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MUSTBE

D.3.3.1. NBS efficiency report

MUSTBE - *Multidimensional storm water treatment in urban areas for cleaner Baltic Sea* project

Rīga

2026

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1. Introduction

Various nature-based solutions (NBS), such as constructed wetlands, biofilters and rain gardens for stormwater management is proposed to reduce the impact from stormwater in urban environment and on the receiving natural water body. It is a sustainable and nature-based solution designed to mitigate the negative impacts of urban water runoff by emulating natural wetland processes. It serves as a treatment system that effectively removes pollutants, such as suspended solids, nutrients, and heavy metals, from stormwater before it enters natural water bodies. Different types of nature-based solutions utilize combined processes of physical filtration, sedimentation, biological uptake, and microbial degradation to improve water quality.

Research by Kadlec and Wallace (2009) emphasizes the role of hydraulic design in optimizing the performance of nature-based solutions for stormwater treatment. By controlling hydraulic retention time and flow patterns, system efficiency can be enhanced, allowing for sufficient contact time between water and the wetland matrix. Additionally, proper design considerations should account for factors such as wetland depth, substrate composition, and hydrologic connectivity to ensure optimal pollutant removal performance.

According to Scholz et al. (2011), constructed wetlands and similar solutions function as "engineered ecosystems" that mimic the functions of natural wetlands, providing habitat for diverse plant and microbial communities that contribute to pollutant removal through processes such as adsorption, sedimentation, and plant uptake. The presence of emergent vegetation plays a pivotal role in enhancing treatment efficiency by facilitating the interaction between plant roots and microorganisms (Vymazal, 2013). This interaction fosters a symbiotic relationship wherein plants provide oxygen to support microbial activity, while microbes aid in nutrient uptake and organic matter decomposition.

By executing this monitoring plan, we strive to enhance our understanding of performance by NBS in stormwater treatment and provide valuable insights for policymakers, urban planners, and environmental agencies. The knowledge gained from this study will play a pivotal role in promoting resilient and sustainable stormwater management strategies in Tallinn, Viimsi, Pori, Rīga and Söderhamn, ultimately contributing to the conservation of our natural resources, and safeguarding our communities against future stormwater-related challenges.

2. Monitoring plan

In recent years, NBS have gained prominence as sustainable and cost-effective methods for stormwater treatment. Recognizing the importance of implementing NBS, this monitoring plan outlines a comprehensive approach to assess the effectiveness and performance of nature-based stormwater treatment systems at selected location in Tallinn and Viimsi in Estonia, Pori in Finland, Rīga in Latvia, and Söderhamn in Sweden.

This monitoring plan aims to address various aspects of stormwater treatment using nature-based techniques, encompassing both qualitative and quantitative measurements. The key objectives of the monitoring activity are:

1. Evaluate the efficiency of nature-based stormwater treatment systems in reducing pollutants and improving water quality.
2. Assess the performance of green infrastructure in managing stormwater runoff and reducing flood risks.
3. Monitor the ecological benefits of NBS, including biodiversity promotion and habitat restoration.
4. Gather data on the cost-effectiveness and maintenance requirements of nature-based stormwater solutions.
5. Provide evidence-based recommendations for integrating NBS into future stormwater management strategies.

To achieve these objectives, a multi-faceted approach is adopted, involving data collection and analysis. The monitoring plan considers the following key components:

1. Site Selection: suitable locations within the target cities and towns to install nature-based stormwater treatment systems, ensuring representation of various urban and rural settings have been selected.
2. Data Collection: Implement a comprehensive data collection process, including hydrological data, meteorological patterns, water quality parameters, and pre-existing infrastructure.
3. Performance Monitoring: Utilize advanced monitoring techniques to assess the efficiency of NBS in pollutant removal, runoff reduction, and water quality improvement.

Before installing the NBS for stormwater treatment, comprehensive pre-installation monitoring activities were conducted to establish baseline data and understand the existing conditions at the site. After the NBS are installed and become operational, post-setup monitoring activities are performed to be carried out to assess their performance, efficiency, and impact.

In order to assess the performance of the demonstration sites for stormwater water quality improvement, relationship between precipitation, runoff, flooding and water quality is established. This is based on real measurements at the sites.

3. Methodology and monitoring parameters for the pilot sites

Nature-based solutions (NBS) for stormwater treatment are designed to mimic natural processes and effectively manage stormwater runoff while promoting environmental sustainability. Monitoring the performance of these solutions requires a comprehensive set of parameters to evaluate their efficiency and effectiveness. The parameters used for monitoring NBS can be classified into four main categories: physical, chemical, meteorological and hydraulic (Table 1.). Depending on the site and its characteristics, parameters include, for example, pH, nutrients, hazardous substances, toxins, temperature, turbidity, flow, oil products, nitrogen, water level, and electrical conductivity. Monitoring will continue after the MUSTBE project ends.

While indicators Table 1 are commonly used to assess water quality, this project establishes specific key targets. Water samples taken before and after NBS construction have defined result targets: it is expected that the NBS will deliver pollutant removal efficiencies of at least 60% for suspended solids, 30% for total Nitrogen, 60% for pathogens (e-Coli), 50% for hydrocarbons (oil products), 40% for metals and 0.5 units for pH.

Table 1. Key Parameters for Water Sampling

Parameter	**Unit**	**Sampling technique**	**Sample analyses**
Electrical conductivity	mS m^{-1}	Locally installed sensor	Real-time
pH	-		
Temperature	°C		
Dissolved oxygen	mg O_2 L^{-1}		
Water turbidity	NTU		
Total Nitrogen	mg N L^{-1}	Manual grab sample or automated sampling tools.	ISO 11905-1:2017 - Water quality - Determination of nitrogen - Part 1: Method using oxidative digestion with peroxodisulfate; ISO 11905-2:2017 - Water quality - Determination of nitrogen - Part 2: Method using hydrazine sulfate.
Total Phosphorus	mg P L^{-1}		ISO 6878:2004 - Water quality - Determination of phosphorus - Ammonium molybdate spectrometric method.
Total Suspended Solids	mg L^{-1}		ISO 7027-1:2016 - Water quality - Determination of turbidity - Part 1: Quantitative methods.

Chemical oxygen demand	mg O_2 L^{-1}		ISO 6060:1989 - Water quality - Determination of the chemical oxygen demand.
Biochemical oxygen demand	mg O_2 L^{-1}		ISO 5815-1:2003 - Water quality - Determination of biochemical oxygen demand after n days (BODn) - Part 1: Dilution and seeding method with allylthiourea added.
Hydrocarbons	mg L^{-1}		ISO 9377-2:2000 - Water quality - Determination of hydrocarbon oil index - Part 2: Method using solvent extraction and gas chromatography. ISO 9377-3:2019 - Water quality - Determination of hydrocarbon oil index - Part 3: Method using infrared spectrometry.
Chlorides	mg L^{-1}		ISO 9297:2010 - Water quality - Determination of chloride - Silver nitrate titration with chromate indicator (Mohr's method).
Heavy metals Zinc (Zn) Chromium (Cr) Lead (Pb) Copper (Cu)	mg L^{-1}		ISO 17294-2:2016 - Water quality - Determination of selected elements including uranium isotopes by inductively coupled plasma mass spectrometry (ICP-MS). ISO 11885:2007 - Water quality - Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES).
Precipitation/rainfall	mm	Locally installed weather station	Real-time
Air temperature	°C		
Relative air humidity	%		
Wind speed and direction	m s^{-1}		
Sunshine hours	hours		
Solar irradiance	W m^{-2}		
Volumetric water content	%	Locally installed sensor	Real-time
Water level retained	mm		
Flowrate	L min^{-1}	Calculated estimations	Calculated from hydraulic and meteorological data
Evapotranspiration	litre		

For the determination of parameters rain gauges and flow/level sensors are installed where necessary. In some locations, where infiltration is the key for NBS operation, soil humidity sensors are installed to measure soil water content and to estimate ground water level. These sensors provide real time online data. The sensor data can also be used to calibrate hydrodynamic models of the sub-catchments developed within WP1, both grab-sampling and continuous online monitoring can be used. Monitoring frequency for specific sites was chosen based on pilot site specifics.

The sampling frequency to assess the performance of NBS for stormwater treatment can vary widely depending on several factors, including the specific goals of the assessment, the characteristics of the NBS, the regulatory requirements, and available resources. However, the most common approaches include event-based sampling and regularly scheduled sampling that have also been used in some MUSTBE pilot areas.

4. Pilot sites

4.1 Pori

Pori is located in the Kokemäenjoki river basin and is one of the most vulnerable flood risk areas in Finland, with around 15000 people living in the flood-prone area. The Pori city area is densely built and river floods and Pluvial floods risks are expected to increase in the future due to climate change.

