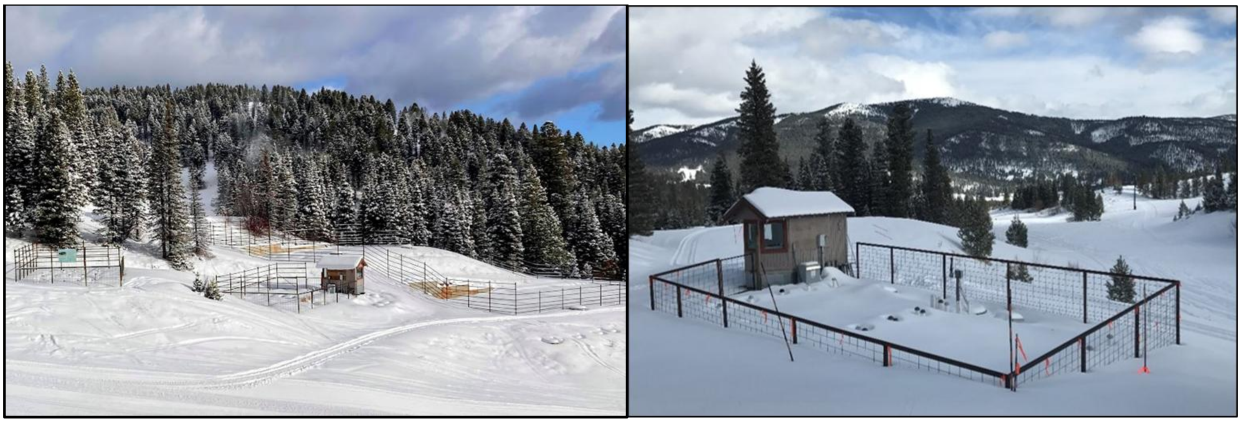


Figure 3.2 Schematic of the Bridger Bowl Vertical Flow Treatment Wetland system. Cells A1 and A2 represent the first stage and cells B1 and B2 represent the second stage.

The bottom 0.7 m of the first stage is maintained saturated to promote anoxic conditions for nitrogen removal. The primary purpose of the partially saturated first stage is the removal of influent COD and the denitrification of nitrate recycled from the second stage effluent. The unsaturated second stage facilitates aerobic nitrification of influent ammonia to nitrate in the presence of low COD.

Figure 3.3. Photographs of the Bridger Bowl TW pilot system. Top – photo in summer, showing both stages of the system within the fenced areas and growth of *Carex* and *Phragmites*. Bottom left – System in winter, with two pilot system stages enclosed within two rectangular fenced areas on left side of the photo. The full scale treatment wetland is within the larger fenced area behind and to the right. Bottom right – closer view of the second stage of the system in winter.



3.2 Overview of the monitoring work

Three full ski seasons of water quality monitoring data have been collected since the inception of the project. The inflow rate was 4 m^3 d^{-1} in the 2021-2022 and 6 m^3 d^{-1} in the 2022-2023 and 2023-2024 seasons. For most of the system's operation, the effluent from the second stage has been reintroduced into the system at a 2:1 volume-to-volume ratio (recycle to influent), thus the total flow through the system is typically three times the inflow rate in the respective ski seasons.

Grab samples and 3-day average composite samples were collected from the septic tank (raw unmixed influent to system), transfer tank (mixed first-stage effluent and second-stage influent), and recirculation tank (final system effluent and partial influent to first stage) (Figure 3.2). Wastewater samples were analyzed at least weekly over the season for COD, ammonia-nitrogen (NH_3-N), nitrate (NO_3^-), nitrite (NO_2^-), and orthophosphate (PO_4^{3-}). Samples were transported on snow/ice and analyzed within one day of collection. COD was measured using HACH® digestion vials (HACH® Co., Loveland, CO, USA). NH_3-N was measured using a modified Berthelot reaction approach for 96 well plates, with absorbance readings taken at a wavelength of 660 nm on a BioTek Synergy HTX Multimode Reader (Agilent Technologies, Inc., Santa Clara, CA, USA). NO_3^-, NO_2^-, and PO_4^{3-} were measured using a Metrohm Eco ion chromatograph with a Metrosep A Supp 5150/4.0 column, Metrohm Suppressor Module and 3.20/1.00 mM sodium bicarbonate/sodium carbonate eluent at 0.7 mL/min (Metrohm USA, Riverview, FL, USA).

During the 2022-23 season, the main operational parameter evaluated was the influence of dose volume of influent onto the first stage on denitrification for a constant overall loading rate. The two septic dosing strategies compared were large doses of 4 cm occurring every eight hours and smaller doses of 1 cm occurring every two hours. In both cases, smaller doses of 1 cm from the nitrate-rich recycle tank were added to the first stage, approximately every hour. This comparison allowed us to evaluate whether large or small septic doses were able to promote more denitrification in the first stage.

During the 2023-24 season, the system was operated to test the capacity of nitrification in the second stage by manipulating the flow rates and recycle ratio. Several different conditions for loading to the two identical cells of the second stage were evaluated, including the standard 50-50 split of flow from the first stage effluent; an 80-20 split to evaluate increased loading onto one cell; and finally a 100% loading onto one cell while eliminating recycle, to maximize ammonia loading to one cell.

In addition to water quality monitoring, sampling for microbial abundance and diversity at various points within the system and sampling of greenhouse gas emissions were conducted. Grab samples of wetland media were collected in December 2020, February 2021, and April 2021 at two depths in the first stage and one depth in the second stage (n = 18). DNA was extracted at Montana State University and sequenced for 16s rRNA community profiling by Kela Weber's laboratory at the Royal Military College of Canada. Microbial samplers were installed at two depths in the first stage and one depth in the second stage in November and December 2021 and removed in March and October 2022 for DNA sequencing and ongoing metagenomics analysis (n = 48).

Gas sampling was performed on the wetland in the months of March 2022, April 2022, February 2023, and March 2023. Emissions of CO_2, CH_4 and N_2O were measured from randomly selected locations in the wetland using 20-cm diameter gas chambers and a Picarro G2508 gas analyser. In March 2022, four random locations per stage were monitored using manual gas sampling chambers over three 8-hour periods (two days in the first stage and one in the second stage). In April of 2022, one location in the first stage was monitored for emissions every ten minutes for 48-hours using a LI-COR 8100-103 survey chamber. In February 2023, gas emissions from all four cells (two cells each in the first and second stages) were collected over a four-day sampling campaign over a 24-hour period in each cell. Measurements alternated between three random locations in the cell using LI-COR 8100A-104 Long Term Chambers and the LI-8150 Multiplexer. In March 2023, only the two first stage cells were analysed to assess the impact of the dosing change on gas emissions.

3.3 Main technical results

Table 3.1 Water quality and removal efficiency of selected WW contaminants during 2021-22, 2022-23 and 2023-24 operating seasons.

Season	Parameter	COD	$NH_3 – N$	TN*	$PO_4 – P$	BOD_5	TSS
2021-2022	Influent Concentration (mg L^{-1})	779 ± 20†	161 ±5	162	14.4 ±0.3	n/a	n/a
	Effluent Concentration (mg L^{-1})	26.0 ±1.3	<0.75	42	12.0 ±0.6	n/a	n/a
	Removal %	96.9	>99	76.5	22.1	n/a	n/a
	number of samples	15	15	15	15	n/a	n/a
2022 - 2023	Influent Concentration (mg L^{-1})	825 ±11	192 ±2	193	14.1 ± 1.5	444 ±26	72.5 ±6.2
	Effluent Concentration (mg L^{-1})	29.2 ±1.7	3.9 ± 1.0	51	9.0 ± 0.9	4.0 ±0.5	1.4 ±0.5
	Removal %	95.8	98.1	71.1	33.6	99.0	98.2
	number of samples	27	27	27	19	4	5
2023 - 2024	Influent Concentration (mg L^{-1})	826 ± 12	188 ± 2.9	190	15.2 ± 0.4	n/a	n/a
	Effluent Concentration (mg L^{-1})	42 ± 2.2	5.1 ± 1.3	55	13.1 ± 0.9	n/a	n/a
	Removal %	94.9	97.3	71.1	13.8	n/a	n/a
	number of samples	20	22	14	15	n/a	n/a

** Calculated not measured.*
† Mean plus or minus the standard error.

Water quality data for the ski seasons is shown in Table 3.1. Throughout the seasons, overall COD removal was >95%, TN removal was >70%, and ammonia removal was >97%. Higher mass loadings were observed in the two later seasons due to the increase in addition of septic water to the system, from 4 $m^3\ d^{-1}$ in 2021-22 to 6 $m^3\ d^{-1}$. The COD mass load onto the first stage (septic and recycle) averaged 61 and 105 g/m^2/day for the 2021 – 22 and 2022 – 23 seasons, respectively. The first stage cells removed 82% of the COD loaded onto them in the 21-22 season and 80% in the 22-23 season. The remainder of COD removal was performed by the second stage. Average total nitrogen load to the first stage from both septic and recycle, as determined by the sum of nitrogen ions (NH_4^+, NO_3^-, NO_2^-) was 18 g N/m^2/day in 2021-22 and 36 g N/m^2/day in 2022-23. Nitrogen removal primarily occurred in the first stage due to denitrification of nitrate, and the second stage successfully converted ammonia to nitrate.

During the 2021 – 2022 and 2022 – 2023 seasons the system overall showed significant resilience to changing operational parameters, i.e., increased hydraulic loading rate and changing septic dose depths. Total nitrogen removal for both seasons remained above 70%, COD removal remained above 95%, and ammonia removal remained above 98%. Overall, the system performed better when operating at a lower daily hydraulic loading rate during the 21 -22 season. However, the removal efficiencies for COD, TN, and ammonia decreased only minimally when total flow was increased to 6 m^3 d^{-1} during the 22 – 23 season.

In the 2022-2023 season, the effect of influent septic dose volume on denitrification was evaluated. Smaller influent doses increased COD and ammonia removal in the first stage and decreased denitrification efficiency, but differences were relatively minor. Since the second stage is nearly 100% efficient at nitrification and removes any carryover COD from the first stage, the conclusion is that larger dose volumes increase total nitrogen removal through enhanced denitrification without affecting COD.

During the 2023-24 season, COD loading rates to the first stage were consistent with the previous year at an average of 111 g/m^2/day and system-wide COD removal was consistent at 95%. The total nitrogen loading onto the first stage was also similar to the previous season at an average of 36 g N/m^2/day. However, although TN removal remained comparable to previous years at 71%, conversion of ammonia in the second stage varied between the two cells and appeared to be less efficient in the cell that received higher loading during the 80-20 split. However, these data are preliminary and continued assessment of the TW is underway to determine which operational parameters correlate most strongly to ammonia removal.

Results of the microbial DNA analysis indicate that the TW performance was complemented by high relative abundances of psychrophiles or psychrotolerant genera, such as *Polaromonas*and *Dechloromonas*, that indicate robust microbial community adaptation to low temperatures. Spatial differences across stages indicated that the first and second stages supported distinct microbial communities and indicator organisms with denitrification and nitrification capabilities, respectively, which agrees with water quality changes across the stages. Temporal shifts in the microbial communities suggest that the seasonal TW operation paired with long, low-nutrient rest periods influenced the community development and enables diverse species to remain viable throughout the year despite extended periods without nutrient input. Microbial community results are published in Ayotte *et al*., 2024, Bioresource Technology Reports.

From the 2022 GHG study, emissions of CH_4 and N_2O were significantly higher in the first stage compared to the second stage of the TW. However, CO_2 emissions were nearly 2.5 times higher in the second stage despite low organic carbon loading. The discrepancies in the carbon balance are hypothesized to be the result of dissolved inorganic carbon produced in the first stage that are then off-gassing in the second stage. Ongoing analysis of GHG emissions from 2023 is determining the carbon mass balances on each stage to better characterize the importance of dissolved inorganic carbon on observed emissions. Data confirmed statistically significant patterns in emissions that emerged with hydraulic loading. However, these patterns pointed more strongly to the impacts of convective transport and mass transfer rather than microbial production. The emission factors for N_2O and CH_4 were similar to similarly operated TW systems and on the low end of most other treatment processes. The results of the study are published in Ayotte *et al*., 2024, STOTEN.

3.4 Main co-benefits results

The co-benefits survey was provided as a Google form to stakeholders of the Bridger Bowl pilot wetland. Stakeholders include the Bridger Bowl operations and sustainability departments, the State of Montana Department of Environmental Quality’s water quality section, the City of Bozeman Public Works division and researchers at MSU working on the pilot. The survey received six responses, three from individuals identifying as from a Research institution/University and one response each from individuals in the public sector, non-profit group and private company.

The environmental co-benefits that respondents would most like to see monitored included: 1) Reduction of energy demand (5 votes); 2) Providing carbon storage/sequestration (4 votes); and 3) Enhancing or preserving biodiversity (3 votes). Other environmental co-benefits that were suggested were reduction of contaminants of emerging concern (micro-pollutants) and nutrient reduction. For the socio-economic co-benefits, two choices received five votes each, including 1) facilitating environmental education and 2) increasing aesthetic value. The remainder of the socio-economic co-benefits received only 1-2 votes. One additional suggestion for an added socio-economic benefit not in the list was enhancing the water supply reliability.

The survey respondents did not vote for as many disadvantages, only one option received four votes, which was the consideration of undesired species (flora and fauna). Several of the other options received zero or one vote, suggesting that respondents were not as concerned with monitoring disadvantages of the TW. Responses to the open-ended question on disadvantages included comments that they are able to be mitigated, although one comment recognized that TW are land intensive.

3.5 Challenges and barriers

The primary challenge with operating a pilot at a seasonally operating ski resort is the limited period within a given year that wastewater is fed to the system. The ski resort is open generally from mid-December to mid-April every year and very little activity occurs within the resort's facilities outside of this timeframe. Thus, the treatment wetland is under operation only four months per year and during the remainder of the year receives only fresh water to maintain saturation for plant growth.

This seasonal operation presents challenges due to the short time frame during the year that optimization and evaluation of the system performance can be done. There is typically a start-up period for the system as well, such that it may be several weeks into the season (early January) before the system arrives at "steady-state" operation in terms of influent water parameters as well as treatment performance. With the short seasonal operation, long-term continuous performance of the system cannot be assessed, though consistent performance across seasons can be evaluated. With only four months to collect data within each year, any operational issues such as a broken valve or pump can also have a major impact on the ability to collect sufficient data for the year.

The environmental conditions that the wetland operates under are also challenging. Snow removal is necessary in order to collect samples directly from the TW media for microbial studies, or to place equipment for gas emissions sampling, or to simply collect water samples from holding tanks. Often, several feet of snow need to be moved, and this operation is always done by hand shovelling. Finally, as the system is located midway up a ski run, researchers working on the system must be comfortable skiing in and out of the location, carrying all supplies in backpacks and performing work in sub-zero conditions. To mitigate freezing of sampling lines and equipment, a heated hut is utilized at the location and houses a composite auto-sampler. Even with these measures, freezing of sampling tubing and formation of ice on the TW surface has been observed at times.

3.6 Main outcomes

International Peer reviewed Publications

Ayotte, S.H., Allen, C.R., Parker, A., Stein, O.R., Lauchnor, E.G. 2024. Greenhouse gas production from an intermittently dosed cold-climate wastewater treatment wetland, *Science of The Total Environment*, Volume 924, 171484, https://doi.org/10.1016/j.scitotenv.2024.171484.

Ayotte, S.H., Wallace, S.J. Allen, C.R., Weber, K.P., Stein, O.R., Lauchnor, E. G. 2024. Microbial community dynamics in a two-stage treatment wetland: Insights from treating seasonal ski resort wastewater, *Bioresource Technology Reports*, Volume 27, 101885, https://doi.org/10.1016/j.biteb.2024.101885.

Conference Presentations

Johnson, L., Allen, C., Carvalho, P., Kisiellus, V., Stein, O., Lauchnor, E. 2024. Micropollutant removal in a two-stage vertical flow treatment wetland [Conference presentation]. *18th International Conference on Wetland Systems for Water Pollution Control*, Fort-de-France, Martinique, November 24-29, 2024.

Johnson, L., Allen, C., Carvalho, P., Kisiellus, V., Stein, O., Lauchnor, E. 2024. Micropollutant removal in a two-stage vertical flow treatment wetland [Poster presentation]. *Montana Section American Water Works Association and Montana Water Environment Association Joint Conference 2024*, Missoula, MT USA, April 23-25, 2024.

Ayotte, S.H., Allen, C.R., Parker, A., Stein, O.R., Lauchnor, E.G. 2023. Greenhouse gas emissions from a cold-climate treatment wetland. (Speaker) *International symposium on Wetland Pollutant Dynamics and Control – WETPOL*, Bruges, Belgium, September 10-14, 2023.

Lauchnor**,** E.G. **,** Ayotte, S.H., Wallace, S., Weber, K., Stein, O.R. 2023. Microbial community dynamics in a cold climate treatment wetland. (Speaker) *WETPOL*, Bruges, Belgium, September 10-14, 2023.

Ayotte, S.H., Allen, C.R., Lauchnor, E.J., Brookshire, E.J., Hartshorn, A.S., Parker, A., Stein, O.R. 2023. Greenhouse Gas Production from Wastewater Treatment Wetlands. (Speaker) *Association of Engineering and Environmental Science Professors (AEESP) Conference*, Boston, MA, USA, June 20-23, 2023.

Ayotte, S.H., Allen, C.R., Lauchnor, E.J., Brookshire, E.J., Hartshorn, A.S., Stein, O.R. (Speaker). 2022. Greenhouse Gas Production from Treatment Wetlands in Winter. *International Water Association 17th International Conference on Wetland Systems for Water Pollution Control*, Lyon, France November 6-10, 2022.

Bowman, T.S. , Ayotte, S.H. , Allen, C.R., Lauchnor, E.J. , Stein, O.R. (Speaker). 2021. Analysis of nitrogen transformation rates within the first stage of a two-stage vertical flow treatment wetland receiving high strength domestic wastewater in cold-climate conditions. *International symposium on Wetland Pollutant Dynamics and Control – WETPOL*, (virtual) September 13-17, 2021.

Outreach Activities

Education and outreach at Bridger Bowl through their Sustainability Office includes informational placards and a summary of the pilot on the ski area website, both tailored towards a general public audience. The ski resort was a recipient of the Environmental Protection Agency's 2024 Regional Pollution Prevention Awards, which cited the resort’s efforts to utilize nature-based wastewater treatment. https://bridgerbowl.com/whoweare/sustainability

4 Pilot 3: Belgium - Rietland - Phytoparking treating pre-treated wastewater

4.1 Pilot 3 description

Climate change has created drought and heavy rainfall challenges for Flanders. Therefore, to buffer rainwater and lessen the amount of drinking water used for toilet flushing, new and renovated buildings should add a rainwater tank (regulation, 2005). However, cleaned wastewater can also be used to flush toilets, allowing rainwater to infiltrate and recharge groundwater.

In areas with limited availability of water, like Belgium, which is rated 18th on the list of regions with extreme high water stress (Kuzma *et al.*, 2023), reuse of treated wastewater can be a part of the answer.

To cover longer periods of drought rainwater tank's capacity should be large enough to use rainwater during extended droughts (up to six weeks without rainfall). However, apartment buildings cannot use this option as the surface area of the roof, which is related to the amount of water that can be stored, is not proportional to the amount of water that is required. In contrast, the benefits of treated wastewater are that it is constantly present and that the buffer capacity needed is typically restricted to the daily required reuse volume. The remaining treated wastewater could be utilized for irrigation and groundwater table replenishment, as only 30% of it will be used for toilet flushing.

Figure 4.1 Pilot location in Ypres in Belgium, in the region of Flanders.

The campsite ‘t Hof Bellewaerde is located in Ypres, province of West-Flanders in Belgium (Temperate Climate). This pilot treats wastewater of 105 population equivalent (PE) in a septic tank followed by an aerated hybrid wetland as the campsite is located too far from the main sewer pipe. The black and grey wastewater flows are treated separately on an area of 32m² and 44m² respectively. In this pilot, the reuse of treated grey wastewater is researched for domestic purposes as toilet flushing and for agricultural use where it should be in compliance with European guidelines for domestic use EN 16941-2 and the European Directive for irrigation (EU 2020/741) respectively. The treated grey wastewater is reused in the toilets after ultraviolet (UV) treatment.

Figure 4.2 a) Campsite 't Hof Bellewaerde with white arrow indicating the location of the shed where the Phytoparking was placed; b) Open day on site; c) The picnic benches and the go-cars are located on top of the Phytoparking in the shed; d) The effluent sampling locations are indicated with an arrow, black for blackwater and grey for greywater.

4.2 Overview of the monitoring work

The Phytoparking system, developed by Belgian company Rietland, is based on the concept of an aerated wetland using Forced Bed Aeration®. The Phytoparking is an aerated hybrid treatment wetland where emergent macrophytes are replaced by a top layer of crushed bricks, covered with turf grids, which are often planted with grass and can sustain an automobile's weight. However, excavation on the site was prohibited due to the archaeological archive in the soil, thus the Phytoparking was built inside a campsite's shed. The turf grids were filled with gravel rather of grass due to the sheds lack of sunlight and rain. The total area of the Phytoparking is 76m² divided in an treatment for black water (32m²) and grey water (44m²). Both systems are built in the same way, with a formwork of 1.30m deep with an flexible Polyester (FPE) foil of 1mm (to prevent leaks). The Forced Bed Aeration principle is applied to both vertical and horizontal flows, which are aerated through a piped network at the bottom. Air is injected by two Bibus/Secoh JDK-S300 (300L/min) and two JDK-S200 (200L/min) membrane blowers for black and grey water respectively. Intermittent aeration fosters alternating aerobic and anaerobic zones, encouraging diverse bacterial development on the substrate. The Argex substrate (lightweight expanded clay aggregates (https://argex.eu), diameter: 8-16mm) fills the entire basin up to 1.10m. Three influent pipes (50mm) with an interval distance of 2m serve 1/3 of the surface (VSSF); the remaining 2/3 (HSSF) has no distribution pipes. The pumps and blowers are controlled by de PLC.

In 2022 and 2023, thirteen samples in total were taken from April until November. The campsite is closed from the first of December until the first of April so most the samples are taken during moderate and high season to check the robustness of the system. The performance of the Phytoparking is monitored by physical-chemical parameters (electrical conductivity (EC) pH, TSS, volatile suspend solids (VSS), COD, BOD, TP, orthophosphoric acid (Ortho-P), TN, NH_4, nitrite (NO_2), NO_3, sulfate (SO_4), the removal of pathogens (*E Coli*, total coliforms, coliphages, helminth eggs, legionella), metals, and organic micro pollutants. The flow rate and hydraulic retention time depends on how much water is used on the campsite. The impact of the UV light on pathogens was tested in 2022. Some optimization of the system was carried out in 2023 to increase the performance of the black water aerated system. Oxygen sensors were placed at the influent and effluent side to fine-tune the aeration to improve the removal of BOD, COD and TN and to lower the energy consumption.

Physico-chemical parameters for wastewater were analysed in the lab of Ghent University (Belgium) as well as the removal of pathogens (*E Coli*, total coliforms, coliphages, helminth eggs) and metals. The legionella analysis was done by a private lab according to the ISO 11731 + WAC/V/A/005 standards. Organic micropollutants were analysed at University of Aarhus.

4.3 Main technical results

During the two touristic seasons of 2022 and 2023, the campsite ‘t Hof Bellewaerde was able to welcome 18071 guests (2022: 7323; 2023: 10748). The average water consumption of the camping guests (table 4.1) was higher in 2023 compared to 2022 and during low season less water was used compared to high season. Over the period of two years, 71% of treated grey water was reused for toilet water and ends up as black water. The normal water consumption in households in Flanders is 102L/d of which 19L/d (VMM, 2022) is used or flushing toilets. The campsite guest only use 52L/d so the percentage of water use for toilet flushing is higher. The maximum water consumption over the course of two years on the camp site was for grey water 4.9m³/d and 3.9m³/d for black water. The hydraulic loading rate ranges from 0.05 m³/m².d in high season until 0.02 m³/m².d in low season.

Table 4.1 Overview of the water consumption in the camp site ‘t Hof Bellewaerde.

Quantity	2022	2023
Q average **high** season (m³/d)	3,2	3,9
Q average grey high season (m³/d)	1,8	2,3
Q average black high season (m³/d)	1,4	1,6
Q average **low** season (m³/d)	1,5	1,9
Q average grey low season (m³/d)	0,9	1,1
Q average black low season (m³/d)	0,6	0,8

Table 4.2 Influent concentrations and removal % of the Phytoparking at ‘t Hof Bellewaerde for grey and black water.

Parameter	Grey water		Black water		Discharge limits Flemish government
	Influent	Removal %	Influent	Removal %	Conc. effluent, Removal %
TSS (mg L^{-1})	20.7 ± 11.35	92.5	103.2 ± 86.4	96.4	≤ 35mg/L, min 70%
Turbidity (NTU)	33.5 ± 33.0	98.3	185 ± 107	99.2	
pH (-)	7.2 ± 0.2	/	7.9 ± 0.3	/	
COD (mg O_2 L^{-1})	115.9 ± 51.9	83.3	575 ± 254	91.6	≤ 125mg/L, min 75%
BOD (mg O_2 L^{-1})	63.9 ± 37.2	98.7	398.5 ± 218.5	98.4	≤ 25mg/L, min 90%
TP (mg P L^{-1})	1.8 ± 1.2	95.6	31.3 ± 10.5	92.6	

TN (mg N L^{-1})	20.3 ± 28.6	71.2	414.2 ± 304.8	71	
NH_4 (mg N L^{-1})	5.6 ± 3.3	99.3	267 ± 79	99.6	
NO_3 (mg N L^{-1})	0.77 ± 0.82	-	2.5 ± 2.9	-	
***E Coli* (#cfu/ml)**	$3.07.10^{5}$ ± $9.46.10^{5}$	Log 5.3	$6.07.10^{4}$ ± $1.06.10^{5}$	Log 4	
Tot col (#cfu/ml)	$2.93.10^{6}$ ±$9.48.10^{6}$	Log 3.6	$6.25.10^{4}$ ± $1.05.10^{5}$	Log 2.2	
Somatic Coliphages (#cfu/ml)	29 ±23	Log 1.4	$5.9.10^{3}$ ± $9.74.10^{3}$	Log 3.8	

The Phytoparking meets the discharge standards of the Flemish government. It performs very good on the removal van BOD (98%) and TN (71%) for two consecutive years at low (grey water) and high (black water) concentrations. COD is removed better with high concentration (black: 575mg/L; 91.6%) in this pilot compared to grey water (115.9mg/L; 83.3%), however, it still meets the effluent concentration standards. Ammonium is almost completely converted into nitrate. After three years of operation, there is no saturation occurring in the substrate at TP is removed with more than 90% in black and grey water. The Phytoparking demonstrates that pathogens can be removed by NBS with Log 5.3 and Log 4 for *E. Coli*, Total coliforms Log 3.6 and 2.2 and Somatic Coliphages Log 1.4 and 3.8 for grey and black water, respectively.

The grey water was tested for 23 metals. 13 metals were tested 7 times and 10 metals were analysed one. For Co, Cu and Ni, 1 up to 3 out of the 7 samples (dissolved metals) surely exceeded the standard (total metals). However, these were always the first (1 up to 3) samples, no exceedances were observed in the last four samples. This would point to leaching which diminishes over time. The opposite occurred for Zn that exceeded the standard only during the last measurement.

Seventy-three Organic Micro Pollutant (OMP) were identified by a target screening at Arhus University. Most of the OMP were only sporadically detected in grey and black water influent. Eight pharmaceuticals (painkiller, betablocker, cholesterol inhibitor, anti-epileptic, cholesterol inhibitor and blood pressure inhibitors) and one insect repellent were present in the influent of all 13 black water samples. These 8 OMP were on average 80% removed with the exception of one blood pressure inhibitor (33.8% Irbesartan) regardless flow variations. 44 and 25 substances were sporadically detected in the influent of black and grey water respectively and respectively 21 and 8 were at least once found in the effluent.

Some optimization of the system was carried out in 2023 to increase the performance of the black water aerated system. Oxygen sensors were placed at the influent and effluent side to fine-tune the aeration to improve the removal of BOD, COD and TN and to lower the energy consumption. However, this did not work as both sensors at influent and effluent side were in contact with stagnant water giving no sharp change in dissolved oxygen concentration. More information is to be found in the reported optimization section.

The EU irrigation regulation (EU 2020/741) focusses on four parameters: *E.Coli*, BOD, TSS, Turbidity. Based on the monitoring over 2 consecutive years, the effluent of the Phytoparking grey can be used as reclaimed water quality class B. Only one sample out of 13 did not meet the requirements for *E. Coli* (40cfu/100ml > 10cfu/100ml) for class A. Also the data of Phytoparking black water looks promising despite one sample exceeding BOD threshold by 4mg/L during a peak load at the campsite in August 2022. If we exclude this data point, this water quality could even meet class A, however to be on the safe side, the effluent meets the reclaimed water quality class B.

According to the European guideline EN 16941-2 on grey water reuse, the Phytoparking effluent cannot be used for toilet flushing. The first two samples of the monitoring period showed a pH lower than 5 (below the threshold) but afterwards the system stabilized and had an average of 6.8 over 13 samples. For reuse purposes laundry and spray applications, *E. Coli* should be not detected, and total coliforms should have a maximum value of 10 cfu/100ml. Although Phytoparking grey and black water are removing pathogens substantial, they do not meet these stringent limits. The influent grey water of the campsite contains a higher concentration of total coliform than the influent black water. These strange values lead to a better outcome for effluent concentrations of black water. Only one sample out of 13 of black water did not meet the requirements for total coliforms (1513cfu/100ml > 1000cfu/ml) during peak load. If we ignore this data point, then black water meets the requirements for reuse and grey water does not.

Currently Flanders has no regulation that dictates the water quality for “second circuit” water. The British standard BS 8525 and the European guideline EN 16941-2 are both cited in the Flemish code of good practice. The project has demonstrated that Phytoparking is a water technology that can be used to treat domestic wastewater (meets the Flemish discharge regulations) and reuse (black) water for toilet flushing, garden watering without spray and irrigation practices as water quality class B.

4.4 Main co-benefits results

The co-benefits of the Phytoparking were tested on 16 stakeholders. Eight women and eight men filled out the survey on co-benefits in April 2024. Half of the group was between 25-34 years old and the rest was older. Researchers, consultants, municipal officials and engineers were part of the group.

This group agreed that the Phytoparking has a great environmental added value in terms of reuse of treated wastewater, water treatment, efficient use of space and creating green urban areas. The Phytoparking contributes to less drinking water use and desiccation. This decentralized treatment systems can be placed at various off grid locations to accelerate the wastewater treatment level in Flanders and to achieve the requirements for the Water Framework Directive. It was less clear for the stakeholders to state socio-economical values. Efficient use of space was the most chosen benefit, supplemented with connection to nature and green spaces and low energy consumption. This system will facilitate environmental education and improve health and well-being. The stakeholders mainly saw a possible disadvantage of the Phytoparking: maintenance costs in comparison to other decentralized systems and possible leakage of hydrocarbons, oil and coolants.

Based on the above-mentioned survey, we have investigated:

1. How much water was reused at the campsite ‘t Hof Bellewaerde,
2. what is the impact of fluids leaking from the vehicles on the Phytoparking,
3. what is the energy use of the Phytoparking compared to other decentralized systems and pumping the wastewater to the main wastewater treatment plant.

Water reuse

The camping guests used on average 52 L of water per person per day, which is low compared to the average water consumption in Flanders (102 L/pers.d). The grey water was treated and reused again on the campsite for toilet flushing. Over the period 2022 and 2023, 389 m^3 or 71% of treated grey water was used for toilet flushing by 18071 people. The total costs saved on drinking water over 2 years is €2339.

Impact of fluids leaking from vehicles on the Phytoparking

The Phytoparking that is being tested in Ypres, Belgium, has a permeable top layer consisting of specific mixtures of gravel and topsoil. When a vehicle parks on top, there is a potential risk that accidentally leaking fluids such as motor oil, petrol or diesel, leach through the permeable top layer and end up in the wastewater biofilter. We are currently running a lab-scale setup to answer the following questions: (1)

how much oil and petrol are retained in the top layer and how much is leaching through, (2) do the oil/petrol that reach the biofilter have an impact on its treatment performance in terms of COD removal and nitrification, and (3) are the oil/petrol that reach the biofilter removed in the biofilter? First results indicate that a relatively large fraction is retained in the top layer. Given this retention and the rather large volume of the biofilter which assures dilution, an impact on treatment performance is not really expected. Based on a literature review, we expect that most of the oil and petrol will be biodegraded in the Phytoparking to acceptable levels in the effluent.

Energy consumption Phytoparking

Surface area and energy consumption comparison of three water treatment technologies for 35 IE wastewater treatment.

	Submerged Aerated Filter (SAF)	Vertical Subsurface Filter (Wetland)	Phytoparking (aerated)
Required surface area (m²)	0	105	0
Energy consumption (kWh/PE.y)	79	6	51

There is clear a trade-off between energy consumption and surface area. Because a VSSF only needs electricity for the pumps, it uses much less energy. 78% of the energy demand in the Phytoparking is caused by the blowers. Phytoparking consumes less energy than SAF while nevertheless complying to legal requirements.

To treat the wastewater of 18071 guests on a campsite during 2 consecutive camping seasons, 1224kWh (€355) was used to treat black and grey water. The pump that facilitates the reuse of the treated wastewater requires only 23% (276kWh) of the treatment energy. As a reference, in Flanders consumes a family on average 3600 kWh per year.

4.5 Challenges and barriers

During this project we had to cope with a few challenges:

1. The project site is situated in the province of West-Flanders in Belgium. Throughout World War I, this area saw numerous battles. Because relics, trenches, and occasionally even bombs can be found in the soil, the entire area is considered to have archeological heritage. For this reason, it is prohibited to excavate the soil without doing an archaeological study. As this is a costly process, the Phytoparking was constructed in an existing shed as the archaeological research primarily looks at the area outside buildings. Since grass cannot grow without rain or sunlight, gravel was used to fill the grid in top the of the Phytoparking.
2. The pilot site is situated on a former farm where the manure cellars were transformed into septic tanks. As the black and grey water are treated separately in this project, two septic tanks and two pump wells needed to be constructed. Making the existing cellars waterproof and resizing them in the proper tanks required a great deal of work and time. The barrier separating the grey and black water tanks had various issues during the first year.
3. Flemish law allows treated wastewater to be discharged into surface water but prohibits it from infiltrating in the soil. Standards for surface water are not as strict as those for groundwater. Because Phytoparking grey's effluent is reused for toilet flushing, less treated wastewater is produced overall. However, there is always an excess of treated wastewater that cannot be

reused and not be discharged into surface water as there is no ditch close to the property. According to a legislative change that occurred in October 2024, the owner can now infiltrate the excess of treated wastewater that he previously had to convey by trucks to a designated facility.

4. It was not always clear to Rietland what was happening on site with the Phytoparking as the owner of the campsite modified some settings without communicating this to us.

4.6 Main outcomes

The Phytoparking is performing well as a decentralized system. It meets the discharge requirements of the Flemish legislation. It removes TN in both Phytoparking grey and black waters for 70% or more. This is a good result as the concentration of nitrogen and carbon are different in both wastewaters. There were more OMP found in black water than in grey water. From the 8 OMP that were found in all samples, 7 compounds were removed on average 80% and 5 minimum 80%.

Phytoparking shows that NBS can remove pathogens, more specifically *E. Coli* with logs of 5.3 (grey) and 4 (black), total coliform logs of 3.6 (grey) and 2.2 (black), and somatic coliphage logs of 1.4 (grey) and 3.8 (black).

Dissemination was carried out throughout the project:

- 2 July 2021: Publication in *Aquarama*: Water sector journal in Flanders: Circular water use at the camp site ‘t Hof Bellewaerde.
- 12 September 2021: Open day to visit the project site: 54 visitors (8 civil society, 42 general public and 4 policy makers).
- 2 December 2021: Webinar for the broad audience (BE & NL): 93 participants (12 civil society, 24 customers, 19 industry, 20 policy makers, 12 academic, 6 others).
- Yearly trade fair visits to Aquarama (BE) and AquaNederland (NL) in 2021, 2022, 2023 and 2024, on average 50 visitors per year, per event.
- 7 November 2022: *IWA 17th International Conference on Wetland Systems for Pollution Control*: Academic audience
- 7 February 2023: Trade fair to create awareness in the touristic sector for water: 80 visitors.
- 20 June 2023: Trade fair on circulair water use in the construction sector: 120 visitors.
- 1 July 2023: Publication in *Aquarama*: Water sector journal in Flanders: Phytoparking as part of circular water use.
- 6-11 September 2023: *10th International Symposium on Wetland Pollutant Dynamics and Control*: Academic audience.
- 21 November 2023: Participated in the Multi Source Splash down Series, topic Pretreated wastewater, 20 participants.
- 1 March 2024: STOWA (NL) Webinar on Wetlands and similar systems: 150 participants.
- 7 May 2024: Participated in the Multi Source Splash down Series, topic Nitrogen removal: 13 participants.
- 26 September 2024: Open day: circular water use by means of Phytoparking: 50 visitors.
- 24-29 November 2024: *IWA 17th International Conference on Wetland Systems for Pollution Control*: Academic audience.

In preparation:

- Publication of a scientific article in spring 2025.
- Final event spring 2025.

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5 Pilot 4: Italy - IRIDRA – Hybrid treatment wetland treating combined sewer overflows

5.1 Pilot 4 description

The experimental case study is located in Merone, Italy (45° 46’N, 9° 14’E).

The centralized WWTP of Merone treats the wastewater from the combined sewer serving 38 towns in Como province (120,000 inhabitants). Combined sewer overflows (CSOs) upstream of the Merone WWTP occur frequently, sometimes lasting for several days even during dry weather after the rain event, due to the long concentration time of the sewer network.

The pilot 4 is an aerated wetland (AEW) fed by the CSO upstream the Merone WWTP (Figure 5.1, 5.2, 5.3), maximum influent flow rate of 900 m^3/h, resulting in a treated volume up 40000 m^3 per CSO event (up to 50 consecutive hours of a single CSO event were registered in the monitoring period 2022 – 2024). The plant is managed by the public water utility COMO ACQUA.

The overflow is pre-treated by an automatic screen and an aerated grit removal. The aerated beds are 4 in parallel with a total surface of 4000 m^2 and they are followed by a surface flow system of 1500 m^2 with naturalistic purposes. The technical specifications of the aerated stages are summarised in Table 5.1. The system is fed by a pumping system and automatically regulated by a PLC to properly aerate and treat the first more polluted fraction of the CSO events (see section 5.3). A regulation manhole permit to keep 70 cm of saturated layer from the bottom of the bed, in order to guarantee an efficient forced aeration. From 70 cm to 105 cm CSO are allowed to accumulate subsurface, while an additional surface storage from 105 to 180, with a freeboard height of 75 cm. The infiltration rate within the aerated beds is controlled by a throttle valve, sized to operate according to common guidelines (Q1-Q3 0.008 – 0.022 l d^{-1} m^{-2}, maximum value 0.035 l d^{-1} m^{-2}; Rizzo *et al.*, 2020) and providing sufficient residence times for effective pollutant removal. The aerated beds are planted with *Phragmites australis*. The average overflow design volume to be treated is about 550,000 m^3/y, spread over about 90 overflow events on average per year.

Figure 5.1 Demo 4 of Merone aerial view. Source: Google Earth.

This project has received funding from the European Union’s Horizon H2020 innovation action programme under grant agreement 101003527.