Pori features two pilot areas - wetland and a parking lot in Central Square - each with unique specifics and plans. With smart nature-based solutions and water quality and quantity monitoring, the city of Pori aims to improve the stormwater quality, enhance the capability in managing stormwater floods as well as find the best methods for reducing and treating the polluted waters in the pilot areas.

Table 2. Pori Pilot Sites Baseline and Target Values

		Suspended solids, mg/L	**Total Nitrogen,** mg/L	**E-coli,** CFU/100 ml	**Hydrocarbons,** mg/L	**Metals,** µg/L
Baseline values	**Wetland**	340	7.5	*4700**	1.3	*93,4**
	Central Square	100	2	*4700**	0.49	315
Target values	**Wetland**	**136**	**5**	**1880**	**0.65**	**56**
	Central Square	**40**	**1.4**	**1880**	**0.24**	**189**

In addition to the NBS installations, measurements, and monitoring by both pilots, a weather station has also been set up in Pori. The weather station is an OTT Hydromet WS700-UMB Smart Weather Sensor, powered by the electricity grid via power distribution lines. It measures atmospheric pressure, precipitation, air temperature, wind speed and direction, and humidity.

4.1.1. Wetland

The wetland is located in the Lotskeri residential area with a catchment area of 55.4 ha. The wetland was constructed about 30 years ago for stormwater treatment and had not been maintained since, resulting in overgrown vegetation. During dry periods, the water level was low or absent, resulting also in an odour nuisance in the area. In addition, the metal and acidification load on the wetland is generally increased by a stormwater pumping station located towards the end of the wetland, through which the wetland receives stormwater from the residential area over an area of 33.3 ha.

Figures 1 and 2. Wetland Before and After Construction

Acid sulfate soils are the main challenge: exposure acidifies soil, leaching metals into the wetland (acidic, metal-rich water flows untreated downstream). Solutions include two stone dams (slow flow, promote sedimentation), two central filtration dams (biochar/gravel bind metals), and a final hollowstone/pumice dam (raises pH, precipitates metals).

In the Lotskeri wetland - continuous discharge water measurement uses pH sensors (Hach Polilyte Plus HF Arc 120), which are moved around from time to time, powered by solar panel and battery (relocated periodically), OTT MF pro flow meter (Hydrometa), and groundwater level meter.

The measurements were conducted in two ways: real-time and occasional water samples. The real-time monitoring devices measured pH, water level, and water flow. The data collected by the meters was transferred to open-source software called Grafana. All the meters measured the value every 30 minutes. Meteorological data, including precipitation, was also used to analyze the pilot site efficiency.

Additional samples were taken post-construction: Sep 18, 2024 (autumn, immediate), Mar 10, 2025 (spring, 6 months), Aug 28, 2025 (summer, 1 year) - assessing seasonal effects (winter omitted due to wetland limitations). Inlet/outlet samples, plus mid-wetland (Mar: between biochar dams; Aug: post-biochar, pre-pumice), evaluated stormwater pumping station impacts from nearby residential area (unknown pre-design).

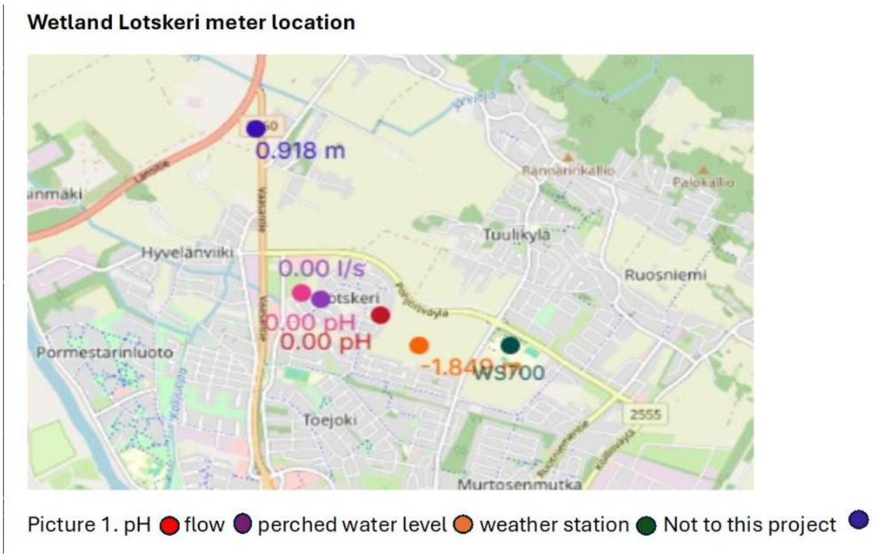


Figure 3. Wetland Lotskeri Sensor Locations

The occasional water samples included total and soluble concentrations of metals, such as arsenic, cadmium, chromium, copper, nickel, zinc, aluminium, manganese, and iron. In addition, phosphorium, total suspended solids, pH, electrical conductivity, total nitrogen, and sulphate were measured most of the time. Some metals, such as antimony, cobalt, lead, molybdenum, vanadium, potassium, calcium, magnesium, and mercury, were only measured on September 18, 2024 and were later determined to be excluded from the future studies. The concentrations of these metallic compounds were low and therefore did not cause a significant impact on the quality of the water.

As mentioned acid sulphate soils and the harmful substances such as heavy metals from stormwater make the water quality poor. For pH analysis two similar 42-day periods - before and after construction - were identified, matching in observation length and rainfall. Measurement results for these periods were downloaded, daily pH averages calculated, and then compared; period averages, minima and maxima were derived. Despite NBS being set up, a slight pH increase appears evident. As mentioned water might be quite acidic due to the acid sulphate soils, but once plants establish and the bed stabilizes, leaching could decrease.

Table 3. pH in Wetland Lotskeri Endpoint

Period in Lotskeri endpoint	Measurement days (n)	Average pH average of all days	Min pH	Max pH
24.6.–4.8.2024	42	4,26	3,87	4,65
11.8.–21.9.2025	42	4,40	4,03	5,11
		increase 0,14		

For this pilot site the Grafana platform displays sensor readings and relationships between parameters, including rainfall's impact on chemical elements, metals, and water quality. Analysis of samples from March 9-10, 2025, reveals effects from recent rainfall, coinciding with sharp pollutant increases - for instance, TSS exceeded pre-NBS construction levels at all points. Total nitrogen and metals show subtler but evident rises. While no clear pollution reduction appears between pre-, mid- and post-wetland points, overall levels have declined markedly since the first 2023 sampling, target values have also been reached.

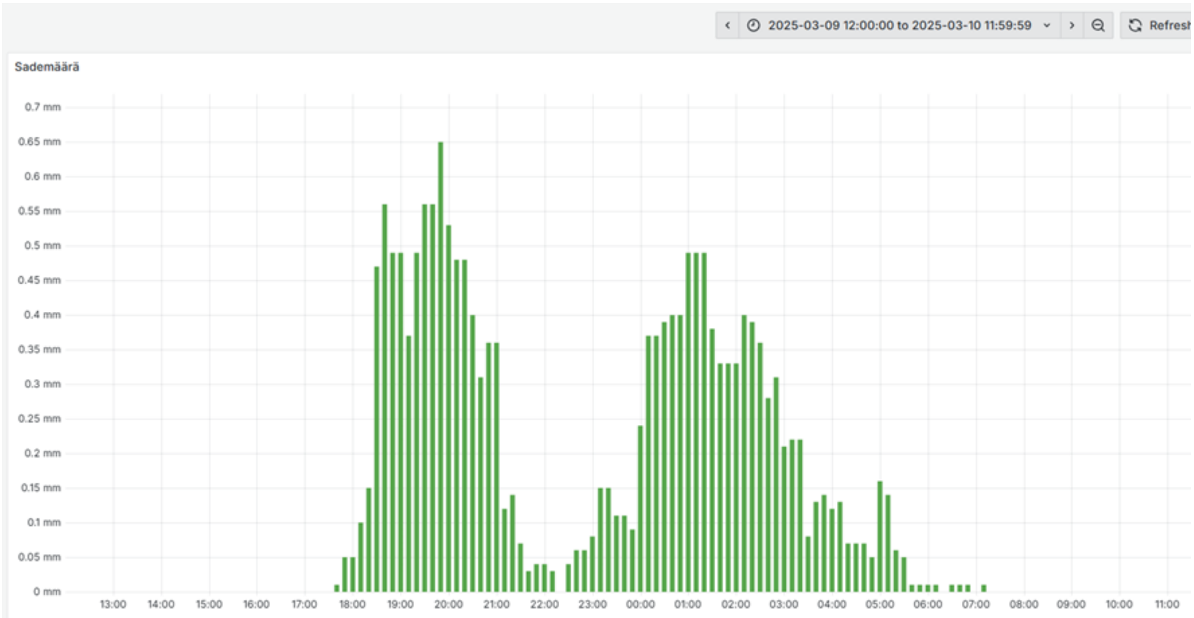
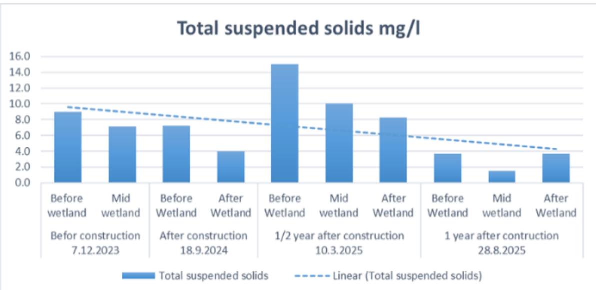


Figure 4. Precipitation in Wetland Lotsheri, March 9–10, 2025



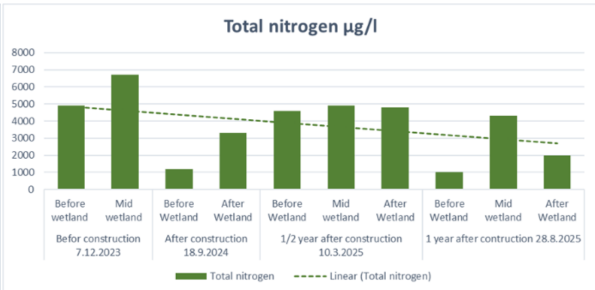


Figure 5. Total Suspended Solids

Figure 6. Total Nitrogen

Further robust data requires ongoing sensor analysis and pre/post-rainfall water sampling, including combined approaches tailored to catchment areas, rainfall duration, and intensity. This would better quantify rainfall impacts demonstrating the longer-term impacts and effectiveness of the NBS.

Further robust data requires ongoing sensor analysis and pre/post-rainfall water sampling, including combined approaches tailored to catchment areas, rainfall duration, and intensity. This would better quantify rainfall impacts demonstrating the longer-term impacts and effectiveness of the NBS.

Metal analyses capture instantaneous concentrations. Compared to baseline (chromium below detection, excluded), total manganese, nickel, iron, and aluminium increased overall, with a notable spike in the March 10, 2025 sample due to cold temperatures, high flow, and soil metal/acidity release during thaw - when wetland processes (especially biological) are inefficient. While aluminium, nickel, and manganese show reductions, iron varies seasonally. Finnish winters weaken performance, leaving post-wetland metals high vs. normal streams.

One of the challenges in the wetland prior to NBS implementation was that the water level was low during dry periods. Based on the measurements, the average water flow and water level have been relatively even, and the water level has remained high enough (well above 0 m) that the bottom of the wetland has not been exposed to oxygen - preventing more harmful effects of the acid sulphate soils. It can be concluded that the construction of the pilot site has helped to keep the water level higher than previous.

Results show that the mid-wetland stormwater pumping station (unknown until construction) significantly impacted water quality, with its pipe between filtration dams treating only downstream flow. Results show rising acidity/metals toward outlet, but residential inflow complicates solution evaluation. Full assessment requires blocking this pipe.

In addition, pH varies drastically at very short intervals, so it is difficult to assess the actual impact of the pilot site on the increase in pH. The quality of the water coming from the stormwater pumping station, precipitation, temperatures, seasons, etc. significantly affect pH.

On the other hand, water from two sources - catchment area and pumping station - reveals significant acid sulphate soil impacts, underscoring their role in land-use planning. The catchment, mostly dredged fields from the 1960s-1970s, shows lower metal concentrations at the wetland inlet (dominated by catchment water), indicating 50-60 years of soil leaching. In contrast, drainage pipe water from a residential area built on acid sulphate soils in the early 2000s is highly acidic with elevated metals, signalling ongoing oxidation. This highlights the need to educate on long-term environmental risks of acid sulphate soils.

Conclusion

The wetland solution has partially reduced acidity, stabilised hydrology, and reduced some metal concentrations, but its effectiveness is strongly constrained by climatic conditions, rainfall events, and untreated inflows from a stormwater pumping station. The results emphasise that NBS in acid sulphate soil regions should be viewed as long term risk management tools, requiring careful hydraulic design, source control, and sustained monitoring rather than short term standalone treatment solutions.

4.1.2. Central Square

The Central Square pilot site is located in the Pori city center. The pilot area is 0.29 ha with a catchment area of 0.11 ha. The pilot site aimed to create a replicable stormwater management solution in a densely built urban area where there are several competing needs for the space: parking lots, green areas, and stormwater management. The goal of the solution was to improve stormwater infiltration in an urban area with limited space.

Previously, the area was affected by flooding during heavy rainfall and snowmelt due to the dense surroundings and inefficient stormwater management. The vegetation was placed higher than the ground, and the area was covered by an impermeable surface, which made the stormwater management insufficient. The vegetation in the area was in poor condition - the roots did not get enough water and oxygen due to the impermeable surfaces and compacted soil. The selected nature-based solution aimed to resolve these issues.

The nature-based design included:

- Renewing the existing vegetation and green lanes
- Levelling the surface so that the water flows to the green lanes and depressions
- Adding different species of trees, shrubs and perennials
- Adding permeable pavement to improve water absorption

The specially designed soil layers at tree's root area facilitate accumulation of peak runoffs. In literature it has been investigated that one tree can absorb up to 6 m^3 of rainwater. This will substantially reduce the need to construct new pipelines and treatment solutions.

Water passing through the solution is directed to an overflow well. This well also serves as a monitoring point for water quality sampling. Any excess water bypassing the solution is further directed to the city's stormwater pipe network.

Figure 7. Parking Lot – Ortophoto Overwiew

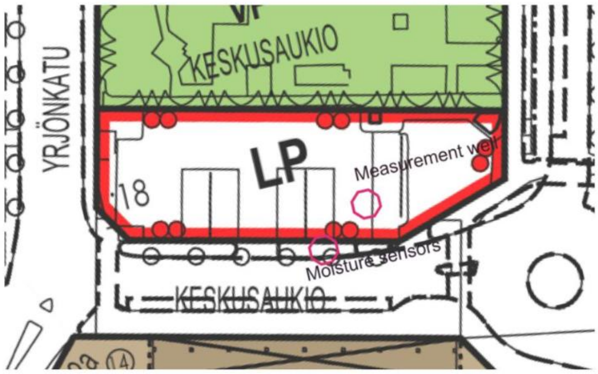


Figure 8. Parking Lot – Shematic Overwiew

Project targets were 60% reduction for suspended solids, 30% for total nitrogen, 60% for pathogens, 50% for oil products, and 40% for metals, calculated from baseline values measured May 25, 2023 (dry weather: only 18.9 mm precipitation). A July 3, 2025 stormwater sample added E. coli analysis.

The studied metals (Table 2) were zinc, chromium, manganese and iron, aluminium, and sulphur with soluble and total concentrations were measured for some. Only the aluminium concentration was left out of the soluble measurement. Baseline values were also determined for phosphorus, chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen and hydrocarbons (Table 3).

Table 4. Baseline Metal Concentrations

Metal	Soluble	Total
Cromium (µg/l)	<2	25
Manganese (µg/l)	71	190
Zinc (µg/l)		74
Iron (µg/l)	230	12 000
Sulphur (mg/l)		5.6

Table 5. Baseline Stormwater Quality

	Value
Phosphorus (µg/l)	1 300
COD mg/l O_2	120
TSS (mg/l)	340
Total Nitrogen (µg/l)	7 500
Hydrocarbons (µg/l)	1 320

The baseline values included more studied parameters than were required in the project, such as phosphorus and COD. Nevertheless, more extensive studies gave a deeper understanding of the quality of the stormwater entering the solution (Table 4).

Table 6. Baseline and Target Values for Pori's Central Square Solution.

	TSS (mg/L)	Total nitrogen (mg/L)	E-coli CFU/100 ml	Hydrocarbons (mg/L)	Metals (µg/l)
Baseline	340	7.5	530*	1.3	93.4
Target	136	5	212	0.65	56

** Baseline taken on July 3rd, 2025.*

The water quality was measured in two ways: through real-time monitoring devices and through occasional water samples. Real-time devices measure parameters, including water level, temperature, electrical conductivity, salinity, total dissolved solids, water flow, and soil moisture.

Two EC-5 soil moisture sensors are installed at different heights in the stormwater basin. An OTT Hydromet OTT PLS-C measures water table variations, temperature, electrical conductivity (calculating TDS/PSU). Sensor readings are recorded every 5 minutes. The measurement well is equipped with sensors that record electrical conductivity, salinity, water temperature, suspended solids, water level (via pressure sensor), and overflow (calculated from level data).

Figure 9. Pressure Level Sensor[1]

Figure 10. EC-5 Sensor[2]

Online data detected with sensors is displayed in Grafana - an open-source data visualization and monitoring platform that allows users to query, visualize, and alert on metrics, logs, and traces from various databases. It enables the creation of customizable, real-time dashboards to track infrastructure health, application performance, and business metrics.