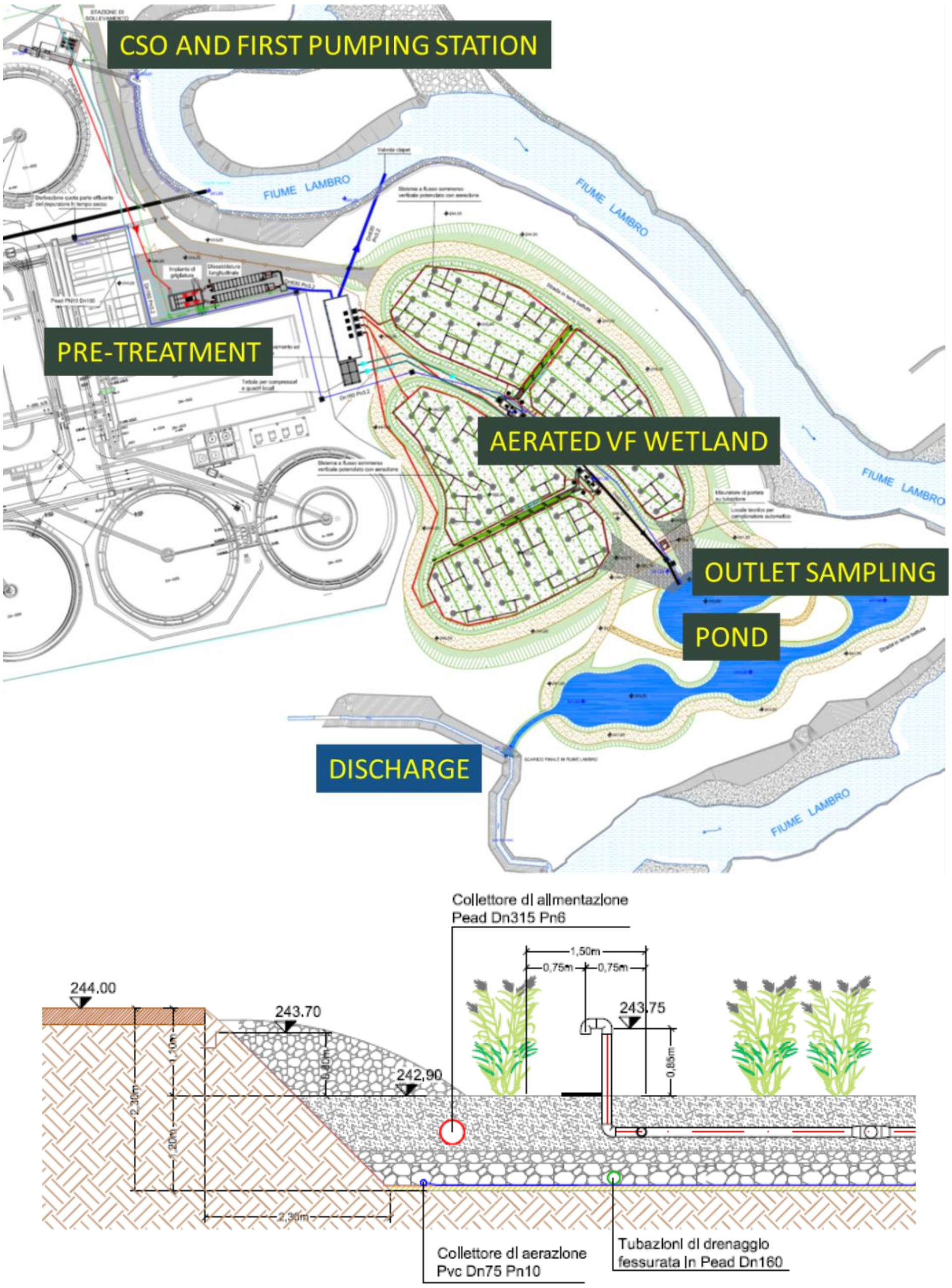

Figure 5.2 Technical drawings of Merone hybrid treatment wetland.

Figure 5.3 Picture of the Merone hybrid treatment wetland, aerated wetland (left) and polishing pond (right). Site visit: September 2023.

Table 5.1 Technical specifications of the 1st aerated wetland of Merone.

Aerated wetland	
n° of parallel line	4
Total surface area AEW	400 m^2
Surface area of each VF line	1000 m^2
Total height of the filter media	1.05 m
Saturated depth	0.7 m
Free board on the surface AEW	0.75 m
AEW filter media layers (from the bottom)	
• coarse gravel – Ø 16–32 mm	0.2 m
• gravel – Ø 8-16 mm	0.15 m
• Pea gravel – Ø 2–6 mm	0.7 m

5.2 Overview of the monitoring work

The monitoring of Pilot 4 had the R&D goals of:

- monitoring the performance of a full-scale intensified aerated wetland for CSO treatment in terms of conventional and emerging pollutant removal;
- investigating the possibility to optimize, in terms of energy consumption, the forced aeration system through conventional monitoring and/or online COD sensors;
- monitoring some of the co-benefits of the nature-based solution.

The construction of Pilot 4 ended before the starting of the MULTISOURCE project and the system started operating in July 2021; first CSO events were used to evidence that the system was working properly, in order to start the monitoring plan.

The **monitoring** lasted from June 2022 to August 2024, including:

- A standard set of wastewater parameters monitored for significant CSO events during the monitoring period: COD, BOD_5, TSS, TN, N-NH_4^+, N-NO_2^-, N-NO_3^-, TP, pH, and heavy metals (As, Cd, Cr, Fe, Mn, Ni, Pb, Cu, Se, Zn, Al, B). IN and OUT samples were collected by two automatic samplers, one at the inlet, the second at the outlet of the aerated wetland, before the discharge in surface flow wetland. Samples were analysed at the chemistry lab of the WWTP of Merone by COMO ACQUA.
- Contaminants of emerging concern (CEC's)/Priority pollutants and microplastics according to sampling and shipping instructions given by Aarhus University and NIVA, respectively.
- Pathogens (Total Coliforms, *E. Coli*, *Enterococci*, *Spores of sulfite-reducing clostridia*, *Salmonella*, *Rotavirus*, *Adenovirus*, *Entevirus*), in support to the work of University of Santa Catarina, analysed by external certified laboratories.
- Two COD online sensors (i::scan V1, minimum time step 10 minute) were placed at the inlet and the outlet of the treatment wetland.
- Data registered by the PLC system of the wastewater treatment plant of Merone (time step every 2 hour), including influent and effluent flow meters, water level sensors within the four beds of the aerated wetlands, power consumption.

Additionally, **co-benefits** were monitored as follow:

- ○ Biodiversity: species richness, Shannon index, and Simpson index for bird habitat in collaboration with University Roma Tre, under the Master thesis of Matteo Guidotti, supervised by prof. Leonardo Vignoli (University Roma Tre), and Dr. Eng. Anacleto Rizzo and Biologist Giulio Conte for IRIDRA as a MULTISOURCE activity.
- ○ Educational value: indicators (number of participants, gender balance, category) from the site visits at the wastewater treatment plant of Merone, extract from the data registered by COMO ACQUA Srl.

- Cost saving: by extrapolating data from the PLC of the wastewater treatment plant for 2023 (treated CSO volume, cumulative energy consumption), cost saving was calculated comparing real CAPEX and OPEX of the aerated treatment wetland with the expected cost of an equivalent grey infrastructure, i.e. a concrete underground detention tank and the expected energy consumption for pumping and treating at the WWTP during dry period.

The dataset collected is summarized in Table 5.2.

Table 5.2 Monitoring overview for Pilot 4: Italy - IRIDRA – Hybrid treatment wetland treating CSO.

Endpoint	Sensor or samples	Sampling point	Monitoring period	Sampling frequency	Number of data points available[1]
Flow	Sensor	Influent, Effluent	June 2022- – August 2024	Every 2 hours (PLC data)	>8000 influents and effluents each (including 0, i.e. dry periods)
Power	Sensor		June 2022- – August 2024	Every 2 hours (PLC data)	>8000 influents and effluents each (including 0, i.e. dry periods)
Water level	Sensor	4 hydraulic sectors of the wetland	June 2022- – August 2024	Every 2 hours (PLC data)	>8000 influents and effluents each (including 0, i.e. dry periods)
Temperature	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	43 influents 41 effluents
pH	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	44 influents 42 effluents
Conductivity	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	43 influents 41 effluents
TSS	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	44 influents 42 effluents
BOD_5	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	38 influents 35 effluents
COD	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	44 influents 42 effluents
COD, Temperature	Sensor	Influent, Effluent	December 2023 – July 2024	Continuous	>65000 influents and

Endpoint	Sensor or samples	Sampling point	Monitoring period	Sampling frequency	Number of data points available[1]
					effluents each (including dry periods)
NH4-N	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	43 influents 41 effluents
NO2-N	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	41 influents 40 effluents
NO3-N	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	42 influents 41 effluents
TN	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	44 influents 42 effluents
TP	Composite samples[1]	Influent, Effluent	June 2022 – July 2024	Selection of significant CSO events	42 influents 40 effluents
As, Cd, Cr, Fe, Mn, Ni, Pb, Cu, Se, Zn, Al, B	Composite samples[1]	Influent, Effluent	June 2022 – June 2024	Selection of significant CSO events	34 influents 38 effluents
E.Coli	Composite samples[1]	Influent, Effluent	June 2022 – October 2023	Selection of significant CSO events	7 influents 10 effluents
Total Coliforms, *Enterococci*, *Spores of sulfite-reducing clostridia*, *Salmonella*	Composite samples[1]	Influent, Effluent	July 2023 – October 2023	Selection of significant CSO events	5 influents 5 effluents
Organic micropollutants	Grab samples	Influent, Effluent	October 2022 to July 2024	Selection of significant CSO events	17 influents, 17 effluents
Microplastic	Grab samples	Influent, Effluent	August 2023 to December 2023	Selection of significant CSO events	3 influents, 3 effluents
Educational visits	-	Overall WWTP+Merone NBS	May 2023 to May 2024	According to received request of visiting the WWTP > 100 visitors	6 visits with diverse participation types (students, private companies, associations)
Biodiversity	-	A square 300x300 metres containing the NBS (wetland)	November 2023	The sampling took place for 5 days, at different time of the day	1

Endpoint	Sensor or samples	Sampling point	Monitoring period	Sampling frequency	Number of data points available[1]
Cost Saving	Reconstructed from result of sensor (Treated CSO volume, Energy consumption) and parametric CAPEX and OPEX of equivalent grey infrastructure	-	2023	Yearly estimation	>4000 influents and effluents volume, cumulative energy consumpion (including 0, i.e. dry periods)

1 Except for outflow samples from June 2022 to December 2022.

5.3 Main technical results

Overall treatment performance

Overall treatment performance of the aerated treatment wetland of Merone are reported in the next tables, from which it can be highlighted that:

- The system performed according to the design expectation for organic and suspended solids removal, with COD 85.3%, BOD_5 89.0%, and TSS: 95.6% considering median value (Table 5.3).
- Oxygen supply by forced aeration was enough for a satisfactory nitrification of 66.6% on median value (Table 5.3), which was not targeted in the design phase; overall, partial denitrification was also developed in the system during no aeration phase (see section 5.3), leading to a removal of 31.9% for TN on median value; as expected and in line with literature expectation (Dotro *et al.*, 2017), TP removal was limited to a 20.9% on median value.
- A general good heavy metal removal was also registered (Table 5.4), on average around 70-90% for the majority of the metals (Cadmium 72.8%, Chromium 61.4%, Iron 78.4%, Copper 80.8%, Zink 83.6%, Aluminium 94.2%, on average values) with minor removal in the order of 10-30% for some specific metals (Manganese 29.9%, Nickel 19.4%, Selenium 36.5%, Boron 9.1%).
- Satisfactory pathogen removal was also observed (Table 5.5), setting around 0.5-2 log (Total Coliform 1.23 log, *Escherichia Coli* 0.75 log, *Enterococci* 2.16 log, Spores of sulphite-reducing clostridia 0.60 log on median values) but, as expected, with an abundance in the effluent still too high for an eventual reuse of the effluent without any post-treatment for any class of reuse set by the EU Reg. 2020/741; in terms of other pathogens, no traces of *Salmonella* (3 samples), *Rotavirus*, *Adenovirus* and *Enterovirus* (1 sample, yes or no presence) were observed.
- A general good microplastic removal was also monitored, on average around 70-90% for almost all the analysed compounds (Poly(methyl methacrylate) (PMMA) (>5µm) 93.8%, Nylon-66 (N66) (>5µm) 89.0%, Polypropylene (PP) (>5µm) 76.3%, Polyvinyl chloride (PVC) (>5µm) 87.6%, Nylon-6 (N6) (>5µm) 90.6%, Polycarbonate (PC) (>5µm) 76.9%, SBR Styrene butadiene rubber (SB) 95.5%, Polyethylene (PE) (>5µm) 79.2%, Acrylonitrile butadiene styrene (ABS) (>5µm) 94.1%, Polystyrene (PS) (>5µm) 78.5% on average values) with the only exception of Polyethylene terephthalate (PET) (>5µm) (14.7% and 20.4% on average and median value); if considering median value, the results are essentially confirmed for all the compounds except for the Polyethylene (PE) (>5µm) showing a negative removal of -21.7%, which evidences the presence of the major peak in the influent of October 2023 of 24.6 µg/L (Table 5.6).
- Trends in removal efficiencies for emerging organic pollutants results more fragmented. A group of compounds shown high mean removal efficiencies >90% (Ciprofloxacin, Trimethoprim, Mycophenolic acid, Citalopram), while good mean removal in the range of 50 – 80% was observed for a second series of compounds (Caffeine, Benzoylecgonine, Rosuvastatin, Amoxicillin). On the

other hand, some compounds shown medium (30 – 50% on average: Atenolol, Losartan, Valsartan, DEET) to low removal (10 – 30% on average: Benzotriazole, Gemfibrozil, Fexofenadine). Finally, some compound did not evidence any removal in the aerated wetland (Venlafaxine, Gabapentin, Diclofenac, Cetirizine, Irbesartan, Carbamazepine, Lidocaine, 4-Methyl-1H-benzotriazole).

Table 5.3 Conventional physicochemical parameters analysed by COMO ACQUA at the influent and effluent of the aerated treatment wetland of Merone. Monitoring period: June 2022 – July 2024.

	pH		Temperature		Conductivity		TSS		BOD_5		COD	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	[-]	[-]	[°C]	[°C]	[µS/cm]	[µS/cm]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]
Mean	7.4	7.6	13.9	15.1	535.9	581.2	197.0	9.2	90.8	8.6	286.7	32.0
Std dev	0.2	0.3	3.1	3.9	141.9	112.2	256.5	9.4	80.4	7.7	260.0	14.7
Min	6.9	7.08	9.7	8.3	286.0	360	16.6	2	9	0	45.0	12
Q1	7.3	7.4	11.7	12	456.5	501	67.8	4	51	3.5	106.3	22
Median	7.5	7.49	12.6	14.9	551.0	552	113.5	5	73	8	201.0	29.5
Q3	7.6	7.74	15.8	18.2	615.5	681	203.5	13	91	12.5	366.8	39.7
Max	7.8	8.15	21.0	22.5	901.0	800	1530.0	56	460	32	1095.0	86
n°	44	42	43	41	43	41	44	42	38	35	44	42

	$N\text{-}NH_4^+$		$N\text{-}NO_2^-$		$N\text{-}NO_3^-$		TN		TP	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]
Mean	7.0	2.3	0.3	0.2	1.4	6.2	15.2	9.8	1.9	1.3
Std dev	3.4	1.3	0.3	0.2	0.9	4.2	8.7	4.5	1.3	0.6
Min	0.94	0.12	0	0.02	0.15	0.94	4.23	3.88	0.35	0.51
Q1	4.49	1.52	0.1	0.1075	0.7075	3.91	8.555	6.7	1.03	0.9775
Median	6.4	2.14	0.17	0.185	1.245	4.79	12.9	8.78	1.51	1.195
Q3	9.46	3.16	0.34	0.29	1.915	7.7	17.8775	11.6975	2.3825	1.61
Max	14.94	4.77	1.74	0.89	3.72	22.15	44.34	25.73	5.61	3.61
n°	43	41	41	40	42	41	44	42	42	40

Table 5.4 Heavy metal parameters analysed by COMO ACQUA at the influent and effluent of the aerated treatment wetland of Merone. Monitoring period: June 2022 – July 2024.

	As		Cd		Cr		Fe		Mn	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]
Mean	0.003	0.003	0.003	0.001	0.013	0.005	0.692	0.150	0.127	0.089
Std dev	0.003	0.003	0.006	0.001	0.022	0.019	0.614	0.201	0.425	0.283
Min	0	0	0	0	0	0	0.053	0	0.018	0.003
Q1	0	0	0	0	0.00225	0	0.2705	0.04375	0.03	0.00925
Median	0.0015	0.002	0.001	0	0.0065	0	0.643	0.0885	0.0455	0.017
Q3	0.006	0.00575	0.00175	0.001	0.013	0.001	0.88125	0.1215	0.0695	0.027
Max	0.01	0.01	0.025	0.008	0.11	0.09	3.283	0.86	2.52	1.65
n°	34	38	34	38	34	38	34	38	34	38

	Ni		Pb		Cu		Se		Zn	
	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]
Mean	0.014	0.011	0.013	0.002	0.056	0.011	0.014	0.009	0.138	0.023
Std dev	0.008	0.006	0.011	0.003	0.034	0.007	0.014	0.010	0.096	0.022
Min	0	0	0	0	0.006	0.003	0	0	0.018	0
Q1	0.01	0.009	0.0045	0	0.03	0.006	0	0	0.05425	0.011
Median	0.012	0.011	0.01	0	0.0515	0.009	0.0115	0.005	0.119	0.0195
Q3	0.0195	0.015	0.018	0.003	0.07825	0.013	0.02275	0.01475	0.1915	0.028
Max	0.035	0.022	0.045	0.01	0.128	0.03	0.053	0.032	0.362	0.12
n°	34	38	34	38	34	38	34	38	34	38

	Al		B	
	IN	OUT	IN	OUT
	[mg/L]	[mg/L]	[mg/L]	[mg/L]
Mean	0.639	0.037	0.639	0.037
Std dev	0.451	0.049	0.451	0.049
Min	0.045	0.002	0.045	0.002
Q1	0.21	0.01025	0.21	0.010
Median	0.572	0.023	0.572	0.023
Q3	0.882	0.039	0.882	0.039

Max	1.858	0.23	1.858	0.23
n°	34	38	34	38

Table 5.5 Pathogens analysed by an external certified lab (iLab) at the influent and effluent of the aerated treatment wetland of Merone (Monitoring period: June 2023 – October 2024), plus few effluent *E. Coli* samples done by COMO ACQUA (Monitoring period: June 2022 – April 2023).

	Total coliform		Escherichia Coli		Enterococci		Spores of sulfite-reducing clostridia		Salmonella	
	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]
Mean	9.94E+05	6.80E+05	3.61E+06	5.40E+05	4.92E+05	2.54E+04	7.35E+04	1.41E+04	0.00E+00	0.00E+00
Std dev	1.15E+06	1.11E+06	7.53E+06	9.64E+05	1.41E+05	3.08E+04	5.20E+04	1.32E+04	0.00E+00	0.00E+00
Min	3.80E+04	3.50E+04	4.60E+03	1.80E+04	3.70E+05	2.90E+03	3.30E+03	4.80E+02	0.00E+00	0.00E+00
Q1	5.90E+05	3.70E+04	4.00E+05	1.90E+04	4.10E+05	3.00E+03	6.70E+04	1.00E+04	0.00E+00	0.00E+00
Median	6.50E+05	3.80E+04	4.60E+05	8.10E+04	4.50E+05	3.10E+03	7.20E+04	1.10E+04	0.00E+00	0.00E+00
Q3	6.90E+05	6.90E+05	1.71E+06	3.32E+05	5.00E+05	5.50E+04	7.50E+04	1.30E+04	0.00E+00	0.00E+00
Max	3.00E+06	2.60E+06	2.06E+07	2.94E+06	7.30E+05	6.30E+04	1.50E+05	3.60E+04	0.00E+00	0.00E+00
n°	5	5	7	9	5	5	5	5	3	3

Table 5.6 Microplastics analysed by NIVA at the influent and effluent of the aerated treatment wetland of Merone. Monitoring period: August 2023 – December 2023.