[1] https://www.otthydromet.com

[2] https://www.onsetcomp.com

Water samples were taken on October 8th, 2025. This sample was used to evaluate whether the project's targets were met. The main issue with sampling the outflowing water from the solution was that there was very little overflow as the solution succeeded in retaining nearly all of the water.

Aluminium, nickel, copper, and zinc were not measured in every sample and are presented in their own section. Chromium, manganese, and iron have been studied in every sample, which made it possible to compare the values. Phosphorus, COD, TSS, electrical conductivity, nitrogen, and hydrocarbons were studied at every sample time. BOD, coliforms, enterococci, and E. coli were measured only on certain sampling occasions and thus have no comparable data.

From the readings of the sensors, the relationship between the readings, such as rainfall to water level or electrical conductivity to suspended solids, etc., can be analysed. For example, chart below show precipitation versus soil moisture at 50 cm and 150 cm depths. Precipitation directly increases moisture at both levels, with similar response patterns; deeper soil remains consistently drier. Precipitation also affects water salinity and total dissolved solids (TDS), which follow nearly identical curves. These are influenced not only by rain but also by snowmelt carrying road de-icing salts from winter applications.

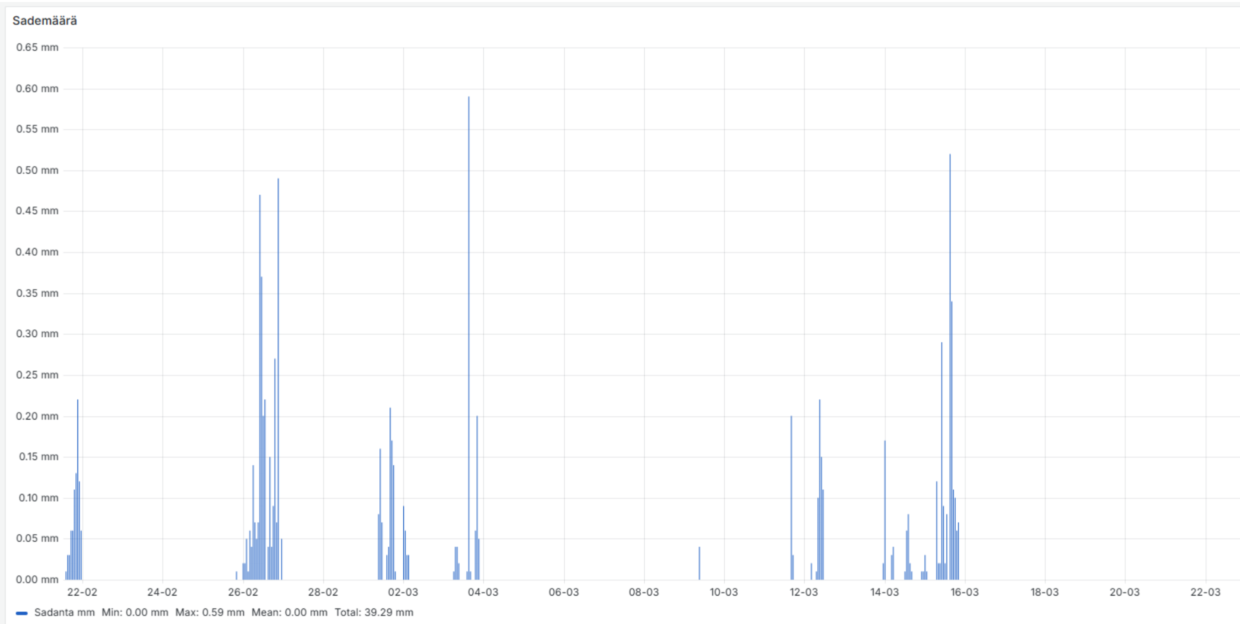


Figure 11. Precipitation in Pori, February 21 – March 21, 2026

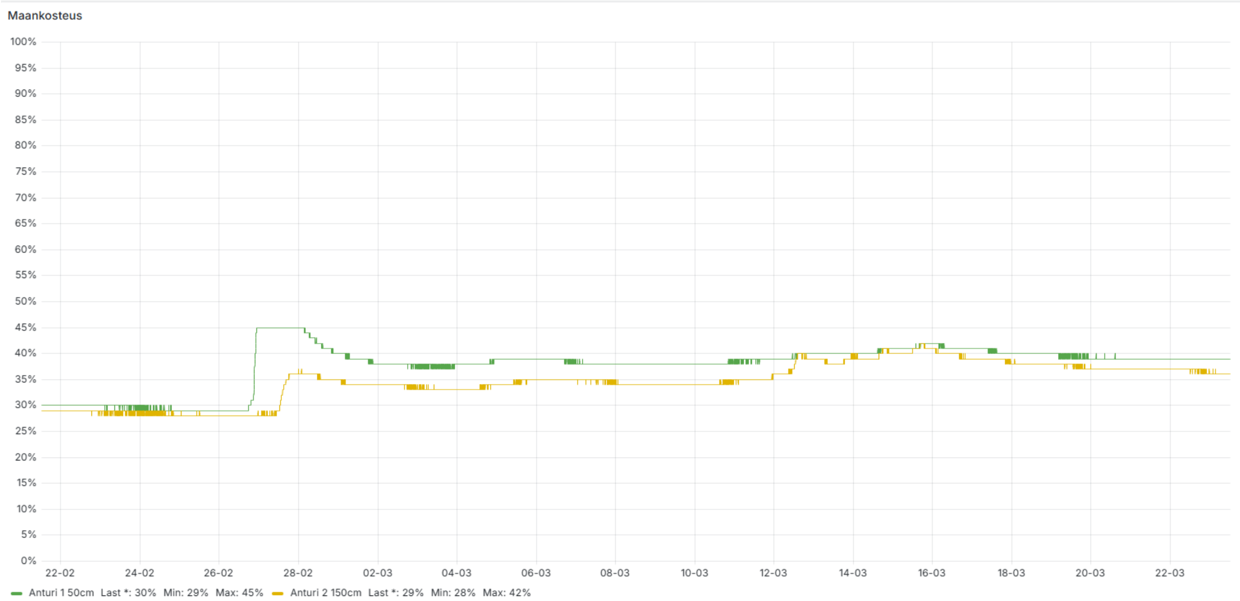


Figure 12. Soil Moisture Dynamics at 50 cm and 150 cm Depths, February 21 - March 21, 2026

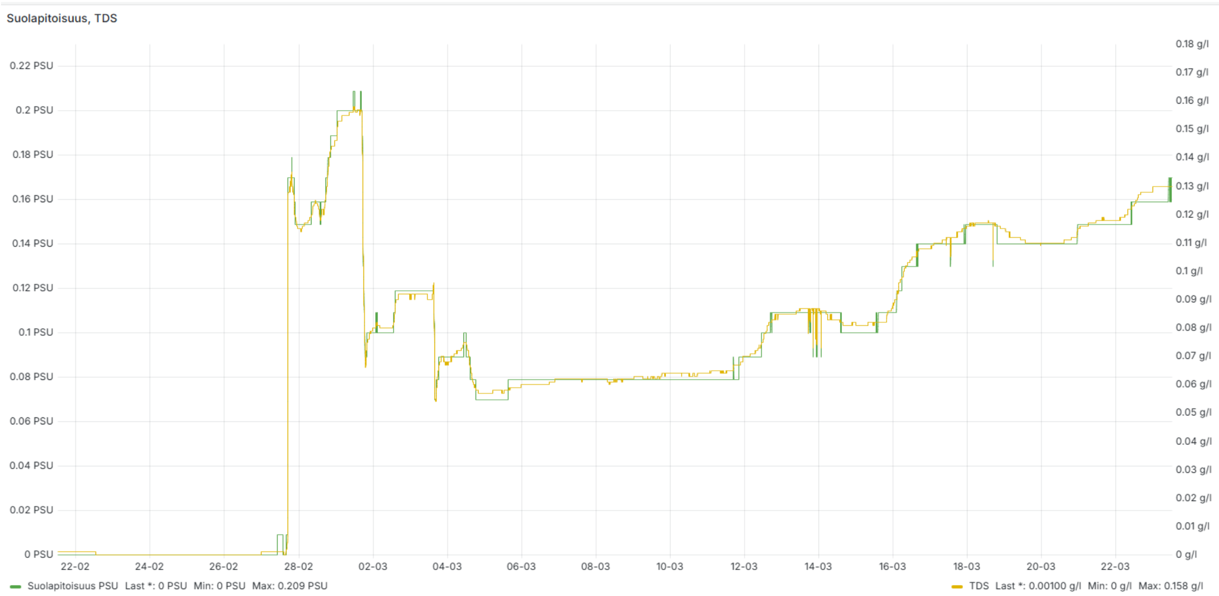


Figure 13. Total Dissolved Solids and Salinity Dynamics, February 21 – March 21, 2026

It should be noted that irregularities in sensor readings are visible in the data and have been recorded. These issues arise from several factors, including initial sensor settings, air and water temperatures, as well as freezing of water and soil.