	Poly(methyl methacrylate) (PMMA) (>5µm)		Nylon-66 (N66) (>5µm)		Polypopylene (PP) (>5µm)		Polyvinyl chloride (PVC) (>5µm)		Nylon-6 (N6) (>5µm)	
	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]
Mean	0.269	0.017	3.667	0.402	3.041	0.722	13.108	1.628	0.856	0.080
Std dev	0.084	0.010	1.675	0.189	2.962	0.169	5.571	1.191	0.588	0.064
Min	0.172	0.010	1.783	0.184	1.162	0.613	7.170	0.491	0.216	0.020
Q1	0.242	0.011	3.007	0.341	1.334	0.624	10.552	1.008	0.598	0.046
Median	0.312	0.012	4.232	0.498	1.506	0.636	13.933	1.525	0.980	0.072
Q3	0.317	0.020	4.609	0.510	3.981	0.776	16.077	2.196	1.176	0.110
Max	0.322	0.028	4.987	0.523	6.455	0.916	18.221	2.866	1.373	0.148
n°	3	3	3	3	3	3	3	3	3	3

	Polycarbonate (PC) (>5µm)		SBR Styrene butadiene rubber (SB)		Polyethylene terephtalate (PET) (>5µm)		Polyethylene (PE) (>5µm)	
	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]
Mean	0.211	0.049	4.525	0.205	0.209	0.179	8.876	1.848
Std dev	0.117	0.054	2.877	0.129	0.056	0.044	13.617	1.357
Min	0.086	0.010	1.889	0.088	0.159	0.148	0.200	0.333
Q1	0.157	0.018	2.991	0.136	0.180	0.153	1.029	1.297
Median	0.228	0.026	4.092	0.184	0.200	0.159	1.858	2.262
Q3	0.273	0.068	5.843	0.263	0.235	0.194	13.214	2.606
Max	0.318	0.110	7.595	0.342	0.269	0.229	24.570	2.950
n°	3	3	3	3	3	3	3	3

	Acrylonitrile butadiene styrene (ABS) (>5µm)		Polystyrene (PS) (>5µm)	
	IN [mg/L]	OUT [mg/L]	IN [mg/L]	OUT [mg/L]
Mean	0.553	0.033	1.003	0.215
Std dev	0.293	0.028	0.371	0.254
Min	0.223	0.010	0.647	0.031
Q1	0.440	0.017	0.811	0.071
Median	0.657	0.024	0.975	0.110
Q3	0.719	0.044	1.181	0.307
Max	0.780	0.065	1.387	0.504
n°	3	3	3	3

Aeration optimization plan

The main scope for the optimization of the Merone plant is to minimize the forced air in the system, keeping stable the treatment performance in terms of COD, BOD_5, and nitrification ($N\text{-}NH_4^+$). The installed blower has the following specifications: air flow 1200 – 2500 m^3/h, frequency 25 – 50 Hz, pressure 100 – 350 mbar.

The monitoring of aerated wetland in Merone started in June 2022. After a start-up phase, where the system was feed with lower CSO volumes and was aerated with less air, the system was started to be monitored at full capacity since September 2022. From September 2022 to May 2023 a first aeration plan (**Aeration plan 1**) was tested, as follow:

- Blower: 90% of maximum capacity (45 Hz), estimated air flow 2275 m^3/h;
- Aeration time: CSO feeding time plus 5 hours after the end of the CSO event.

During the Aeration plan 1 the system performed in line with the design values in terms of COD, BOD_5 and $N\text{-}NH_4^+$ removals (84.9%, 85.5%, and 70.1%, respectively on median values).

Due to the good results of Aeration plan 1, it was decided to start the optimization plan for energy saving and increasing of the aeration efficiency. From May 2023 to August 2023, a second aeration plan (**Aeration plan 2**) was tested, reducing both air flow rate and the duration of aeration, as follow:

- Blower: 50% of maximum capacity (25 Hz), estimated air flow 1156 m^3/h;
- Aeration time: CSO feeding time plus 1 hours after the end of the CSO event.

During the Aeration plan 2 the system kept similar performance in comparison to Aeration plan 1 for COD, BOD_5 and $N\text{-}NH_4^+$ removals (84.6%, 86.2%, and 62.6%, respectively on median values), demonstrating the possibility of reducing the oxygen input and decreasing the energy consumption of aerated wetlands for CSO, without compromising the removal efficiencies.

Despite the good results, it was decided to set a more conservative **Aeration plan 3** from September 2023 for the next monitoring phase, in agreement with the Water Utility. In particular, it was increased the frequency of the blower (i.e. the air flow) in order to conservatory guarantee an efficient treatment during autumnal rainy seasons. In summary, the Aeration plan 3 was:

- Blower: 90% of maximum capacity (45 Hz), air flow 2273 m^3/h;
- Aeration time: CSO feeding time plus 1 hours after the end of the CSO event.

Even during the Aeration plan 3 the system kept similar performance in comparison to Aeration plan 1 and 2 for COD, BOD_5 and $N\text{-}NH_4^+$ removals (83.5%, 93.8%, and 66.1%, respectively on median values), confirming the flexibility of aeration system in delivering efficient removal performance.

Nitrite effluent concentration results equal to 0.19 mg/L, 0.42 mg/L, and 0.16 mg/L on median values during aeration plans 1, 2, and 3 respectively. The increase during the period of Aeration plan 2 suggests that the most conservative proposal of Aeration Plan 3 is the preferred one, permitting an efficient biological degradation of organic pollutants and more stable nitrification, limiting nitrite formation and, probable, N_2O emission.

On average, Aeration plan 3 saved 6.5 hour of aeration per CSO event; considering an average of 40 CSO events per year, it could bring a saving of about 13000 kWh/y, i.e. about 3900 €/y.

Role of COD online sensors

COD sensors for measuring influent and effluent concentrations from the aerated wetlands were installed, aiming to investigate the possible use for guiding an aeration optimization.

The COD sensors were operated according to an operational and maintenance plan that aligns with a realistic working load for the Water Utility COMO ACQUA, resulting in the following O&M activities during the functioning period (6 months):

- three manual calibrations (on average, one calibration every 2 months);
- self-cleaning of the sensor with compressed air every 15 minutes;
- one manual cleaning with hydrochloric acid.

Analyses were done considering the **CSO event** defined by including both CSO influent pumping time and the effluent tail for emptying the beds, see Figure 5.4.

Despite the O&M activities, the accuracy of COD measures during CSO events were poor, with a median error, if compared to composite samples, of 105% and 136% for influent and effluent concentrations, respectively. The inaccuracy is mainly driven by the incapability of sensors to measure significantly lower or higher concentrations in comparison to the calibrated values.

If the accuracy for monitoring the treatment performance was not satisfactory, the use of monitored signal could still have potentiality in terms of aeration efficiency, as visible from Figure 5.4:

- The signal for the **effluent COD concentration** is stable, highlighting an efficient performance; if a sharp peak was present, effluent COD sensor could have behaved as a signal of insufficient aeration, permitting to change aeration strategy.
- Contrarily, the **COD influent sensor** shows evident spikes at the beginning of CSO event after a significant dry period (see one of the examples in Figure 5.4), which can be interpreted as a signal of first flush pollutograph or first more polluted fraction of CSO event upstream a centralized WWTP, as discussed in Masi *et al*. (2023); therefore, it can be proposed a use of influent COD sensor as a proxy to guide an optimized aeration, for which we propose two options:
  - Option 1 would propose to train an artificial intelligence tool able to predict the median concentration of the running CSO event; in this case, if we define the spike as a concentration higher than +30% the median COD concentration of the running CSO event, only 165 hours out of a total of 2066 hours of CSO events during the monitoring period (6 months) would have experience a high spike concentrations, in other words, only 8% of the hours of CSO events would have required a maximum aeration.
  - Option 2 would propose a simplified approach, based on the definition of a fixed median value for all the CSO events (248.9 mg/L of COD during the monitoring period of six months); in this case, only 205 hours out of a total of 2066 hours of CSO events during the monitoring period (6 months) would have experience a high spike concentrations, in other words, only 10% of the hours of CSO events would have required a maximum aeration with a very simplified optimization scheme.

If automatic aeration reduction of 50% (operating the blower at 25 Hz) on 90% of the aeration time was adopted, the aeration consumption would have been 57,000.00 kWh/y during the observation period, with a potential saving of 43,000.00 kWh/y (43% less) and a potential operational cost saving of about 6.500 €/y.

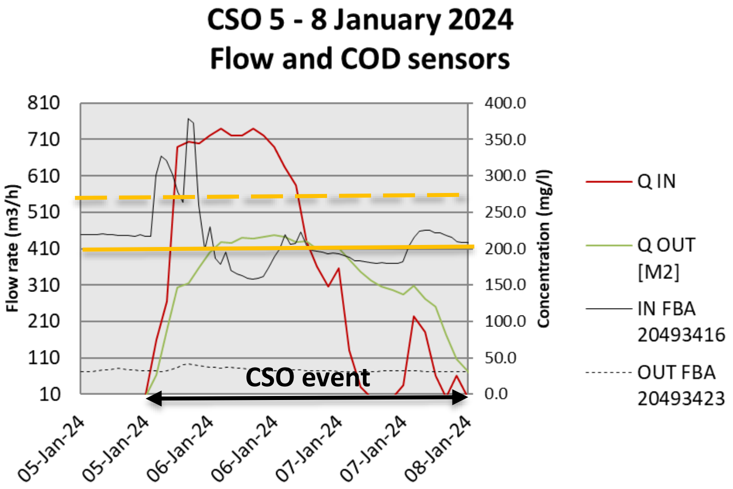

Figure 5.4 Example of the level on information available from the SCADA system of the wastewater treatment plant (influent and effluent flow rate in red and green, respectively; time frame 2 hours) and COD online sensors (concentration in and out, continuous and dashed line, respectively; hourly average from the minimum time step of 10 minutes) for the CSO event between 5th to 8th January 2024. Dry period antecedent the CSO event, 3.6 days. Median value of the CSO event, yellow continuous line; +30% of median event (qualitatively graphical representation), dashed yellow line.

5.4 Main co-benefits results

Cost saving

The cost saving was calculated comparing the CAPEX and OPEX of the aerated wetland of Merone with an hypothetic alternative grey infrastructure, i.e. a first flush tank upstream the WWTP of Merone. The methodology is the same used for the benefit evaluation of the Gorla Maggiore Water Park by Liquete *et al*. (2016). The following assumption were taken:

- The 2023 was taken as a reference year for the comparison, due the complete dataset available for entire year.
- The alternative grey infrastructure was preliminary sized with a retention volume equal the one given by the aerated wetland (about 3300 m^3, considering both surface and subsurface retention volume) plus maximum 10 hour of continuous effluent during the CSO event (median throttled effluent rate about 240 m^3/h), for a total tank volume of 5500 m^3.
- The hypothetic tank is assumed to be equipped with a pumping system able to empty the tank volume in 24 hours, i.e. with a pump of about 65 l/s (230 m^3/h, 10 kW), that starts any time the tank is not receiving an inflow from CSO.

The **construction cost (CAPEX) of the Aerated wetland** for the CSO treatment in Merone was € 1,500,000.00 in 2018 including all the equipment, that actualized at a rate of 2% per year at 2023 would result equal to **€ 1,689,244.63**.

The **operational cost (OPEX) of the aerated wetland** was estimated during design phase in 2018 equal to 37000 €/y. Considering the actualization at a rate of 2% per year at 2023, we obtain around **42000 €/year**. This theoretical estimation includes all the ordinary and extraordinary maintenance required by the system, the harvesting of the reeds and the energy consumption, and can be considered purely theoretical and conservative. Indeed, the total energy consumption in 2023 resulted equal to 64000 kWh/y from the monitoring data that, considering a cost for energy of 0.2 €/kWh, would result in only 13000 €/year. Therefore, the actual OPEX could have been even lower considering the really occurred additional maintenance, reed harvesting, etc. in 2023.

The **CAPEX of alternative grey infrastructure** was calculated using the parametric cost for underground tank given by the Regulation of Lombardia Region 07/2017, equal to 800 €/m^3, plus reconstructing the construction costs of minimum required components as pipes, control panel etc., as detailed in the next table. The total CAPEX for the grey alternative results equal to about **4,800,000.00 €**, i.e. almost 3 times higher than the cost of the aerated wetland.

Construction cost (CAPEX) grey alternative	
Tank cost including cleaning equipment	4,400,000.00 €
Pumps	40,000.00 €
control panel, cabling and electrical connection	15,000.00 €
pipeline for WWTP connection	60,000.00 €
Complementary works	225,750.00 €
Safety works	118,518.75 €
CAPEX total	**4,859,268.75 €**

The **OPEX of the alternative grey infrastructure** was calculated simulating the functioning of the designed first flush tank, based on monitored data for 2023 from the SCADA system with a time span of 2 hours. The alternative tank would have captured only a CSO volume of 207,000 m^3/y (against the 402,000 m^3/y of the aerated wetland), with an overall pumping time for emptying the tank of 906 h/y and an overall energy consumption of 9059 kWh/y. The OPEX were detailed considering the treatment cost of CSO volume at the WWTP of Merone (0.34 €/m^3) and other operational and maintenance activities, as detailed in the next table.

Operational cost (OPEX) grey alternative	
treatment cost	70,128.41 €
Energy cost for pumping	1,811.81 €
Civil work maintenance costs	22,000.00 €
Electromechanical maintenance costs	2,100.00 €
OPEX total	**96,040.22 €**

Due to the different intercepted volume, the cost saving for OPEX must be dimensionless in terms of €/m^3 of intercepted and treated CSO volume, as summarized in the next table, showing how the aerated wetland is expected to guarantee operational and maintenance cost 4-5 lower than equivalent grey solution.

	Green infrastructure – NbS Aerated wetland	**Grey instrastructure Tank**
Intercepted volume in 2023 (m3/y)	402,642.52	207,603.33
OPEX in 2023 (€/y)	41,668.00	96,040.22
OPEX per cubic meter CSO (€/m3)	**0.10**	**0.46**

Biodiversity

The biodiversity was monitored choosing birds as a proxy, thanks to the collaboration with the University Roma Tre, with which IRIDRA followed and sustained the activities of the ornithologist Matteo Guidotti for his Master Thesis, under the scientific supervision of Prof. Leonardo Vignoli.

Merone aerated wetland was monitored together with a seminatural wetland in the nearby area using the same sampling method. Considering the small size of the wetlands, sampling took place within 300-meter-square plots that include both the wetland area and the surrounding landscape. Bird counts were conducted using point counts, where all observed or heard individuals were counted from a fixed position for five minutes. Beside every wetland, a control site without the wetland habitat has been monitored. Two monitoring campaigns took place in November 2023 and May 2024. The two monitoring campaigns produced a quantitative bird species list (number of species and of individuals for each species) for each wetland (treatment or seminatural) and control site. Bird biodiversity was evaluated through Hill numbers: unified family of diversity indices that incorporate relative abundance and species richness commonly used in ecological research. Three biodiversity indices were used: Species richness (SR), Shannon index, and Simpson index.

The indexes between aerated wetland of Merone and seminatural wetlands did not show statistically significant difference, suggesting that artificial wetland could behave as habitat for bird species with the same value of seminatural ones. Observing the trend of the indexes, the following indications can be also extrapolated:

- In autumn the diversity of the ornithic community in aerated wetland is comparable to the ones of seminatural wetlands, while in springtime the indices show slightly lower values.
- Generalists species, however, are dominant in both kind of wetlands with only a few aquatic species (biodiversity indices of control areas without wetland show similar values).
- Even though small wetlands – including aerated wetland – can support biodiversity, to surrogate habitat for birds, larger artificial wetlands are most likely needed (more than 10.000 m^2 of reed beds or free water systems).
- Analysis of different taxonomic groups, such as insects or amphibians, are suggested to be assessed for a more complete analyses on the possible contribution of small artificial wetlands to biodiversity.

Educational value

The educational value of the aerated wetland was monitored using, as a proxy, the participants to visits occurred at the WWTP of Merone within one year of the monitoring period (May 2023 – May 2024). Visits were to the overall WWTP, that always include also the presentation and visit to the aerated wetland for CSO treatment. The signed visit documents were revised, extracting data, affiliation, category, and gender. Six visits were registered in the monitoring period (excluding the MULTISOURCE project meeting) for a total of 103 visitors, with majority of students (59.2%) accompanied by professors (3.9%), followed by associations (31.1%) and private companies (5.8%), with a slightly gender unbalance (55.3% men, 44.7% female).

5.5 Challenges and barriers

The main challenge in monitoring a full-scale system like the one in Merone was coordinating activities with the local water utility, COMO ACQUA. Although their support and interest were consistent, COMO ACQUA was not a direct project partner, and an official collaboration agreement with the MULTISOURCE project was established between IRIDRA and COMO ACQUA at the project's outset.

A key difficulty was balancing the research requirements with the realistic demands of the water utility, which operated a large wastewater treatment plant (WWTP) with a capacity of 120,000 PE on a daily basis. To facilitate this, IRIDRA conducted site visits approximately every 2–3 months during the project period, despite the 350 km distance, to oversee operations and arrange the shipment of samples to NIVA and Aarhus University.

One prominent example of the encountered challenges and barriers was the installation and maintenance of COD sensors. As discussed in Section 5.3, the process required a reasonable effort from the water utility. While the applied procedures did not achieve highly accurate COD monitoring for inflow and outflow, expecting more frequent manual calibration or additional effort was not feasible. Nevertheless, the experience with online COD sensors was valuable, demonstrating the type of information that could help optimize the performance of aerated wetlands within a reasonable time commitment for operators working under real-world conditions.

5.6 Main outcomes

Overall, the aerated wetland of Merone treated more than 400,000.00 m^3/y in the years 2023-2024, with an hydraulic loading rate (HLR) of 100 – 150 m/y and keeping stable high performance for the targeted design pollutants TSS, COD, BOD_5 and $N\text{-}NH_4^+$. Therefore, the aerated wetland of Merone is the first full scale system suggesting that forced aeration would permit to go beyond the general design indication for HLR of 40 – 60 m/y for passive wetland systems treating CSO (Rizzo *et al*. 2020), but even higher than the maximum HLR of 100 m/y proposed in Rizzo *et al*. (2020) for French CSO passive wetland and monitored for the Carimate full scale system by Masi *et al*. (2023). Such high loading rates should be verified with the continuation of the long term monitoring, before an eventual entrance in future design guidelines for wetland treating CSOs.

In terms of other pollutants of interest, heavy metals and microplastic were generally satisfactorily removed. The monitoring of organics of emerging concern should be compared with similar data from passive wetlands treating CSOs, to guess if the low removal of some compounds could have been negatively affected by the lower hydraulic retention time of aerated wetlands. Good pathogen removal was observed but, as expected, a tertiary disinfection step would have been required if the effluent wastewater was reused according to new EU Reg. 2020/741.

The different aeration optimizations tested during the monitoring period (aerations plans, COD sensors) suggest that there is still space to optimize the aeration supply in highly variable wetland, such as the one treating CSOs, in comparison to conventional design assumptions (see Nivala *et al*., 2020).

The results of the monitored pilot were presented in the following conferences (including publication in conference proceedings):

- Bresciani R., Sarti C., Rizzo A., Lasio F., Masi F. 2024. Aerated wetland for combined sewer overflow upstream the WWTP: results from 2 years of monitoring at Merone (IT), Oral, *18th IWA International Conference on Wetland Systems for Water Pollution Control*, ICWS 2024. 24 - 29 November. Martinique, France.
- Bresciani R., Sarti C., Rizzo A., Lasio F., Masi F.2023. First monitoring results of aerated wetland for combined sewer overflow upstream the WWTP of Merone (IT), Oral, *10th International WETPOL Symposium*, Bruges, Belgium, September 10-14 2023.

The following peer review papers are under preparation:

- Bresciani R., Sarti C., Rizzo A., Lasio F., Masi F. 2024. Aerated wetland for the treatment of combined sewer overflow upstream of centralized wastewater treatment plants: long-term monitoring from the full-scale system of Merone, Italy. *Possible journals: Science of the Total Environment, Ecological Engineering, Blue-Green Systems (Special Issue of ICWS2024)*
- Guidotti M, Battisti C., Conte G., Rizzo A., Vignoli L. 2025. Are Constructed Wetlands suitable surrogate habitats for birds? A study on avian biodiversity in Northen Italy. *Journal to be decided.*
- Sarti C., Kisielius, V., Bresciani R., Rizzo A., Masi F., Carvalho P.N. 2025. Aerated wetland for the treatment of combined sewer overflow upstream of centralized wastewater treatment plants: organic micropollutants in the full-scale system of Merone, Italy. *Journal to be decided.*

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6 Pilot 5: Spain - ICRA - WetWall treating greywater

6.1 Pilot 5 description

The WetWall or ICRA greenwall is a nature-based technology for greywater treatment and onsite reuse. It will be composed of three total sectors, comprising two modules each (vertical flow + horizontal flow) with a total vertical surface area of 11.4 m^2, which will be built for the treatment of greywater coming from the bathrooms and kitchen of the H2O building (ICRA). However, due to an externalised process of patentability study, its construction public tender was delayed. The construction of this system finally begun in August 2024 and finished in December 2024. The system is ready for tuning and hydraulic tests in January 2025, and therefore the WetWall should be operational from February 2025.

As a contingency measure and thanks to a collaboration with the Catalan Housing Agency (https://web.gencat.cat/ca/inici) and the Austrian company alchemia-nova, the functioning and treatment capabilities of a greenwall combined with ozonation located in Sant Quirze del Vallès (Barcelona, Spain) is under monitoring.

The greenwall system site in Sant Quirze del Vallès treats greywater and rainwater to be reused as service water for toilet flushing (Figure 6.1).

Figure 6.1 The Greenwall system site in Sant Quirze del Vallès. Photos taken on 04/04/2024 (left) and on 04/09/2024 (right).

Three apartments provide greywater from 3 showers and 2 handwash sinks in the respective bathrooms. The greywater and rainwater from 120 m^2 roof area are collected in a storage tank (Tank 1), from where the water is sent to the top of the Greenwall with a submerged pump. Based on the greywater production per day of the connected flats and the daily need for flushing, a daily hydraulic flow of ca. 100 L d^{-1} is set (maximum flow is theoretically up to 400 L d^{-1}). Water treatment in the 4 parallel lines results from the filtering effect in the substrate and from the metabolism of microorganisms in the root space of the plants. Contaminants present in shampoo, soap, detergents and other substances in the greywater are

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adsorbed and removed from the water with the actions of plants and microorganisms, being some valuable nutrients for the plants.

The planter box in each column were arranged to create an S-shaped path for water flow. Water enters from one end of the planter box, travels through the planter box, and exits through drainage holes, allowing it to reach the planter box below. This process continues from the first level to the next until the water reaches the bottom of the green wall.

The planter box's growing medium was a mix of relatively lightweight substrates characterised by high porosity and strong sorption capacity as expanded clay and perlite. A combination of Mediterranean climate-adapted plants was used (*Acorus gramineus*, *Campanula carpatica*, *Carex acutiformis*, *Carex comans*, *Euphorbia amygdaloides*, *Galium odoratum*, *Hedera helix*, *Heuchera*, *Mentha spicata var. crispa*, *Mentha spicata var. hispanica*, *Miscanthus sinensis*, *Muehlenbeckia axillaris*, *Myrtus communis*, *Ocimum basilicum*, *Origanum vulgare*, *Pachysandra terminalis*, *Salvia officinalis*, *Sedum*, *Sempervivum*, *Senecio cineraria* and *Thymus vulgaris*), planted in a random distribution.

The treated water is then collected and stored in a second tank (Tank 2) from where it is pumped through an ozonation unit to the connected toilets in the three apartments. The water which is stored in tank 2 is also recirculated through the ozonation unit for around 30 min. twice a day, in order to ozonate the water sufficiently. In case there is not enough treated water required for the toilet flushing, an emergency tap water inflow is guaranteed through a water level sensor in Tank 2, which opens the tap inflow in case the water level in Tank 2 is too low. Recently, an emergency connection for potable water to Tank 1 was established. This system activates an electro valve when the water level in Tank 1 does not provide an adequate supply for the greenwall. This measure was implemented to ensure the survival of the plants, in case residents of the connected apartments do not generate enough greywater (due to simultaneous absences) and there is a shortage of rain. Both tanks have overflows which jointly lead to the sewer, which is especially important for Tank 1 as it potentially receives peak loads during heavy rainfall events. In this way, the water can be safely used three times: for showering or hand washing, for irrigation of the plants in the greenwall and then for toilet flushing in three flats. Furthermore, a certain amount of water will evaporate through the plants, which has positive effects on the micro-climate and increases biodiversity.

6.2 Overview of the monitoring work

The overview of the monitoring work performed in the Sant Quirze del Vallès pilot for MULTISOURCE is summarized in Table 6.1.

Table 6.1 Monitoring overview for Pilot 5: Spain - ICRA - Greenwall treating greywater (St. Quirze del Vallès). Three sampling points: Influent (greywater), Effluent GW (greenwall treated water) and Effluent O_3 (ozonation treated water).

Endpoint	Sensor or samples	Sampling point	Monitoring period	Sampling frequency	Number of data points available[1]
pH	Grab samples	Influent, Effluent GW, Effluent O_3	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O_3
EC	Grab samples	Influent, Effluent GW, Effluent O_3	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O_3
TSS	Grab samples	Influent, Effluent GW, Effluent O_3	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O_3
COD	Grab samples	Influent, Effluent GW, Effluent O_3	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O_3

BOD	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
TOC	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
TN	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
N-NO$_2$	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
N-NO$_3$	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
P-PO$_4$	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
N-NH$_4$	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	36 Influent, 36 Effluent GW, 36 Effluent O$_3$
E. Coli	Grab samples	Influent, Effluent GW, Effluent O$_3$	March 2024 - June 2024	Monthly	11 Influent, 11 Effluent GW, 11 Effluent O$_3$
Total coliforms	Grab samples	Influent, Effluent GW, Effluent O$_3$	March 2024 - June 2024	Monthly	11 Influent, 11 Effluent GW, 11 Effluent O$_3$
Organic micropollutants	Grab samples	Influent, Effluent GW, Effluent O$_3$	May 2023 - June 2024	Monthly	33 Influent, 33 Effluent GW, 33 Effluent O$_3$
Microplastics	Grab samples	Influent, Effluent GW	16/11/2023	Punctual	1 Influent, 1 Effluent GW

[1]until June 2024.

6.3 Main technical results

The average water quality data for conventional physicochemical and microbiological parameters from May 2023 to June 2024 are shown in Table 6.2, while the results of organic micropollutants analysis are shown in Table 6.3. A total of 64 organic micropollutants were analysed and only eleven compounds were detected. Finally, the results of the microplastic analysis are shown in Table 6.4.

The combination of the GW and O$_3$ treatment provided significant removal of organic pollutants (COD, BOD, TOC), suspended solids (TSS), and moderate reductions in nitrogen compounds. The GW proved most effective in removing solids and organic matter, while O$_3$ treatment further enhanced oxidation processes, particularly for COD and BOD. As shown in Table 6.5, the green wall effectively complies with the stringent limits established by European regulations (BOD < 10 mg/L and TSS < 10 mg/L) and Spanish regulations (*E. Coli* = 0 CFU/100 mL and TSS < 10 mg/L) for the reuse of treated water in toilet flushing systems.

The analysis of micropollutants (Table 6.3) across the three sampling points reveals notable trends in removal efficiencies. Overall, both treatment methods significantly reduced most pollutants compared to the influent. Compounds like Caffeine, Tramadol, Gemfibrozil, Sulfamethoxypyridazine and 4-Methyl-1H-benzotriazole were effectively removed, especially by the greenwall system, reaching below detection limits in same cases. Sotalol was not detected in the influent but appeared at trace levels post-treatment, possibly due to transformation or analytical sensitivity. A drastic reduction was also observed in DDAC-

C10, from over 16 µg/L to just 0.15 µg/L. Estrone, a hormone, remained relatively stable, indicating it is more resistant to both treatments. Lidocaine was detected at very low concentrations in all three sampling points, indicating that it is a stable compound that is resistant to degradation. In contrast, DEET concentrations increased after passing through the green wall, suggesting a potential leaching effect or an interaction within the green wall system or environment that could release DEET or its related compounds. In conclusion, ozonation generally outperformed the greenwall in reducing persistent pollutants, though both treatments proved effective for many contaminants.

A similar outcome was observed in the analysis of microplastic samples from Influent and Effluent GW. Effluent O_3 samples were not collected in this case, as the ozone system does not provide treatment for microplastics. Overall, the greenwall effectively captured and reduced the concentration of 9 out of 12 detected microplastics to below detectable limits and removed 50% to 98% of the remaining three microplastics: PP (C9'), PVC (Nap), and PET (BP).

Table 6.2 Conventional physicochemical and microbiological water quality parameters during thirteen months (May 2023 to June 2024) of the greenwall, three sampling points: Influent (greywater), Effluent GW (Greenwall treated water) and Effluent O_3 (ozonation treated water). Average and standard deviation.

	pH	**EC (mS/m)**	**TSS (mg/L)**	**COD (mg O_2/L)**	**BOD (mg O_2/L)**	**TOC (mg/L)**	**TN (mgN/L)**	**N-NO_2 (mgN/L)**	**N-NO_3 (mgN/L)**	**P-PO_4 (mgP/L)**	**N-NH_4 (mgN/L)**	***E. coli* (ufc/100 ml)**	**Total coliforms (ufc/100ml)**
Influent	6.9± 0.6	707.7± 183.7	28.4±9	131.7± 49.4	73.7± 24.8	39.3± 17.5	11.9±3.9	0.020± 0.084	0.005± 0.016	0.212± 0.525	7.385± 4.042	425±862	3.21E+08± 5.61E+08
Effluent GW	7.9± 0.3	680.9± 165.9	<2	<30	2.4±1.4	4.5±1.6	1.3±0.8	0.004± 0.006	0.884± 0.902	0.199± 0.348	0.005± 0.008	0	9.61E+03± 1.98E+04
Effluent O_3	8.0± 0.2	704.1± 150.1	<2	<30	2.6±2	3.2±0.9	1.5±0.9	0.005± 0.009	1.097± 0.885	0.156± 0.345	0.01± 0.04	0	5.99E+02± 9.90E+02

Table 6.3 Results of organic micropollutants analysis samples (May 2023 to June 2024) in the three sampling points: influent (greywater), effluent GW (greenwall treated water) and effluent O_3 (ozonation treated water). Only detected compounds are indicated with the average and standard deviation concentrations.

	Influent	**Effluent GW**	**Effluent O_3**
Lidocaine (µg/L)	0,005 ± 0,018	0,003 ± 0,013	0,003 ± 0,007
Caffeine (µg/L)	1,073 ± 0,606	0,069 ± 0,046	0,046 ± 0,086
Diethyltoluamide (DEET) (µg/L)	0,086 ± 0,069	1,242 ± 0,481	0,028 ± 0,016
Tramadol (µg/L)	0,06 ± 0,141	<LOD	0,009 ± 0,047
Benzotriazole (µg/L)	2,021 ± 4,712	0,018 ± 0,017	0,018 ± 0,026
4-Methyl-1H-benzotriazole (µg/L)	2,224 ± 2,566	<LOD	<LOD
Sotalol (µg/L)	<LOD	0,003 ± 0,008	0,001 ± 0,006
Gemfibrozil (µg/L)	0,002 ± 0,006	<LOD	<LOD
Sulfamethoxypyridazine (µg/L)	0,002 ± 0,002	<LOD	<LOD
DDAC-C10 (µg/L)	16,106 ± 29,763	0,15 ± 0	0,15 ± 0
Estrone (µg/L)	0,409 ± 0,193	0,45 ± 0,15	0,375 ± 0,216

Table 6.4 Results of microplastic analysis of the Greenwall at two sampling points (sampling date 16/11/2023): Influent and Effluent GW.

Sample	Unit	Sample Volume (L)	PMMA (MMA)	N66 (CP)	PP (C9')	PVC (Nap)	N6 (Capro)	PC (IPP)	SBR (SB)	PET (BP)	PE (C21'')	PU (MDA)	ABS (SAS)	PS (SSS)
Influent	µg/sample	5	<0.01	0.599	3.665	1.086	0.1272	<0.01	0.114	0.4	12.944	<0.2	0.054	0.69
Effluent GW	µg/sample	5	<0.01	<0.1	0.074	0.112	<0.02	<0.01	<0.1	0.2	<0.2	<0.2	<0.01	<0.01

6.4 Main co-benefits results

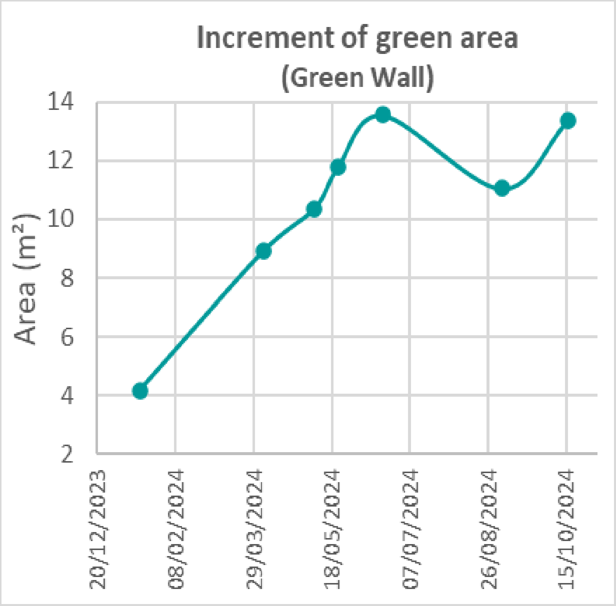
Four socio-economic and environmental co-benefits were identified, and the monitoring period is being carried out. The selected co-benefits are the following:

1. Increase stakeholder engagement.
2. Increment of green areas.
3. Enhance/preserve biodiversity.
4. Provide carbon storage/sequestration.

1. The increase in stakeholder engagement was assessed through a survey submitted to the residents of the building where the greenwall is installed. In December 2023, in the Sant Quirze del Vallès building, 28 out of a total of 30 apartments were occupied and 19 out of the 28 residents participated in the survey. Respondents were mostly long-term residents, aged between 31 and 50, with a significant number having a university education. Both male and female participants were represented (respectively 31.57% and 68.42%), providing a diverse perspective on the project. The survey was designed to gauge awareness, perceptions of benefits, and engagement levels among stakeholders. Most residents had a moderate awareness of local water consumption (84.21%) and the importance of treating used water (89.47%). While many recognized the region's water shortage, knowledge about the water's source and disposal varied, with some uncertainty among respondents. Residents generally understood that greenwall recycles greywater, and many believed it provided environmental benefits, such as reducing the water footprint and enhancing biodiversity. Most of them valued it as aesthetically positive (89,47%), and many of them thought it contributed to well-being (63.15%), although opinions on its health benefits were mixed. A significant number of respondents (78% of interviewed) were interested in being more involved in the greenwall project, with varying satisfaction levels. Engagement could be enhanced through better communication and participation opportunities. Knowledge of the greenwall's promoters and funders was limited, with only some residents (57.89%) aware of the Catalan Housing Agency's involvement. Many supported public funding for such initiatives (78.93%), seeing them as beneficial for sustainability and social well-being (68.41%). At the same time, the greenwall has achieved considerable success and generated widespread social interest, with workshops and guided visits organized for various groups, including students from the Engineering Master's Program at the University of Barcelona, representatives from the Housing Agency, the Catalan Water Agency, water utilities, and private companies. In total, these activities engaged 40 participants from diverse sectors of society.

2. Increment of green areas is estimated with the analysis of green pixels on the 11 m^2 green wall photos. It reveals a rapid increase in vegetation cover between January and April 2024, with the green area increasing from 4.19 m^2 to 8.91 m^2, an increase of 112.5%, likely due to the intensive planting and landscaping efforts typical of the early establishment phase of an NBS. By June, vegetation appeared to have reached its maximum cover with a total green area of 13.55 m^2. By August, an 18.5% reduction in this area was observed, likely related to the intense summer heat, bringing the area back to 11.05 m^2. However, autumn conditions favored regrowth, with the green area returning to 13.35 m^2 (Figure 6.2).

Figure 6.2 Increment of green area in the green wall.



3. Enhance/preserve biodiversity: planting 24 plant species in this greenwall increased the specific richness in the area that contributed to urban diversity. In addition, the system should provide a habitat for microfauna. Indeed, flowering species like *Heuchera sp.*, *Campanula sp.*, and *Myrtus sp.* attracted vital pollinators, such as bees, flies and butterflies, promoting insect populations essential for ecosystem functioning. Groundcovers, ferns, and grasses like *Dryopteris sp.* and *Miscanthus sp.* provide shelter and nesting opportunities for invertebrates and small birds. Moreover, plants such as *Pachysandra sp.* and sedges effectively stabilize substrates, fostering microbial diversity and improving substrate quality. Fruiting species like *Hedera sp.* and herbs such as *Ocimum sp.* and *Mentha sp.* provide essential food resources, supporting various bird and insect populations. The inclusion of drought-tolerant succulents like *Sedum sp.* and *Sempervivum sp.* further enhances ecosystem resilience, ensuring plant survival under varying environmental conditions. Overall, this greenwall design promotes ecosystem health and contributes to local biodiversity and ecological services.
4. Assuming that the carbon content is about 45% of the plant biomass, we were able to calculate the amount of carbon stored (Ma *et al.*, 2018). In November 2023 and 2024, the greenwall was pruned. The collected biomass was sorted by species, dried, and weighed. Between May 2023 and November 2023, the entire Greenwall produced approximately 2.2 kg of dry biomass, meaning almost 1 kg of stored carbon, while from November 2023 to November 2024 approximately 9.5 kg of dry biomass and 4.3 kg of stored carbon. Highlighting the wall's contribution to carbon sequestration over this period of one year and a half. Thus, over these eighteen months, this green wall enabled carbon sequestration at a rate of 505 gC/m^2, unlike conventional wastewater treatment plants, which emit approximately 5 to 800 grams of CO_2 per cubic meter of treated water (Hugh *et al.*, 2005).

6.5 Challenges and barriers

Given that the entire facility is owned by the Housing Agency, one of the primary challenges encountered was the prolonged response and planning time required for maintenance activities, such as pruning. Additionally, there are potential concerns from neighbours regarding issues like falling leaves or water dripping from the walls, which can lead to complaints and further complicate the scheduling and prioritization of necessary upkeep. Another issue we encountered is that, during heavy rainfall, the green wall leaches sand and humic acid, causing the effluent water to appear yellow. This has led neighbours to mistakenly believe that the discharged water used for toilets is dirty. To address this, we have already installed a supplementary filter.

6.6 Main outcomes

The main outcomes associated with our research project are categorized into scientific publications, conference presentations, technical and educational events, and community outreach efforts.

1. Scientific Publications in international peer reviewed journals

- **Paper in preparation:** A manuscript is currently in development, aimed at submission to a peer-reviewed journal. This study evaluates the greenwall system for wastewater treatment, focusing on its capacity to remove conventional pollutants and emerging contaminants (organic micropollutants) through physicochemical and biological processes. The research also examines public perception, highlighting the importance of social acceptance for widespread adoption. Findings aim to support greenwalls as both an effective and publicly acceptable urban water treatment solution.
- **Future papers:** We plan to develop two additional papers: the first will focus on the CAPEX and OPEX analysis of the green wall, along with an assessment of its co-benefits; the second will present findings from experimental trials of various substrates for green walls conducted in collaboration with the NICE project.

Mendoza, E., Vosse, J., Azzellino, A., Santos, L.H., Semitsoglou-Tsiapou, S., Comas, J., Buttiglieri, G. 2024. From shower to table: fate of organic micropollutants in hydroponic systems for greywater treatment and lettuce cultivation. *Blue-Green Systems*, *6*(1), pp.70-89.

2. Conference Presentations

- **Next Built 2024 Conference (9-10 May 2024, Bologna - Italy):** Massimiliano Riva participated at the Next Built conference, showing all the results of the water analyses, the activities carried out, and demonstrating the applicability of NBS for wastewater treatment.
- **ICWS Conference (25–29 November 2024, Martinique - France):** Marco Hartl participated at the International Conference on Water Sustainability (ICWS) 2024, where team members shared research findings and discuss implications for water sustainability with an international audience.