The effectiveness of the NBS in treating incoming rainwater was also analysed. Analysis covered July 31, 2025, to January 15, 2026, incorporating catchment area, rainfall (mm), and outflow to the pipe network. As shown in Figure 13.93% of rainwater infiltrates, evaporates, or transpires, with only 7% flowing to the pipe network. Laboratory analysis of this outflow (sample taken on October 8th, 2025) assessed suspended solids, total nitrogen, hydrocarbons, E. coli, and metals. Water quality shows substantial improvement (98-100%) compared to surface runoff and baseline targets.

Table 7. Rainfall Measurements, Chemical Results from the Outflow (7% from total rainfall)

Rainfall 31.7.2025-15.1.2026		**299,7 mm**	
Catchment area		1700 m2	
Rainwater total (5,5 months)	299,7 mm x 1700 m2=	**509,5 m^3**	100 %
Measured outflow to pipe network		**37,5 m^3**	7 %
infiltration, evaporation, transpiration		**472 m^3**	93 %

	concentration of harmful substances in basevalues (analyzed)	**Total rainfall 31.7.2025-15.1.2026 (5,5 months)**	**calculated amount of harmful substances in stormwater (rainfall x concentration)**	measured concentration of harmful substances in outflow	**outflow from keskusaukio 31.7.2025-15.1.2026 (5,5 months)**	**amount of harmful substances in outflow to pipe network and to receiving waters**	**target (%)**	**total reduction of harmful substances in outflow (%)**	(reduction in concentration)
		509 m^3			**37,5 m^3**				
Suspended solids	340 mg/l		**173,06 kg**	28 mg/l		**1,05 kg**	**-60 %**	**-99 %**	-92 %
Total nitrogen	7500 µg/l		**3,82 kg**	2000 µg/l		**0,08 kg**	**-30 %**	**-98 %**	-73 %
Hydrocarbons	650 µg/l		**330,85 g**	50 µg/l		**1,88 g**	**-50 %**	**-99 %**	-92 %
Metals									
Zn	74 µg/l		**37,67 g**	21 µg/l		**0,79 g**	**-40 %**	**-98 %**	-72 %
Cr	25 µg/l		**12,73 g**	2,3 µg/l		**0,09 g**	**-40 %**	**-99 %**	-91 %
Mn	190 µg/l		**96,71 g**	24 µg/l		**0,90 g**	**-40 %**	**-99 %**	-87 %
Fe	12000 µg/l		**6,11 kg**	1900 µg/l		**0,07 kg**		**-99 %**	-84 %
E-coliform	**530 CFU/100 ml**			**0 CFU/100 ml**		0	**-60 %**	**-100 %**	-100 %

Conclusions

The Central Square pilot solution has managed to reach the targets set by the project i.e. reduce nitrogen, TSS, hydrocarbons, and metals of the stormwater. The most significant result is that the solution can retain nearly all (>90 %) of the incoming stormwater, except for heavy rainfall, when a small amount of water passes through the solution to the overflow well and from to the city's stormwater pipe network. The Central Square pilot solution not only improves the quality of the water but also reduces the stress on the city's stormwater pipe network, showcasing how flood risk can be reduced in compact urban areas.

4.2. Viimsi

The Viimsi pilot site is located at Randvere Road 21 in Haabneeme Parish, Estonia, covering an area of 0.35 hectares owned by Viimsi Municipality. The stormwater system catchment area is 11.6 ha. The site is situated near Lubja cliff, which discharges significant volumes of groundwater year-round, contributing to frequent flooding during heavy rainfall and snowmelt. Additionally, runoff from nearby traffic junctions introduces pollutants into the stormwater system, which ultimately degrades the water quality of the Baltic Sea. To address these challenges, the municipality is implementing a smart, nature-based stormwater management system that includes a stormwater pond with a sedimentation trap and a weir for water level adjustment, a water cascade, interactive elements, and a stormwaterfed fountain. The system is designed to slow peak flows, improve water quality, and demonstrate how stormwater can be reused in urban environments.

Figure 14. Viimsi Pilot Site Shematic Overwiew

Due to the exceeded budget, some modifications were needed in Viimsi pilot site, such as omitting some of the sensors that were initially planned to be included. However to ensure precise monitoring and automated water management, a comprehensive sensor network and data logging system were installed across the pond overflow and the storage tank. At the pond overflow concrete retaining wall, continuous monitoring is carried out using a closed-case Huba Control Type 681 level sensor operating on a 13 to 30 VDC power supply, which measures water levels up to 4 meters with an accuracy of plus-minus 10 millimeters via a 4 to 20 mA output. Water quality at the overflow is monitored by two Aqualabo sensors powered by 5 to 12 VDC and utilizing Modbus RTU RS-485 outputs: a Type C4E sensor measuring electrical conductivity from 0-200 µS/cm to 0-200 mS/cm and temperatures from 0 to +50 °C, and a Type NTU turbidity sensor with an integrated mechanical cleaning mechanism to measure water cloudiness up to 4000 NTU.

Figure 15. Huba Control Type 681 Level Sensor[3]

Figure 16. Type C4E Sensor Measuring Electrical Conductivity[4]

Inside the storage tank, water levels are measured by a second Huba Control Type 681 level sensor with identical technical specifications, while a 230 VAC powered +GF+ Type 2285 float switch provides relay control to automatically turn the pump on and off based on water levels. All sensor readings and operational data are gathered by an OMC-048 data logger operating on a 12 to 24 VDC power supply. The complete system operates locally, with data stored and accessed strictly on an internal, private network platform.

Baselines for suspended solids, nitrogen, E. coli, metals, and hydrocarbons - targeted for reduction across all pilot areas - were established from project-start estimates.

Table 8. Viimsi Pilot Site Baseline and Target Values

	Suspended solids, mg/L	**Total Nitrogen,** mg/L	**E-coli,** CFU/100 ml	**Hydrocarbons,** mg/L	**Metals,** µg/L
Baseline values	282	2	*4700**	*0,002**	*93,4**
Target values	**112**	**1,2**	**1880**	**0,001**	**56**

Samples were collected before NBS establishment (May 15, 2023) and after (March 4-6, 2026), with total suspended solids and total nitrogen analyzed on dry days. Another sample was taken for the determination of petroleum products on August 5, 2026. Precipitation was minimal over the three sampled days in March (Figure 19) and day in August. No water quality improvement appears in March, though post-installation readings may reflect spring snowmelt, salts, etc. The August analyses showed that the concentration of petroleum products was below the laboratory detection limit of <20 µg/L. Therefore, it is not possible to determine whether the target value has been achieved or to assess progress relative to the baseline concentration. These results are incomplete, as other project indicators remain unanalyzed for now.

[3] www.hubacontrol.com

[4] www.aqualabo.fr

Table 9. Water Quality Parameters in Viimsi Pilot Site

	15.05.2023	04.03.2026	05.03.2026	06.03.2026	05.08.2026	Unit
Suspended solids	3	4	<2	2	-	mg/L
Total Nitrogen	0.65	1.6	1.6	1.7	-	mg/L
Hydrocarbons	-	-	-	-	<2	µg/L

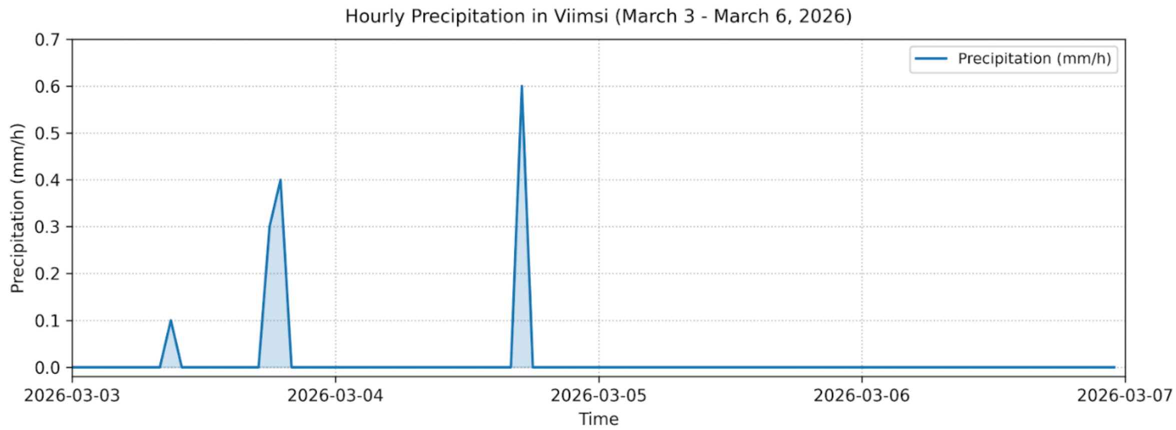


Figure 17. Hourly Precipitation in Viimsi, March 3 to March 6, 2026[5]

Meanwhile the sensor data demonstrate clear correlations. An analysis of hourly environmental data collected from the Viimsi pond between June 1 and June 10, 2026 (analyzed a 10-day summer period that included both dry days and significant precipitation), reveals a strong physical and chemical responsiveness to precipitation events. By comparing local hourly rainfall rates with the pond's electrical conductivity and dissolved oxygen levels, two distinct hydrodynamic mechanisms emerge: mineral dilution and mechanical aeration.