3. Technical and Educational Engagements

- **Training Sessions:** Four bachelor's theses and two master's theses were conducted in collaboration with the University of Girona and Alchemia Nova.
- **Meeting with the students of an engineering Master's Program (University of Barcelona):** A meeting conducted in Sant Quirze to discuss and show the treatment capacity of the system and further implementation in other buildings, broadening the educational reach of our research.
- **Elicitation Workshop on Greywater Policy – Barcelona:** Participation in a greywater policy development workshop in Barcelona, where Joaquim Comas contributed to help shape local policies and practices on water reuse based on his expertise.

4. Communication to the General Public

- **Nit de la Recerca (Girona – Spain):** Participation in "Nit de la Recerca" (Researchers’ Night), an event that bridges science with society, allowing the public to engage directly with researchers and learn about the project's goals and impacts.

- **Semana de la Naturaleza (Girona – Spain):** Engagement in "Semana de la Naturaleza" (Nature Week), an event focused on environmental education for the public, where the team promoted awareness of sustainable water practices and environmental protection.

- **Agora School Replica – Primary School Engagement (Girona – Spain):** The construction of a replica of ICRA's greenwall for greywater treatment and reuse for irrigation purposes, at Agora primary school at the beginning of 2025, aims to introduce students to the principles of environmental sustainability and water management, sparking interest and raising awareness among young audiences. Education project based on the Agora greenwall will be prepared jointly between primary school teachers and ICRA researchers.

- **Basket Girona Events (Girona – Spain):** Participation in a local event with Basket Girona, 1st division basketball local team, designed to connect the community with sustainability projects, encouraging local support and raising awareness about water reuse.
- **Workshop at Salvador Sunyer i Aimeric Highschool (Salt, Girona):** on November 16th, 2024, Esther Mendoza participated in a session within a series of informative talks for high school students of the optional subject Ecoprojects. She gave a presentation about tourist activities and their impact on water resources and conducted a workshop for the students about ideas for sustainable tourism in the area, which included information about greywater reuse and NBS.
- **Flash Seminar about Nature-Based Solutions (December 12th, 2024 Girona - Spain):** A brief, targeted presentation designed to convey essential research findings in a quick and accessible format, suitable for general audience attending in ICRA (H2O building), and streamed via YouTube (https://www.youtube.com/watch?v=sEBIopBb2O8).

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Monteith, H.D.,Sahely, H.R., MacLean, H.L., Bagley, D.M. 2005. A Rational Procedure for Estimation of Greenhouse-Gas Emissions from Municipal Wastewater Treatment Plants. *Water Environment Research*, 77, 390-403. https://doi.org/10.1002/j.1554-7531.2005.tb00298.x.

7 Pilot 6: Norway - NIVA/Oslo Municipality - Raingarden treating road runoff

7.1 Pilot 6 description

The Norwegian pilot is a rain garden located along Tåsenveien in the City of Oslo, designed to manage runoff from an area of about 1300 m^2. It was constructed prior to the MULTISOURCE project as part of a broader urban upgrade initiative aimed at improving mobility and climate resilience. The upgrade in the area included the installation of sidewalks and bike lanes on both sides of the road encourage more people to walk, cycle and travel by public transport. The upgrade project on Tåsenveien spans approximately 730 m and includes a stretch of road prone to flooding. It incorporates the planting of over 50 trees and the establishment of rain gardens to mitigate flooding and treat runoff.

Although pollutant retention was not the original design purpose, the raingarden still contributes to water quality improvement by intercepting sediments and other contaminants typically found in road runoff. Within the project, the rain garden's role in retaining and removing road runoff pollutants, those that would otherwise enter water pathways and eventually pollute the Oslofjord, is monitored. Figure 7.1 illustrates key moments in the development and operation of the pilot rain garden, including its construction, a heavy rain event, and the installation of monitoring equipment.

Figure 7.1 A) The road and the raingarden during a heavy rain event (August 2023), B) the raingarden under construction (summer 2022), C) sensors installed in the influent monitoring box, D) the raingarden and the influent monitoring box, E) the raingarden and the influent monitoring box showing water flowing over the v-notch.

The catchment area contributing runoff to the rain garden comprises a mix of 26.5% impervious surfaces (i.e., roadways and sidewalks) and 73.5% pervious area (lawn adjacent to it). Runoff is collected from both sides of the road and directed toward the raingarden through two inlet gutters. Each inlet serves a distinct portion of the catchment (Figure 7.2A).

The first inlet directly collects runoff from an area of 384 m^2, consisting of impervious (SC 1-1) and pervious (SC 1-2) areas of 78.7 and 21.3%, respectively. The second inlet receives runoff directly from an

This project has received funding from the European Union's Horizon H2020 innovation action programme under grant agreement 101003527.

impervious area of 201 m^2 (SC 2-1). Additionally, the lawn next to the rain garden can contribute runoff from a total area of 838 m^2 (SC 1-3, SC 2-2 and SC 3) as a spatially varied overflow between the first inlet and the outlet manhole.

Based on the precipitation time series derived from the Bjølsen station (SN18390), the annual precipitation for 2023 and 2024 was 905 mm and 1085 mm, respectively. The total rainfall during the snow-free season (May to September), was 545 mm in 2023 and 595 mm in 2024. The annual average precipitation and annual average temperature for the reference period 1991-2020 are 783 mm and 7 °C, respectively.

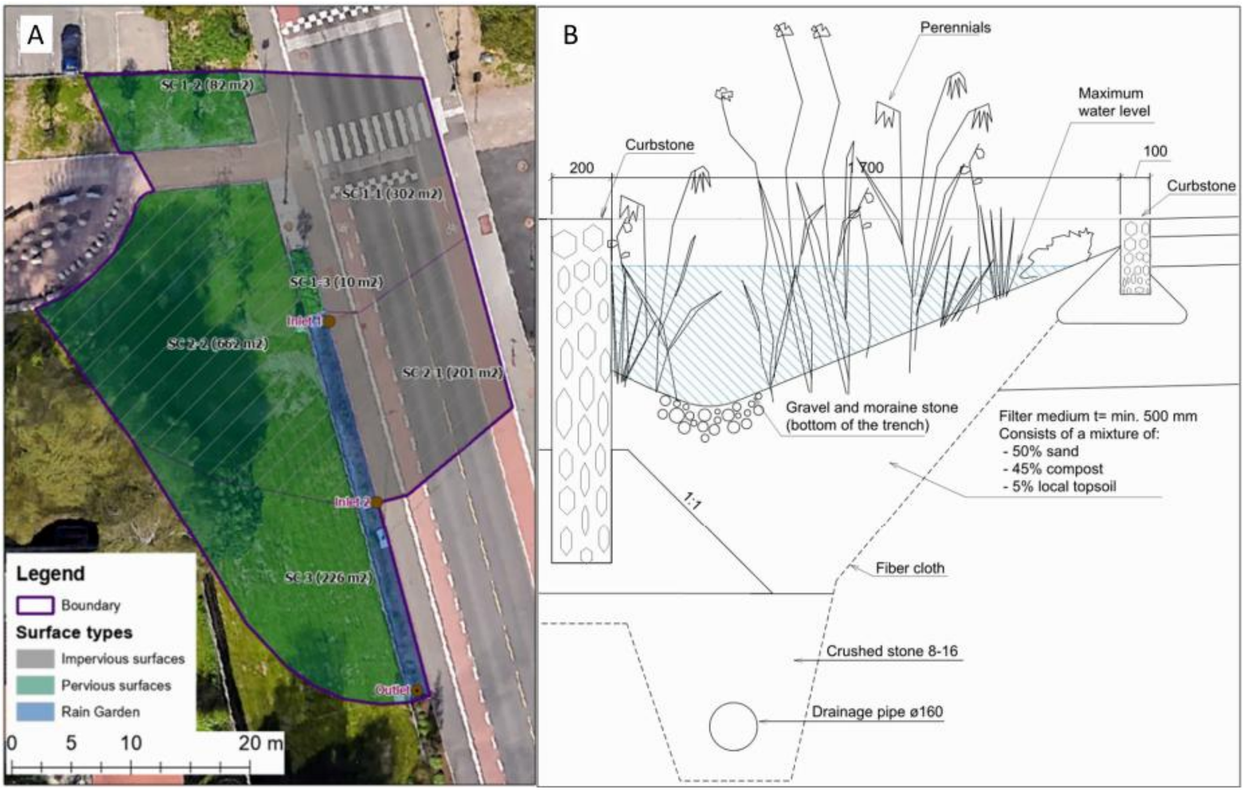


Figure 7.2 A) Catchment layout showing sub-catchments (SC 1-1 to SC 3), inlet locations, and land cover distribution; B) Cross-section of the raingarden build-up, including vegetation, filter medium (sand, compost, topsoil), drainage layers, and overflow structure.

The pilot raingarden has an area of about 60 m and is designed to provide a surface storage volume of around 19.6 m along its 33.5 m length. It receives runoff through the two inlet gutters, each measuring 20×15 cm and spaced about 16 m apart (Figure 7.2A). The raingarden is constructed with a multi-layered build-up designed to support vegetation, manage stormwater, and facilitate drainage (Figure 7.2B). At the surface, perennials are planted to enhance biodiversity and contribute to pollutant uptake. The system is bordered by a 200 mm and 100 mm width curb stones on both sides, which help contain runoff and define the garden's edges.

Beneath the vegetation lies a filter medium with a minimum thickness of 500 mm, composed of 50% sand, 45% compost, and 5% local topsoil. This blend supports plant growth while promoting infiltration and pollutant filtration. Below the filter medium is a fibre cloth layer, which acts as a separation barrier to prevent mixing with the underlying drainage layer.

The drainage layer consists of crushed stone (8-16 mm), providing structural support and facilitating water movement. Embedded within this layer is a drainage pipe (Ø160 mm), which ensures excess water is conveyed away from the system during high-flow events. At the base of the trench, gravel and moraine stone further aid in drainage and stability. The system is designed to accommodate a maximum water level, ensuring temporary surface storage during intense rainfall events while maintaining efficient subsurface drainage.

7.2 Overview of the monitoring work

A total of 7 rainfall events have been monitored from June 2023 to July 2024. Automatic ISCO samplers placed at the influent and effluent of the raingarden have sampled time-paced composite water samples for each rainfall event, resulting in 1 sample from the inlet and 1 sample from the outlet. These have been analysed for total phosphorus (TOT-P), total nitrogen (TOT-N), phosphate, chloride (Cl), total suspended solids (TSS), metals (Al, Fe, Pb, Cu, Cd, Na, Ni, Cr, Zn, W), organic micropollutants (37 compounds) and tire wear particles (TWP). Several compounds were analysed as technical replicates, in addition to blank samples, thus resulting in some variation in the number of measured values available for each analysed parameter (Table 7.1). Only rainfall events 1-5 were analysed for tire wear particles (TWP). For all rainfall events, sensors monitored turbidity, water level, water temperature and conductivity in the influent and effluent (Table 7.2).

Table 7.1 Overview of number of samples analysed for each group of parameters (metals, organic compounds, tire wear particles (TWP) and quality parameters for each rainfall event.

Sampling events	Season	Metals	Organic compounds	TWP	Quality parameters
Rainfall event 1	June 2023	22	192	4	10
Rainfall event 2	September 2023 (1)	22	142	4	8
Rainfall event 3	September 2023 (2)	44	144	4	14
Rainfall event 4	November 2023	40	186	4	16
Rainfall event 5	October 2023	22	144	4	8
Rainfall event 6	May 2024	33	186	-	12
Rainfall event 7	July 2024	44	174	-	16

Sensors were installed at the inlet and outlet of the rain garden (same location as the ISCO samplers) to evaluate the performance of this system by measuring turbidity, temperature, and water level. In December 2022, the weir box (container) keeping these sensors at the inlet was damaged during snow removal. This has been reinstalled, and automatic water samplers were in use from spring 2023 until July 2024. For the sensors, dataloggers at the inlet and outlet collected the data from the sensors and sent them to the NIVA Cloud automatically. Measurements were taken every 5 minutes and sent immediately. The high frequent datalogging ensured insight in the fast dynamic changes during a rain event.

Table 7.2 Overview of the sensor monitoring for Pilot 6: NIVA/Oslo Municipality - Raingarden treating road runoff

Endpoint	Sensor or samples	Sampling point	Monitoring period	Sampling frequency	Number of data points available[1]
Turbidity[1]	Sensor	Influent, Effluent	October 2022 - September 2024	5 minutes	~350 000
Water level[1,2]	Sensor	Influent, Effluent	October 2022 – September 2024	5 minutes	~350 000

Water temperature[3]	Sensor	Influent	October 2022 – September 2024	5 minutes	~175 000
Conductivity	Sensor	Influent, Effluent	May 2023 – September 2024	5 minutes	~280 000

[1] Influent monitoring box was damaged during snow ploughing in December 2022 and sensor data were not monitored again before end of April 2023. [2] Water level is monitored both in influent and effluent. However, water flow is only available for the influent where a monitoring box with a v-notch was installed. [3] Water temperature is monitored in the influent monitoring box. During winter period the box is heated to avoid freezing of sensors. Hence, water temperature data is not representative for the ambient temperature during winter.

7.3 Key results

Tables 7.1 and 7.2 summarized the data available for each sampling event, including what time of the years each sampling took place. As seen in Table 7.1, there is a good spread throughout the year, covering spring, summer and autumn, and slightly also the change between autumn and winter by the samples taken in November. However, no water samples were taken during the winter months of December to March, as there were heavy snow falls and very little rainfall during this time in 2023-2024. The sensors did however log values continuously, also through the winter months. As samples were taken at both the inlet and the outlet of the raingarden, there is a potential for assessing how much of the pollutants are retained by the raingarden. However, it should be stated clearly that the raingarden does not have a closed bottom and there is no drainage system leading water that has gone through the soil layer to the outlet. This means that water infiltrates through the raingarden and leaves the system through this infiltration, which is not sampled and measured.

7.3.1 Tire wear particles

The average concentration of TWP was 2.57 ± 2.30 mg/L (average ± SD) in the inlet and 0.488 ± 0.188 mg/L in the outlet, resulting in 81% potential reduction by comparing the inlet to the outlet, which suggest that the levels of TWP coming into the raingarden directly from the road has a lot higher levels compared to what is coming into the outlet (Table 7.3). There is also a large variation between the sampling time points, in which the highest levels in the inlet (6.93 mg/L) and the outlet (0.758 mg/L) were observed for November 2023 (Rainfall 04).

Table 7.3 Summary statistics for tire wear particles (TWP) for all events, showing the average and standard deviation (SD) of the inlet and outlet and the potential retention (%) in the raingarden.

	Inlet		Outlet		Retention %
Chemical	**Mean**	**SD**	**Mean**	**SD**	
TWP mg/L	2.570	2.301	0.488	0.188	81.0

7.3.2 Organic compounds

For the organic compounds, the samples were analysed for 37 individual compounds, resulting in a total of 1478 datapoints. Only 9 compounds had concentration levels >LOD (6PPD-Quinone, Aminobenzothiazole (ABT), Hydroxybenzothiazole (OHBT), Methylthiobenzothiazole (MTBT), Benzothiazole (BT), Naphthalene, Tebuconazole, Phenanthrene, Fluoranthene), resulting in 138 measured values. In total, 1011 measurements across all 37 compounds were <LOD and 17 were <LOQ. For these samples, values were substituted by LOD/2 for statistical purposes. As this NBS pilot specifically treats road runoff water, special attention has been given to investigate those chemical compounds related to vehicles and tires. Six compounds were selected as target compounds related to vehicle tires (6PPD, 6PPD-Q, ABT, BT, MBT, MTBT and OHBT). For 6PPD and MBT, all reported values were <LOD. The concentration varied greatly between the rainfall events, with the overall highest levels found in Rainfall

event 1 for all compounds (Table 7.4). The highest level in the inlet was observed for Benzothiazole (BT) (9.73 ± 6.76 µg/L), a compound strongly related to the vulcanization of tires. In addition, we found high levels of the other benzothiazole-derivatives such as OHBT (9.29 ± 7.72 µg/L), MTBT (1.23 ± 1.08 µg/L) and ABT (0.380 ± 0.247 µg/L). Another tire-derived compound, 6PPD-Q, which is a transformation product of the tire-related antioxidant 6PPD, was also found in higher levels in the inlet of rainfall 1 (0.227 ± 0.160 µg/L). Comparing inlet values to outlet values for all compounds suggest a high retention of these compounds from rainfall 1 (Table 7.4). If we compare the average inlet values to the outlet values of all rainfalls (Table 7.5), we do see lower levels of all compounds in the outlet, however, the potential retention values have also changed. Again, it needs to be highlighted that due to the technical construction of this raingarden, with no possibility to sample from the water passing through the soil system, these retention values and comparisons between inlet and outlet need to be considered carefully and most likely does not give us a good overview of the functionality of the raingarden.

Table 7.4 Summary statistics for the selected organic tire-associated chemicals (6PPD, 6PPD-Q, ABT, BT, MBT, MTBT and OHBT) for rainfall event 1, showing the average and standard deviation (SD) of the inlet and outlet and the potential retention (%) in the raingarden.

Rainfall 1	Inlet		Outlet		Retention %
Chemical	Mean	SD	Mean	SD	
6PPD-Q µg/L	0.227	0.160	0.062	0.113	72.8
ABT µg/L	0.380	0.247	0.140	0.204	63.2
BT µg/L	9.73	6.76	2.80	4.59	71.2
MTBT µg/L	1.23	1.08	0.336	0.641	72.8
OHBT µg/L	9.29	7.72	2.69	5.12	71.1

Table 7.5 Summary statistics for the selected organic tire-associated chemicals (6PPD, 6PPD-Q, ABT, BT, MBT, MTBT and OHBT) for all rainfall events, showing the average and standard deviation (SD) of the inlet and outlet and the potential retention (%) in the raingarden.

All rainfall events	Inlet		Outlet		Retention %
Chemical	Mean	SD	Mean	SD	
6PPD-Q µg/L	0.117	0.112	0.0229	0.055	80.5
ABT µg/L	0.121	0.185	0.0529	0.103	56.4
BT µg/L	3.18	4.84	1.011	2.26	68.2
MTBT µg/L	1.05	0.796	0.109	0.309	89.6
OHBT µg/L	2.82	5.10	0.817	2.47	71.0

7.3.3 Inorganic compounds

A total of 10 metals and 5 water quality parameters were reported in the water samples, resulting in a total of 309 individual datapoints over 7 rainfall events. Values were <LOD for 102 of the samples, of which 89 of these were the blank samples. For these samples, values were substituted by LOD/2 for statistical purposes. Large variations were observed between the different sampling time points and the different compounds. For all rainfall events, the highest levels of metals (Table 7.6) were found for Na (77.8 mg/L), which is likely due to road salt (NaCl) coming into the raingarden during winter, and being present in the raingarden over time, as the salt does not dissolve or break down, but is potentially stored and released during rainfall. This is supported by also finding high levels of the water quality parameter Cl (94.2 mg/L) and by the negative retention observed for both Cl (-248%) and Na (-215%), as well as high conductivity observed by the sensor data. Another interesting result is the negative retention of Zn (245%), with more than 3 times as high levels of Zn observed in the outlet compared to the inlet. As Zn is used in the vulcanization of tires, it is often used as an inorganic marker of tire wear particles. However, the high levels of Zn observed in the outlet do not match the levels of TWP in the outlet, nor the levels of

organic tire-related compounds. Although there is no clear indication of any additional sources close to the raingarden, the raingarden does also receive runoff from the nearby parking area and housing area, thus, tires might not be the only source of Zn present for the outlet water of this raingarden. For the remaining water quality parameters, only TSS had higher levels in the inlet (115 ± 118 mg/L) compared to the outlet (13.3 ± 10.9 mg/L) (Table 7.7), resulting in a potential reduction of 89%. For all the other parameters, higher levels were observed in the outlet, suggesting potentially that some of these compounds are being washed out of the raingarden soil.

Table 7.6 Summary statistics for metals Al, Cd, Cr, Cu, Fe, Na, Ni, Pb, W and Zn (average) for all rainfall events.