During dry periods (June 1 - 4), water parameters remain highly stable, with electrical conductivity hovering between 780 µS/cm and 830 µS/cm and dissolved oxygen staying low at 10 mg/L. Incoming rainwater - which is naturally low in minerals - dilutes the pond's ionic concentration. Heavy rain on June 5 - 6 (1.1 mm/h) dropped EC to 535 µS/cm, while a second major downpour on June 9 (2.0 mm/h) caused another sharp decline from 900 µS/cm down to 554 µS/cm. Raindrops physically churn the surface layer and introduce cooler, oxygen-rich water into the pond. This caused dissolved oxygen levels to spike rapidly during the June 5 - 6 event (exceeding 150%) before returning to baseline levels as aeration stopped and respiration resumed.

[5]www.open-meteo.com

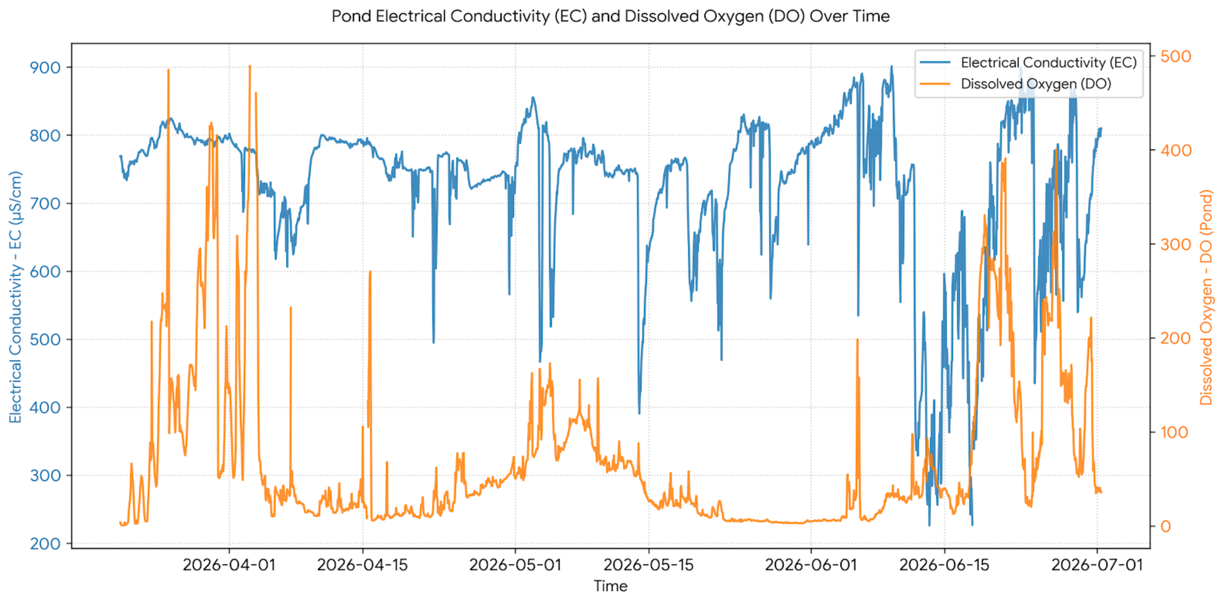


Figure 18. Electrical Conductivity and Dissolved Oxygen in Viimsi Pilot Site, April to July

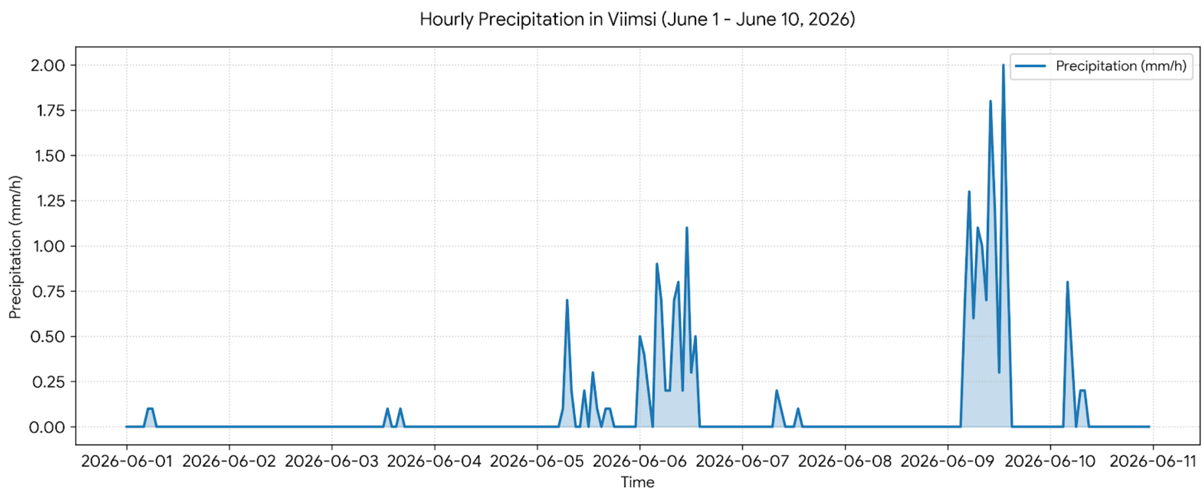


Figure 19. Hourly Precipitation in Viimsi, June 1 to June 10, 2026[6]

Conclusions

Rainfall acts as a natural regulator, temporarily boosting oxygen levels through surface mixing while softening the pond's mineral concentration through dilution. The sensor data on water levels in the tank and pond also show a clear correlation with precipitation. Accordingly, the water level rises shortly after precipitation. Overall, the pond metrics recorded during rainfall are consistent with those expected for a typical pond.

[6] www.open-meteo.com

To fully assess the effectiveness of Viimsi's pilot solutions, further analysis of the sensor data and a complete evaluation of the water sample quality should be carried out at different times and over a longer period, once the pond vegetation and other mitigation elements have fully developed.

4.3. Söderhamn

There are two separate pilot sites in Söderhamn - Söderhamnsporten and Broberg - each with its own specific conditions and solutions.

Söderhamnsporten is one of two pilot sites simultaneously implemented in Söderhamn and aimed at the sustainable management of stormwater and improved biodiversity in urban and coastal areas. The Söderhamnsporten pilot site is located in the vicinity of the new transportation hub that combines rail- and highway junctions, and connections to the centre of Söderhamn. Recent construction activities and increased traffic volumes have led to a significant rise in impermeable surfaces, posing challenges for stormwater management. Over the past decade, the area has experienced recurring flooding events, highlighting the urgent need for improved and sustainable stormwater solutions. The Söderhamnsporten pilot area focuses on proactively managing stormwater through a retention facility that reduces peak flows and improves water quality before discharge into the Söderhamn river with the use of a combination of sensors and nature-based approaches.

Söderhamn River receives untreated runoff from approximately 1 hectare of impervious surfaces, including the parking lot (ca 0.7 ha) and roof (ca 0.3 ha) of a supermarket. Prior to the intervention, this stormwater was discharged directly into the river without any form of treatment or retention.

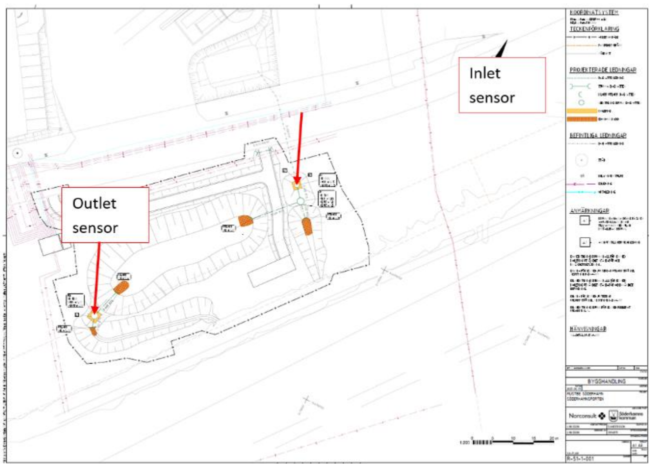


Figure 20. Söderhamnsporten Pilot Site Shematic Overwiew

The second pilot site in Söderhamn is Broberg - area is reserved for the new municipal elderly home. Broberg is located in a low-lying coastal area where water naturally accumulates, making stormwater management a central focus of the pilot. The project aims to ensure proper stormwater treatment and construct a new outlet to Söderhamn’s bay, addressing both current and future runoff pressures. The site presented several challenges, including high groundwater levels, sulfidic clay soils, fluctuating sea levels, ageing stormwater infrastructure, and heritage-listed buildings. The presence of oxidised sulphide clay added complexity to excavation and construction.

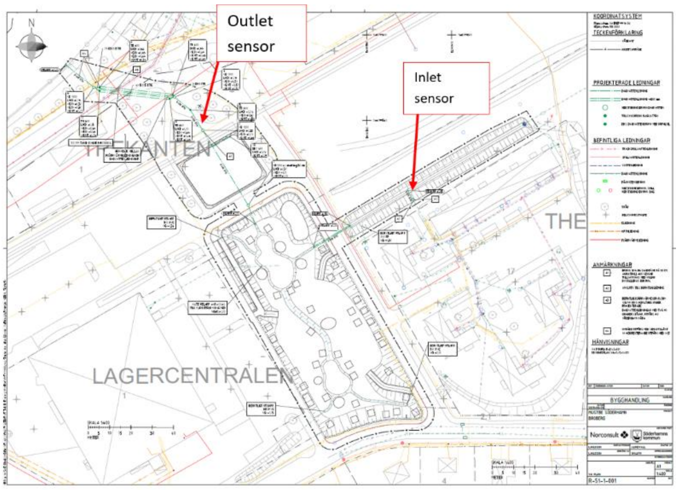


Figure 21. Broberg Pilot Site Shematic Overwiew

The sensors used in pilot sites are an Aqua Troll 500 multiparameter probe manufactured by In-Situ, powered by lithium batteries. It measures conductivity, turbidity, temperature, and water level at a 5-minute reading and transmission frequency. Rain gauge data is provided separately by the water company. Data from the AquaTROLL 500 are sent over the cellular network (SIM cards) to an FTP server to minimize transfer costs. The collected data is available internally to authorised municipal personnel.

As with all pilots, baseline and target values were calculated for both Söderhamn pilot sites. In 2023, sediment and water samples were collected. At that time, the specific MUSTBE demonstration sites had not yet been finalized, so sampling locations did not fully align with the actual pilots in Söderhamn. To ensure comparability, baseline water quality thresholds were established using the StormTac database instead. The 2023 samples thus served only to characterize general area conditions, not to evaluate MUSTBE pilot performance.

Table 9. Söderhamn Pilot Sites Baseline and Target Values

		Suspended solids, mg/L	Total Nitrogen, mg/L	E-coli, CFU/100 ml	Hydrocarbons, mg/L	Metals, µg/L
Baseline values	**Söderhamnsporten**	174	2.3	*4700**	*0,002**	*93,4**
	Broberg	88	1.3	*4700**	*0,002**	*93,4**
Target values	**Söderhamnsporten**	**69**	**1.4**	**1880**	**0,001**	**56**
	Broberg	**35**	**0.8**	**1880**	**0,001**	**56**

4.3.1. Söderhamnsporten

Laboratory Water Quality Results

Although the samples were not collected directly at the current pilot sites and omit some required parameters, the analyses remain comprehensive. Söderhamnsporten samples - taken from the adjacent former pond during early and mid-summer - provide relatively close baseline data. Sediment samples were also analyzed but are unlikely to be repeated due to budget constraints; they could still offer valuable insights into sediment accumulation overnight.

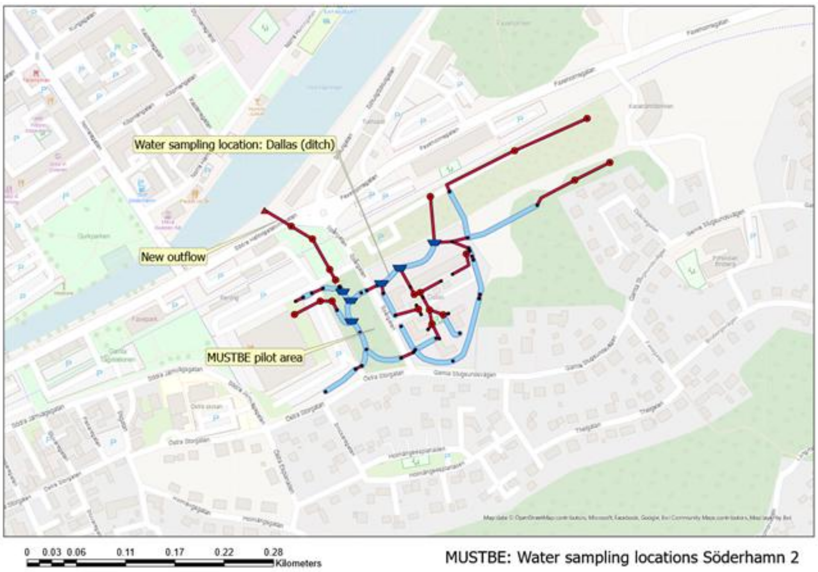


Figure 22. Södershamnporten Pilot Site Shematic Overwiew with Sampling Location, 2023

The laboratory analysis of the stormwater sample shows overall low levels of pollution with some moderate elevations typical for urban runoff. Oil-related compounds and PAH substances were all below detection limits, indicating no significant contamination from petroleum or organic pollutants. Most heavy metals, including arsenic, lead, cadmium, chromium, nickel, and mercury, were found at low or very low concentrations and are within acceptable environmental standards. However, aluminium, copper, and zinc showed slightly to moderately elevated levels, which is common in stormwater influenced by traffic and urban surfaces.

Nutrient analysis revealed low concentrations of nitrogen compounds such as ammonium and nitrate, suggesting limited impact from wastewater or fertilizers. In contrast, phosphorus levels were moderate, which could contribute to eutrophication in receiving waters if discharged continuously. Suspended solids were also at a moderate level, reflecting typical particle content in runoff water.

Other measured elements such as silicon, magnesium, and sulfur were within normal background ranges and do not indicate any environmental concern. Overall, the water quality can be described as typical stormwater with no major contamination issues, although moderate levels of certain metals and phosphorus suggest a need for monitoring to prevent potential ecological effects.

Following implementation of the pilot site solutions, water samples were collected on two additional occasions, on May 5 and June 26, 2026, allowing changes over time to be assessed. In 2026, sampling was carried out at more specific locations at each pilot site individually. It should be noted that, at Porten, samples could only be collected at the inlet because the outlet point was dry.

In May, the water exhibits a very high degree of discoloration and suspended matter. The water color is exceptionally high at 490 mg Pt/L, which is far above the baseline for typical, clear natural streams. In Nordic geographies, a value this high strongly indicates a massive influx of humic substances dissolved from surrounding bogs, wetlands, or forest soils. This is further corroborated by an elevated iron content of 3.7 mg/L, as iron binds tightly to organic humic complexes. Additionally, the water is noticeably murky, with a turbidity of 31 FNU and a suspended solids concentration of 35 mg/L.

Table 10. Porten Water Analysis Inlet Data, May 5, 2026

Parameter	Result	Unit	Measurement Uncertainty
Microbiological Analysis			
Escherichia coli	< 10	MPN/100 ml	-
Coliform bacteria 35°C	10	MPN/100 ml	-
Physical & Chemical Analysis			
Water temperature at sampling	7.3	°C	-
Turbidity	31	FNU	20%
Color (410 nm)	490	mg Pt/L	25%
Suspended solids	35	mg/L	10%
pH	7.7	-	0.2
Temperature at pH measurement	21.1	°C	-
Alkalinity	130	mg HCO_3/L	10%

Conductivity	56	mS/m	10%
Ammonium nitrogen (NH4-N)	0.16	mg/L	20%
Phosphate phosphorus (PO4-P)	0.2	mg/L	20%
Nitrate + Nitrite nitrogen	2.1	mg/L	10%
Phosphorus (P, total digested)	0.43	mg/L	25%
Nitrogen (N, total)	4	mg/L	25%
Iron (Fe, digested)	3.7	mg/L	25%
Lead (Pb, digested)	0.0059	mg/L	20%
Cadmium (Cd, digested)	0.000065	mg/L	25%
Copper (Cu, digested)	0.2	mg/L	25%
Chromium (Cr, digested)	0.0053	mg/L	25%
Mercury (Hg, digested)	< 0.00010	mg/L	25%
Nickel (Ni, digested)	0.0038	mg/L	25%
Zinc (Zn, digested)	0.25	mg/L	25%
Oil Index	0.91	mg/L	40%

The chemical analysis reveals heavy nutrient enrichment, pointing toward a high risk of eutrophication. The total nitrogen concentration stands at 4.0 mg/L, while the total phosphorus level is 0.43 mg/L. In a pristine natural aquatic ecosystem, these elements are found in much lower fractions. Concentrations of this magnitude typically stem from external inputs, such as agricultural runoff containing fertilizers, or the discharge of inadequately treated municipal wastewater into the catchment area.