	Inlet		Outlet		Retention %
Chemical	**Mean**	**SD**	**Mean**	**SD**	
Al µg/L	2331	3220	917	577	60.7
Cd µg/L	0.0256	0.0252	0.0319	0.0163	-24.6
Cr µg/L	6.67	6.88	2.07	0.91	69.0
Cu µg/L	11.4	9.31	9.33	2.72	18.3
Fe mg/L	5.12	2.87	0.535	0.300	89.5
Na mg/L	77.8	157	245	200	-214.8
Ni µg/L	5.63	4.51	3.66	1.31	35.0
Pb µg/L	3.43	3.51	0.669	0.376	80.5
W µg/L	0.857	0.945	0.814	0.549	5.0
Zn µg/L	47.8	46.4	165	164	-244.9

Table 7.7 Summary statistics for water quality parameters TSS, TOT-N, TOT-P and phosphorous.

	Inlet		Outlet		Retention %
Chemical	**Mean**	**SD**	**Mean**	**SD**	
Phosphate mg P/L	0.0096	0.0104	0.144	0.0525	-1404
TOT-N mg N/L	1.054	0.891	4.10	3.10	-289
TOT-P mg P/L	0.142	0.087	0.313	0.139	-121
Cl mg/L	94.2	199	328	323	-247.7
TSS mg/L	115.4	118.1	13.3	10.9	88.5

7.3.4 Sensors

Sensors were deployed at the two monitoring stations in the rain garden to continuously collect water level, turbidity, and conductivity data at 5-minute intervals. This real-time data provides valuable insights into the performance of the rain garden during different weather events. The collected data is automatically transmitted and securely stored in NIVA’s cloud storage system, enabling seamless remote access through the open-source data visualization platforms Superset (accessible to the public) and Grafana (used internally by NIVA staff). Figure 7.3 gives an overview of the sensor monitoring data collected over a period of nearly two years. Combining the sensor data with the measured levels of pollutants gives a better understanding of the results. For example, it is useful to investigate sensor data to see if there have been longer periods of dry weather before a rainfall event, as this could potentially explain higher levels of pollutants due to accumulation over time. Or the opposite, where longer periods of heavy rainfall may have already washed away particles and pollutants, thus explaining lower pollutant levels in the samples. This data will be further explored in the dissemination activities and publications planned for this pilot.

Figure 7.3 Overview of the sensor monitoring data from the inlet (Multisource 1) and the outlet (Multisource 2) for the parameters turbidity (NTU), water level (m, only for inlet)), water temperature (Co) and conductivity (µS/cm) over the complete project period October 2022 - September 2024.

7.4 Main technical results

On the 23rd of October 2023 we conducted a stress test to evaluate the rain garden's actual infiltration capacity, including the surface storage and the retention capacity of the subsoil layers. A fire truck with a 9000-liter capacity was used for the test, limiting the scale of the rainfall simulations that could be mimicked. The initial idea was to discharge a controlled volume of water on the road surface upstream of the rain garden's inlet for the test.

The stress test revealed significant structural shortcomings at the junction where its inlet gutters connect to the driveway that hinder the rain garden's optimal functionality. A significant portion of water bypasses the inlet and flows to the downstream drain due to the steeper slope along the road compared to the inlet gutters' slope, as well as the perpendicular connection between the inlet gutters and the curb stone. This causes the water to gain speed along the driveway and makes it difficult to redirect into the inlet. To address this issue, we employed two strategies: placing a physical barrier to manually divert water from the road into the rain garden; and directly flushing water from the fire truck hose into the inlet. In the first approach, water was released on the road surface upstream of the first inlet at a rate of 250 litres/second for 12.5 minutes, totalling approximately 3000 litres. In the second approach, 5500-6000 litres of water was discharged directly into the rain garden's inlet over about 6 minutes. The approach created artificial inflows and provided valuable insights into the rain garden's intended functionality and water flows through it. For instance, it was noted that the rain garden's overflow outlet is set too low, preventing meaningful utilization of the surface depression for stormwater storage. This design flaw needs to be corrected for the future function of the raingarden. While the raingarden demonstrated good capacity, the test's water volume limitations prevented a full assessment of its maximum handling capability. Further analysis of sensor-based data at a later stage is expected to provide deeper understanding of the rain garden's performance during the stress test.

7.5 Main co-benefits results

We evaluated co-benefits with stakeholders, focusing on environmental and socio-economic values. The top three environmental co-benefits were increasing/preserving biodiversity, increasing green infrastructure, and reducing flood risk. The key socio-economic benefits were improved public health and well-being, increased traffic safety, and facilitating learning. Two disadvantages identified were increased operational costs and the presence of unwanted species. After this, we evaluated the co-benefits and disadvantages together, which is summarized in Table 7.8. We conducted an in-depth study focusing on increased green infrastructure, increased operational costs, and improved traffic safety. More areas were allocated to green infrastructure, but the new vegetation isn't thriving as well as the old. However, people perceive the street as greener due to the proximity of greenery to pedestrians. The exact figures for maintenance costs were hard to determine, but it's clear that costs have increased due to the need for specific upkeep of designed solutions. Surveys indicated that people feel safe on the street, but they also felt safe before the intervention, making it hard to attribute this as a co-benefit of the project.

Table 7.8 Summarized results from the co-benefit evaluation.

Type	Name	Data/Method	Assessment
Environmental co-benefits	Increase/preserve biodiversity	Counting (native) species per m^2	Establishment care required, not naturally occurring vegetation. Not suitable for evaluation.
	Increase green infrastructure	Checking the area before and after the intervention and making a quantitative assessment of land use change	Relatively simple to carry out. Can be done for both Tåsenveien and another test site.
	Reduce flood risk	Based on the results from the stress test	See results from the stress test
Socio-economic co-benefits	Improve public health and well-being	Relevant in a survey. Interviews with passersby.	Difficult to make a good evaluation
	Improve traffic safety	Relevant in a survey. Interviews/inspections focused on traffic safety.	Relatively simple to conduct. Can compare solutions in Tåsenveien and another test site.
	Facilitate learning	Surveys. Interviews with passersby.	Difficult to make a good evaluation
Disadvantages	Increased operational costs	Consult Park Maintenance. Using standard costs for rain gardens and runoff catchers.	A simple evaluation can be conducted

		Assessing the situation before and after the intervention.	
	Unwanted species	Counting native species per m^2	Establishment care required, not naturally occurring vegetation. Not suitable for evaluation.

7.6 Challenges and barriers

The work on this pilot has revealed three main challenges that need to be addressed. The first is that road runoff does not flow into the rain garden from the road, especially when there is heavy rainfall. This has been described in 7.4 in more detail, and how this is a design problem related to the inlet of the raingarden. The second challenge is that the runoff received by the rain garden comes from more than the road surfaces, which only account for 40% of the watershed area. While road surfaces make up 78% of the area contributing runoff to the first monitoring station, runoff from the surrounding lawn dominates the runoff monitored at the outlet (see Figure 7.2.A).

The third challenge identified for this pilot is that the raingarden does not have a closed bottom, which means that water is infiltrating through the soil and leaves the raingarden without any possibility to monitor the levels of pollutants in this water after passing. For monitoring purposes, it would be better to have designed the raingarden with a closed bottom and a way to also sample the water that has been through the soil before it is being released. With the current set-up, we do not really know how much of the pollutants are retained in the soil and also, we do not know what the levels found in the outlet represent. The outlet values for this pilot likely represents the water that has either i) passed through the surface of the raingarden and flowed into the outlet or ii) directly entered the outlet through “splash and spray” from the road by passing vehicles or through the snow ploughing. To address this challenge, additional sampling of the raingarden has been conducted in November 2024, where soil cores from several locations from the inlet to the outlet of the raingarden has been sampled and will be analysed for TWP, metals, organic compounds and water quality parameters. This will add valuable information on what has been retained in the soil of the raingarden and the results will be included in the pilot fact sheet and disseminated as part of the pilot results.

7.7 Main outcomes

Results from this pilot will be used in a publication about the technical specifications and the sensor monitoring (Gragne *et al*., *in prep*) and one publication on the pollutant data (Rødland *et al*., *in prep*). In addition, the results have been disseminated already at two seminars/conferences, and will be presented in additional conferences in 2025. The large datasets collected will also contribute to master thesis work in 2025. The sensor data has been published openly accessible to the public through NIVAs website: Rain Garden Real-time Sensor Data | NIVA.

A video was made about road runoff treatment and nature-based solutions, using the pilot as an example. This has been published through Youtube (Handling road runoff using nature based solutions (DigiVEIVANN) - YouTube) and funded through the MULTISOURCE-project with additional funding from the Norwegian Research Council.

8 Pilot 7: Germany - UFZ - Green roof rainwater

8.1 Pilot 7 description

The UFZ Research Green Roof is tackling key urban challenges related to climate adaptation, exploring the potential of green roofs as multifunctional blue-green infrastructure. These systems contribute to stormwater management, mitigate urban heat through evapotranspiration, serve as sinks for CO_2 and airborne pollutants, and enhance urban biodiversity by providing habitats for plants and animals.

Research at the UFZ focuses on optimizing green roofs for a range of environmental and urban needs. This includes investigating their effectiveness in stormwater retention, temperature regulation, and improving urban microclimates. Researchers are also examining the most resilient plant species for green roofs, their role in supporting biodiversity, and their potential as decentralized treatment systems for low-polluted wastewater, such as greywater. In addition, studies are evaluating how different green roof types can act as pollution sinks, absorbing airborne contaminants, while reducing pressure on urban drainage systems.

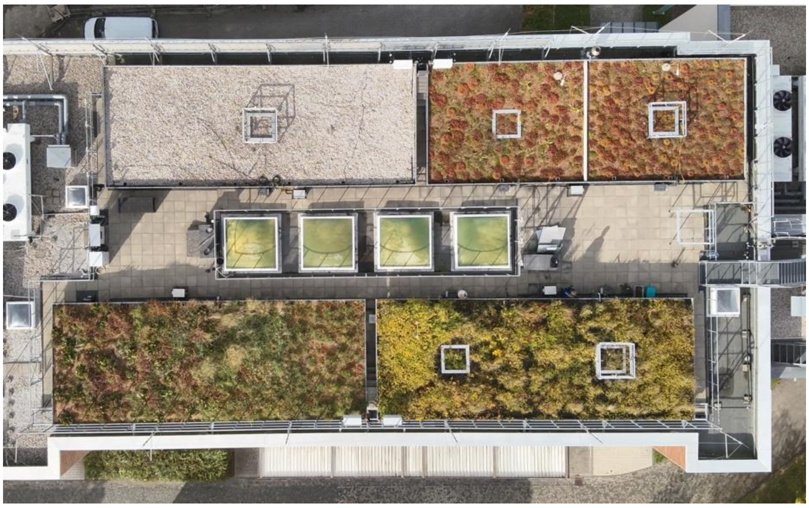


Figure 8.1 Aerial photo of the four roof segments (Photo by K. Bernhard, UFZ).

The UFZ Research Green Roof, located on a four-storey building at the UFZ campus in Leipzig, Germany, features four distinct roof segments (Fig. 8.1): an extensive green roof, an intensive green roof, a wetland roof, and a reference gravel roof, each equipped with technology to monitor overflow as well as water levels within the green roofs and meteorological parameters such as radiation fluxes and classic weather station parameters including precipitation. This infrastructure supports ongoing efforts to enhance rainwater management, improve inner-city microclimates, and provide critical insights into the role of green roofs in sustainable urban development.

In addition to the four roof segments, further blue-green infrastructures are associated to the UFZ Research Green Roof lab, (i) a retention green roof carport, as well as (ii) a suite of urban trees including tree swales (Fig. 8.2). In the framework of MULTISOURCE rainwater and overflow samples were collected from the green roofs and vegetation data were monitored for tree swales and urban trees.

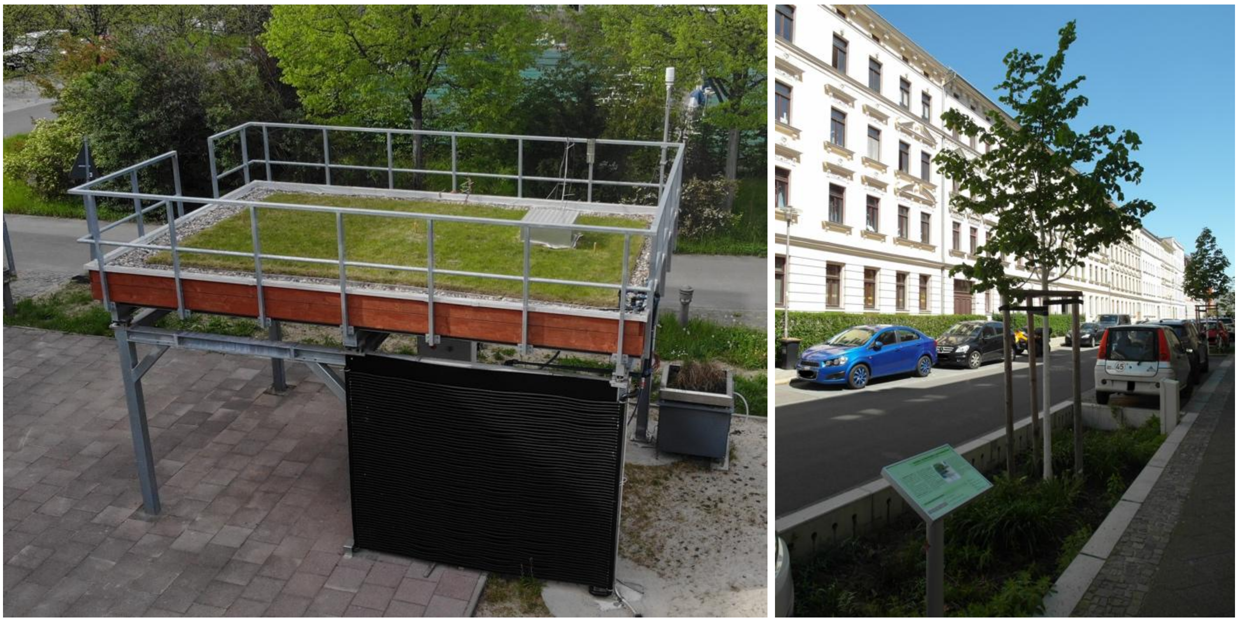
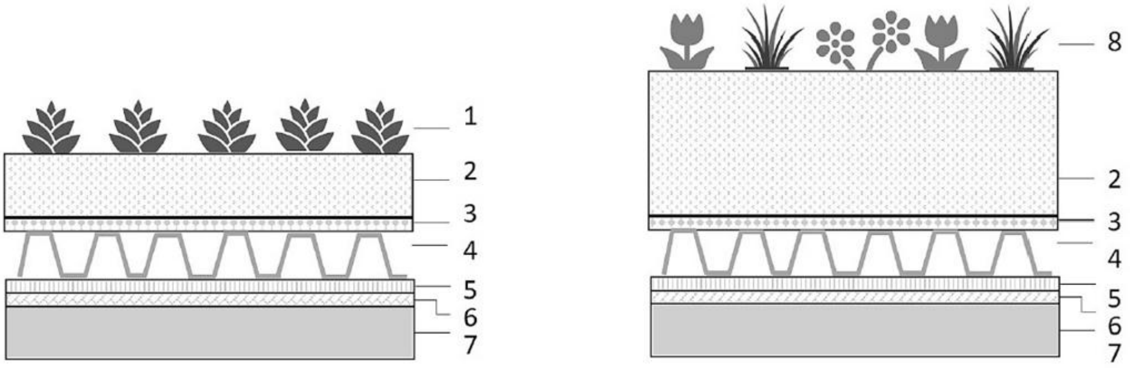


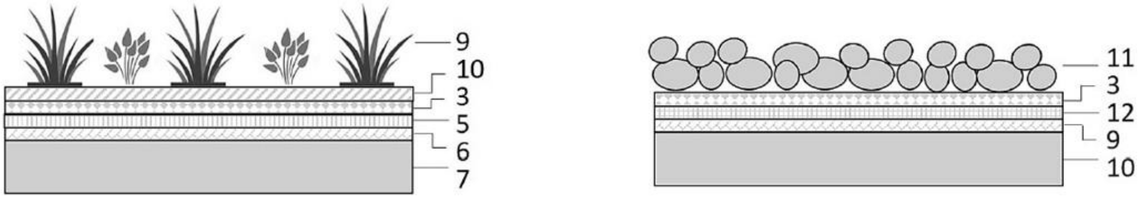
Figure 8.2 Retention green roof (left) and tree swales (right). Photos by K. Bernhard, UFZ.

Results for the research green roof (Moeller et al. 2025) and the tree swales (Moeller et al. 2025) have recently been published. Figure 8.3 shows cross-sections for different green roof types.



Extensive Green Roof

Semi-Intensive Green Roof



Wetland Roof

Gravel Roof

Figure 8.3 UFZ green roof cross sections for four systems. Numbers refer to different elements: (1,8,9,11 surface layers; 2,10 substrate or water; 3,5,6 liners and fleeces; 4 drainage mat; 7 wooden construction). Modified after Moeller et al. 2025.

8.2 Overview of the monitoring work

For MULTISOURCE the four roof segments on the UFZ Research Green Roof were equipped with stormwater samplers to provide samples for micropollutant and microplastic analyses at AU and NIVA. Precipitation samples were collected at the retention green roof carport. Sampling dates are shown in Fig. 8.4.

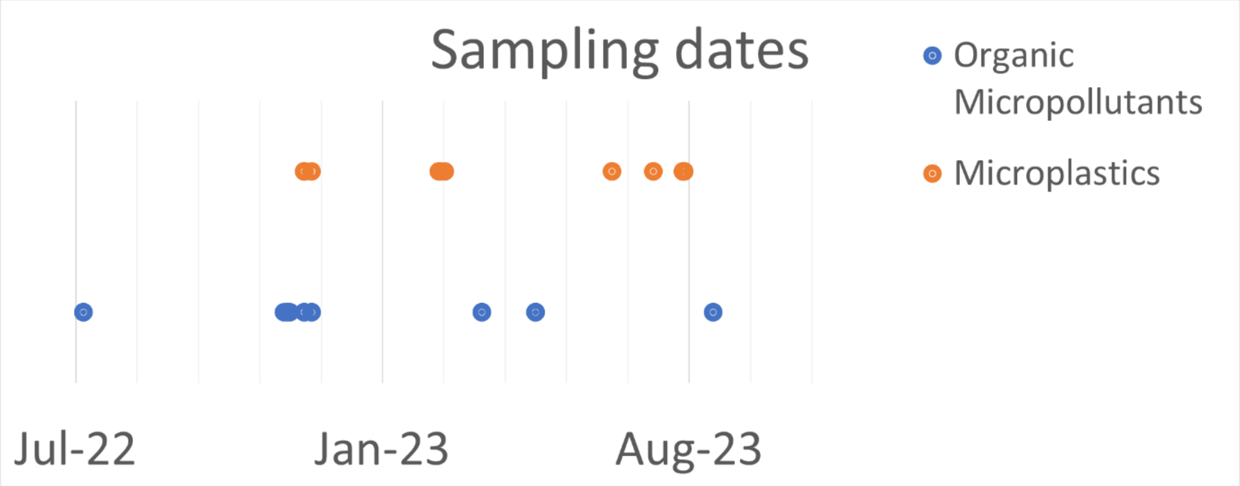


Figure 8.4 Sampling dates for the organic micropollutants and microplastics for the UFZ pilot in the period 2022-2023.

8.3 Main technical results

The UFZ green roofs are fed by precipitation and irrigation water (Fig. 8.5). Irrigation is essential as the green roofs, next to stormwater management, are also operated towards biodiversity by several research groups.

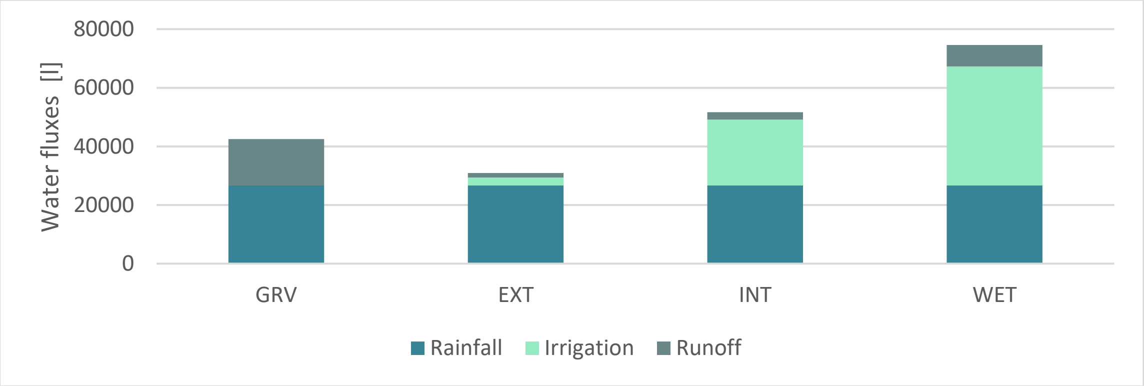


Figure 8.5 Water fluxes (rainfall, irrigation, and runoff) for four roof types: gravel (reference), extensive, intensive, and wetland. The fluxes (in liter) are totalled over a period of 8 months (Apr-Nov).

Overall, the four green roof types - gravel (reference), extensive, intensive, and wetland – show a high retention capacity ranging from 40 to over 95%. The gravel reference roof has the lowest retention (40%) and all other roofs range from about 89 to 95% rainwater retention. Compared to literature values of green roof retention capacities these numbers are rather high. Reported annual retention capacities are 10-30% for gravel, 27-85% for extensive 65-85 % for intensive, and up to 90% for wetland roofs

(Landschaftsbau 2008, Chen et al. 2022, Fei et al. 2023, Mantilla et al. 2023). These capacities depend on design parameters (e.g. substrate depth, drainage or retention mats) and climate and vegetation with respect to evaporation and interception.

Next to the long-term retention capacities green roof functionality for different rainfall events is another important aspect. Figure 8.6 shows an overview per roof type for four rainfall event groups, below 1 mm, 5mm, 10mm, and above 10mm.

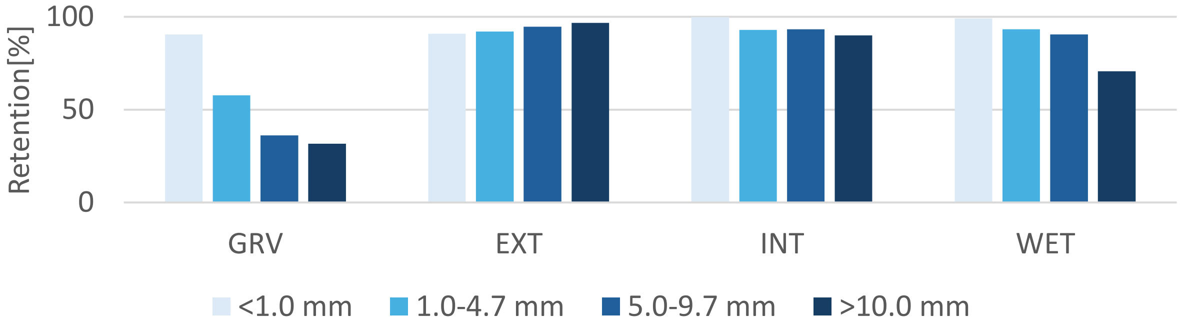


Figure 8.6 Retention capacities for four roof types: gravel (reference), extensive, intensive, and wetland. Each roof shows the retention capacity in percent for different rainfall event classes.

The gravel reference roof, of course, shows the lowest performance (30-90%). Extensive and intensive green roofs both show retention above 90%. The wetland roof generally also is above 90% and above 10 mm dropped to 70%. Especially for the wetland roof this variability, next to design, is largely affected by the water level that depends on roof operation. As a wetland roof is designed to be permanently inundated it is operated to maintain a certain water level. In principle this can be controlled, i.e. release water before a storm event, and would further improve the retention capacity. Concerning overflow monitoring the good retention performance results in relatively few overflow events for water quality monitoring and are thus limited to stormwater events. In addition, green roof influx is rainfall and irrigation water and thus, do not provide a large array or micropollutant signals. The few detectable organic micropollutants are detailed in Table 8.1.

The green roof inflows are based on precipitation and thus, do not provide a large array or micropollutant signals. The few detectable organic micropollutants are detailed in Table 8.1.

Table 8.1 Green roof results from micropollutant analyses.

Roof type	Date	Flow	Parameter	Value [ug/L]
Gravel roof	20221121	OUT	Mercaptobenzothiazole (MBT)	0.69
Gravel roof	20221124	OUT	Hydroxybenzothiazole (OHBT)	0.77
Green roof (carport)	20220707	IN	Hydroxybenzothiazole (OHBT)	1.61
Gravel roof	20221121	OUT	Hydroxybenzothiazole (OHBT)	2.12

Following the pre-screening performed in 2022, during 2023 a dedicated analysis of microplastics in the different green roofs was carried. Results shown in Table 8.2 and exemplary for PP in Figure 8.4 denote the presence of several polymers in the influent and effluent of the different green roofs.

Table 8.2 Green roof results from microplastic analyses. All units are in μg/sample.

Date	Source	BGI	Type	PMMA	N66	PP	PVC	N6	PC	SBR	PET	PE	PU	ABS	PS
20230623	RAIN	GRV	OUT	0.023	0.405	12.792	1.765	0.057	0.034	1.456	0.234	2.726	-	-	0.069
20230809	RAIN	RAIN	IN	-	0.385	0.329	0.811	0.026	-	0.512	0.2	1.346	-	0.024	0.049

20230804	RAIN	EXT	OUT	-	0.279	2.241	0.999	-	-	0.255	0.281	0.544	-	-	0.083
20230809	RAIN	GRV	OUT	0.012	0.336	8.906	4.133	0.045	0.019	0.544	0.243	<0.2	-	0.032	0.077
20230804	RAIN	GRV	OUT	0.015	1.075	10.557	3.904	0.162	0.055	0.966	0.408	38.809	-	-	0.422
20230822	RAIN	WET	OUT	0.017	0.781	12.123	2.217	0.514	0.021	0.42	0.25	2.087	-	-	0.141
20230804	RAIN	RAIN	IN	0.011	0.842	4.721	1.574	0.198	0.049	1.062	0.203	4.636	-	-	0.072
20230623	RAIN	RAIN	IN	0.045	0.686	1.151	3.17	0.028	0.045	1.104	0.407	2.603	-	0.033	0.108
20230720	RAIN	RAIN	IN	0.03	1.122	1.85	2.187	0.239	0.165	1.558	0.601	5.177	-	-	0.232
20230809	RAIN	EXT	OUT	0.062	1.147	1.725	5.161	0.378	0.064	1.078	0.595	17.048	-	-	0.083
20230720	RAIN	GRV	OUT	0.134	4.341	15.136	14.501	2.113	0.097	5.037	1.001	15.306	-	0.268	2.024
20221209	RAIN	GRV	OUT	0.025	0.892	5.495	1.323	0.517	-	-	-	1.44	-	-	0.238
20230302	BLANK	BLANK	BLANK	0.028	0.142	0.384	0.278	0.032	0.017	-	-	0.102	-	-	0.014
20230303	BLANK	BLANK	BLANK	-	0.361	0.238	0.266	0.029	-	-	-	0.115	-	-	0.013
20230306	BLANK	BLANK	BLANK	-	0.088	0.187	0.216	0.018	-	-	-	0.074	-	-	0.008

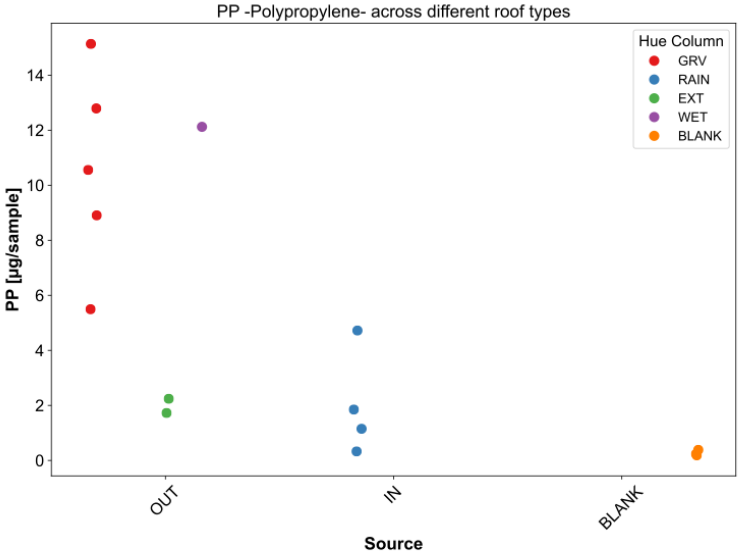


Figure 8.4 Polypropylene results for overflow from different roof segments (extensive - EXT, intensive - INT, wetland - WET, and reference gravel - GRV). In addition, results for inflow (rainwater - RAIN) and laboratory blanks (BLANK) are shown.

8.4 Main co-benefits results

The UFZ Research Green Roof is a joint research infrastructure that is utilized by multiple departments at UFZ as well as external partners from the University of Leipzig. Within MULTISOURCE we synthesized multiple studies from several student projects to give an overview of the co-benefits studied at the UFZ Research Green Roof based on findings from 14 different thesis and research projects conducted between 2021 and 2023 (Tab. 8.3). The studies focused on the four roof segments: a reference (gravel) roof, an extensive, an intensive, and a wetland green roof. The following offers a concise overview of co-benefits and key insights from these projects. The primary objective was to identify how green roofs contribute to urban sustainability, focusing on areas such as biodiversity, climate regulation, water management, and social well-being.

Table 8.3 Overview of the studies.

2021	2022	2023
Use of 3D scanning and image processing for monitoring vegetation on green roofs	Potential of green roofs for preserving and promoting biodiversity in urban areas	Impact of climate and construction on flora and vegetation of passenger shelters

Degradation of phthalates by fungi	Vegetation description and ecological modeling of different types of green roofs	Influence of plant coverage and irrigation on surface temperatures of green facades
Occurrence and biotransformation of environmental pollutants by fungi on green roofs	Pollutant retention through the integration of adsorber materials in green roofs	Rainwater retention capacities of various green roof variants and microclimatic effects
Investigation of soil heat flux in green roofs	Investigation of rainwater retention capacity and purification performance of wetland plant roofs	GIS-based analysis of green roof stock and potential in Leipzig
		Impact of arthropod occurrence on the acceptance of facade greening
		Comparison of vegetation of different green roof types and their influence on ecosystem functions

The co-benefits were extracted from different studies and systematically reviewing the key findings and the mentioned co-benefits. The main themes – ecosystem services, climate adaptation, water resource management, air quality improvement, and building protection – were identified across the studies. Key facts and outcomes of each study were highlighted, and the co-benefits were categorized into subcategories and overarching categories. This systematic approach provided a comprehensive synthesis, ensuring that overlapping themes were clearly identified and categorized, contributing to a deeper understanding of the collective green roof benefits (Tab. 8.4).

Table 8.4 Key co-benefit insights.

Main Topic	Key Insights	Co-Benefit Categories
3D scanning for green roof monitoring (Arnold 2021)	3D scanning and image processing are effective tools for collecting detailed data on green roof vegetation	Ecosystem Services
Phthalate degradation by fungi (Clauß 2021)	Specific fungi on green roofs can effectively break down phthalates	Ecosystem Services Air Quality & Pollutant Reduction
Pollutant biotransformation by fungi (Sehrt 2021)	Fungi on green roofs can effectively break down micro-pollutants	Ecosystem Services Water Resource Management Air Quality & Pollutant Reduction
Soil heat flux in green roofs (Stoeckel 2021)	Green roofs can significantly reduce soil heat flux	Climate Adaptation & Mitigation Ecosystem Services
Green roofs and biodiversity (Fischinger 2022)	Green roofs can improve urban air quality, control temperature, and protect and promote biodiversity	Ecosystem Services Climate Adaptation & Mitigation Water Resource Management
Ecological modeling of green roofs (Härtel 2022)	Green roofs fulfill different ecological functions depending on vegetation type and management	Ecosystem Services Water Resource Management Climate Adaptation & Mitigation
Pollutant retention in green roofs (Heisig 2022)	Adsorber materials in green roofs improve the retention of surfactants and pollutants from greywater	Water Resource Management Air Quality & Pollutant Reduction

Rainwater retention in wetland roofs (Stüllein 2022)	Wetland plant roofs improve water retention and play a significant role in greywater purification	Water Resource Management Climate Adaptation & Mitigation Ecosystem Services
Climate impact on shelter vegetation (Neiding 2023)	Climate and surroundings have a significant impact on the diversity and vitality of vegetation on passenger shelters	Ecosystem Services Air Quality & Pollutant Reduction Climate Adaptation & Mitigation
Plant coverage and facade temperatures (Fraass 2023)	Green facades with sufficient irrigation and optimal plant coverage can effectively lower facade temperatures	Climate Adaptation & Mitigation Ecosystem Services
Rainwater retention in green roofs (Hofmann 2023)	Green roof systems can effectively retain rainwater and lower surface temperatures	Water Resource Management Climate Adaptation & Mitigation Ecosystem Services
GIS analysis of green roofs in Leipzig (Münch 2023)	Analysis shows significant potential for expanding green roof areas in Leipzig	Ecosystem Services Climate Adaptation & Mitigation Water Resource Management
Arthropods and facade greening (Schneider 2023)	Acceptance of facade greening is influenced by positive perceptions of arthropods	Ecosystem Services Air Quality & Pollutant Reduction Health & Social Impacts
Green roof vegetation and ecosystem functions (Ziehlke 2023)	Green roof types and management significantly influence biodiversity and water retention	Ecosystem Services Water Resource Management Climate Adaptation & Mitigation

Green roofs provide essential habitats for flora and fauna, contributing to increased urban biodiversity. Certain types of roofs, such as those with wetland plants, have demonstrated a particularly strong ability to support various species, highlighting their unique role in enhancing biodiversity within cities.

These roofs contribute not only to biodiversity but also to urban climate regulation. By reducing the Urban Heat Island effect, they help regulate temperatures and insulate buildings. Roofs with high plant coverage and efficient irrigation systems have been shown to significantly lower surface temperatures, thereby reducing the need for air conditioning and stabilizing building temperatures. In addition to regulating climate, green roofs play a vital role in water management. They retain rainwater, reduce runoff and helping to prevent urban flooding. Wetland roofs, in particular, enhance rainwater retention and even contribute to the purification of grey water. By absorbing rainwater and filtering pollutants, green roofs lessen the pressure on urban drainage systems. Furthermore, these roofs act as natural air filters, capturing dust and pollutants from the atmosphere. Specific types of roofs have even been found to host fungi capable of degrading harmful chemicals like phthalates, contributing to cleaner urban environments. Green roofs also offer significant energy efficiency benefits. Acting as insulators, they reduce the need for both heating and cooling in buildings. By stabilizing indoor temperatures, especially during the summer months, green roofs can lead to substantial energy savings. Beyond their ecological and energy benefits, green roofs also foster social and mental well-being. In densely populated urban areas, these green spaces provide much-needed areas for relaxation and interaction, reducing stress and improving the quality of life for residents.

Figure 8.5 Overview of the multifunctional co-benefits of the UFZ green roofs.

As cities continue to expand and face rising environmental challenges, integrating nature-based solutions like green roofs becomes increasingly vital. Beyond their ability to mitigate climate impacts, green roofs significantly enhance urban biodiversity, improve air and water quality, and offer valuable social benefits, such as promoting mental well-being and fostering community interaction (Fig. 8.5). The co-benefits discussed in this report underscore how green roofs contribute not only to creating sustainable and resilient urban ecosystems but also to reducing energy demands and protecting buildings from environmental stressors. As environmental pressures intensify, the widespread adoption of green roofs will play a critical role in shaping the future of urban development, ensuring that cities can thrive sustainably while enhancing the quality of life for their residents.

8.5 Challenges and barriers

The UFZ Research Green Roof lab infrastructures mainly focus on biodiversity and urban water budgets. In that sense they are mainly designed to retain stormwater and provide biodiversity through different plant mixes. Within MULTISOURCE we provided only few samples as sampling depended on a few intense storm events that led to rare overflow events.

8.6 Main outcomes

By focusing on stormwater and irrigation water demand, data and models were provided to assist dimensioning and modeling of green roof systems. To this end a robust dual layer green roof model was developed that enables the inclusion of green roofs in water infrastructure planning and dimensioning (Knappe *et al.*, 2023). Further vegetation monitoring methods were developed to monitor tree crowns in urban settings. For urban trees a smartphone assisted canopy monitoring method has been established that evaluates the effect of tree swales on canopy status (Sippel *et al.*, 2023).

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9 MULTISOURCE Monitoring outcomes

9.1 Common results

All in all, the monitoring work of MULTISOURCE was achieved according to the expectations raised at the beginning of the project and according to the monitoring plans laid down. No case study was comparable, results are pilot and case specific. In that sense, it is not possible to provide results across the project, but only per pilot. However, this enabled very detailed assessments of their performance and providing remarkable examples of tailored optimization and local stakeholder assessment.

Moreover, it can be said that the degree of collaboration among partners has been very high. Through WP1 online meetings, project annual meetings and several bilateral initiates partners have shared results, discussed challenges and opportunities and tried to ensure that common results in the sense of shared know-how was effectively developed during the monitoring work. These implies a high degree of sharing experiences with different technology designs and operation, water types (raw, high-strength, black, greywater, wastewater; CSO; stormwater; rainwater), pollutants (from conventional to micropollutants, microbiological indicators and microplastics), as well as on stakeholder activities and co-benefits monitoring.

9.2 Common achievements

MULTISOURCE WP1 monitoring work led to establishing a common framework for exploring the implementation and optimization of online sensors and control, as well as for the activities with stakeholders and co-benefits monitoring, as detailed in D1.1.

9.3 Challenges

Beyond the individual operational challenges of each pilot, MULTISOURCE work with the stakeholders identified and discussed with the different local stakeholders' challenges for the future implementation of nature-based solutions. Main general concerns related to operation strategies tailored for urban areas, need for disinfection of effluents to meet European regulation for water reuse, invasive species and biodiversity control, existing regulations and general practice for urban areas, which hinder implementation of nature-based solutions as decentralised treatment options, and the fact that NBS can be land-intensive. A highly relevant barrier noted was ownership of the projects and/or technical systems and ensuring continuous and reliable operation on a client ground.

9.4 Future perspective

There are still several results to be treated, discussed and organized. MULTISOURCE WP1 work will continue for the next months focused on T1.3: Pilot evaluation (M36 – M48), and bringing several of the results reported herein, as well as all detailed components of the monitoring and evaluation out into the scientific community, practitioners, water sector and general public. The next key deliverable of WP1 will be the pilot factsheets (D1.3). Meanwhile, all pilots and WP1 partners are invested in pushing the scientific publications into open access papers, make the data available, and invest the last months of the project in dissemination and communication activities promoting the outcomes of WP1 work.

At the local level, there are several lessons being learned, new plans being made for how to further test the existing pilots, or implement the knowledge gathered in new systems and new research projects. The next months will also be used for quantifying the impacts of each pilot, and WP1 as a whole.

The overall goal of MULTISOURCE is to, together with local, national, and international stakeholders, demonstrate a variety of about Enhanced Natural Treatment Solutions (ENTS) treating a wide range of urban waters and to develop innovative tools, methods, and business models that support citywide planning and long-term operations and maintenance of nature-based solutions for water treatment, storage, and reuse in urban areas worldwide. The project includes seven pilots treating a wide range of urban waters. Two individual municipalities (Girona, Spain; Oslo, Norway), two metropolitan municipalities (Lyon, France; Milan, Italy), and international partners in Brazil, Vietnam, and the USA will contribute to each of the main project activities: ENTS pilots, risk assessment, business models, technology selection, and the MULTISOURCE Planning Platform. The use of urban archetypes in the Planning Platform will enable users to quickly classify regions (in both developed or developing countries) suitable for the application of nature-based solutions for water treatment (NBSWT) and compare scenarios both with and without NBSWT.

MULTISOURCE
enhanced natural treatment solutions

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