The most telling signs of human and industrial impact come from the heavy metal and hydrocarbon readings, where copper and zinc are present in notable quantities at 0.20 mg/L and 0.25 mg/L respectively. Their presence here is a classic signature of urban street runoff originating from vehicle brake pad wear, tire degradation, and building roof materials. Furthermore, the oil index of 0.91 mg/L delivers definitive proof of technical petroleum pollution, providing a hydrocarbon fingerprint that typically points to runoff from nearby roads, gas stations, parking lots, or industrial and boating activities.

Interestingly, despite the pronounced chemical and industrial pressures, the microbiological contamination remains remarkably low. The negligible counts of coliform bacteria and Escherichia coli indicate that, at the time of sampling, the water body was not facing active pollution from raw domestic sewage or intensive livestock farming. This critical distinction allows us to conclude that the nutrient and metal loading is driven primarily by urban surface runoff and environmental leaching, rather than fecal or sanitary wastewater failures.

On May 5, 2026 this water body behaves as a highly stressed urban-industrial catchment inlet. It represents a complex environmental cocktail where natural, iron-rich wetland waters merge with heavily contaminated urban stormwater. While microbiologically safe from a sanitary perspective, the heavy organic, metal, and nutrient load poses a significant ecological threat, necessitating targeted treatment or retention strategies before downstream discharge. As mentioned, the results are also affected by the weather at the time of sampling.

Figure 23. Soderhamn Weather Indicators, May 26, 2026[7]

When looking at the incoming water quality on May, baseline conditions appeared favorable relative to project targets. If these inlet readings were evaluated against typical outflow thresholds, parameters such as *E. coli* (target: 60% reduction), total nitrogen (target: 30% reduction), total suspended solids (target: 60% reduction), and heavy metals such as copper and zinc (target: 40% reduction) all showed low baseline concentrations, while oil index levels remained below laboratory detection limits. However, in the absence of outlet data, these results represent the initial water quality only and cannot be used to confirm the treatment performance of the pilot facility. Nevertheless, because the water was retained or infiltrated within the pilot area and no discharge was observed at the outlet during the monitoring period, the measured pollutants were not directly transported further downstream or to the Baltic Sea under those conditions.

In June the inlet demonstrates very strong microbiological conditions, with *E. coli* levels at a minimal 40 MPN/100 ml and coliform bacteria at 790 MPN/100 ml. This indicates little to no recent fecal contamination or biological stagnation entering the system at this point.

The physical profile reflects clean, clear surface water. Turbidity is very low at 1.6 FNU, suspended solids are minimal at 6.1 mg/L, and the color reading of 69 mg Pt/L remains low compared to surrounding catchments. Concurrently, digested iron levels are low at 0.35 mg/L, pointing to limited soil erosion, resuspension, or humic leaching upstream.

[7] www.predictwind.com

Nutrient concentrations are well within healthy, unpolluted limits. Total nitrogen is relatively low at 1.5 mg/L and is dominated by oxidized forms, with nitrate and nitrite combining for 0.66 mg/L. Ammonium levels are very low at 0.22 mg/L, confirming a well-oxygenated aquatic environment free of significant anaerobic decomposition. Additionally, both phosphate phosphorus at 0.035 mg/L and total phosphorus at 0.082 mg/l remain low, representing a minimal risk for eutrophication or nuisance algal blooms.

Most heavy metals, including lead, cadmium, copper, chromium, and nickel, are present in negligible or non-detectable concentrations. Zinc levels stand at 0.087 mg/L, which is slightly elevated compared to other metals - a typical pattern for urban run-off - but remains within acceptable ecological bounds. Petroleum hydrocarbons are entirely absent above detection limits, registering at less than 0.10 mg/L.

Table 11. Porten Water Analysis Inlet Data, June 26, 2026

Parameter	Result	Unit	Measurement Uncertainty
Microbiological Analysis			
Escherichia coli	40	MPN/100 ml	—
Coliform bacteria 35°C	790	MPN/100 ml	—
Physical & Chemical Analysis			
Turbidity	1.6	FNU	20%
Color (410 nm)	69	mg Pt/L	25%
Suspended solids	6.1	mg/L	35%
pH	7.4	—	0.2
Temperature at pH measurement	22.1	°C	—
Alkalinity	45	mg HCO_3/L	10%
Conductivity	16	mS/m	10%
Ammonium nitrogen (NH_4^+-N)	0.22	mg/L	20%
Phosphate phosphorus (PO_4-P)	0.035	mg/L	20%
Nitrate + Nitrite nitrogen	0.66	mg/L	25%
Phosphorus (P, total)	0.082	mg/L	25%
Nitrogen (N, total)	1.5	mg/L	25%
Metals & Hydrocarbons			
Iron (Fe), digested	0.35	mg/L	25%
Lead (Pb), digested	0.00069	mg/L	20%
Cadmium (Cd), digested	0.000036	mg/L	25%
Copper (Cu), digested	0.011	mg/L	25%
Chromium (Cr), digested	< 0.00050	mg/L	25%
Mercury (Hg), digested	< 0.00010	mg/L	25%
Nickel (Ni), digested	0.0018	mg/L	25%
Zinc (Zn), digested	0.087	mg/L	25%
Oil index	< 0.10	mg/L	40%

By June 26th, the inlet sample values reflected expected seasonal shifts in the surrounding catchment. While incoming levels for Total Nitrogen and heavy metals remained within ranges that would typically align with reduction goals, parameters like E. coli and suspended solids recorded higher concentrations at the inlet - a trend commonly driven by warmer summer temperatures, organic decay, and upstream stagnation. Ultimately, because monitoring was limited strictly to the inlet point, any conclusions regarding Söderhamnsporten's true removal efficiency remain unverified until paired inlet and outlet data are available.

Real-Time Sensor Monitoring Results

Sensors were installed at the pilot site to record different types of data at both the inlet and outlet, but since the outlet was dry, only inlet data were collected. Clear correlations are visible in the data, for example between rainfall, TDS, and turbidity at the Porten inlet.

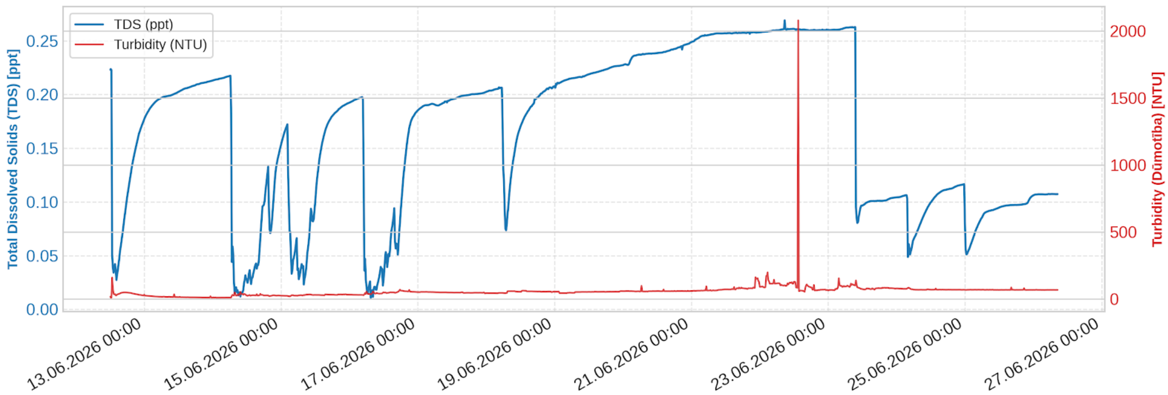


Figure 24. Total Dissolved Solids and Turbidity, June 13 to June 27, 2026

The TDS data directly mirrors the June precipitation pattern, demonstrating clear rainwater dilution effects. During the heaviest rainfall events on June 14 (13.8 mm) and June 16 (11.4 mm), inlet TDS levels experienced steep, instantaneous plunges from baseline levels of ~0.20 - 0.22 ppt down to near-zero minima of 0.012 ppt and 0.011 ppt, respectively. This dramatic drop illustrates how rapid, uninhibited rainwater runoff entering the system swiftly dilutes the background concentration of dissolved salts and minerals.

As precipitation ceased from June 18 through June 22 (0 mm rainfall), TDS shifted into a steady, monotonic upward trajectory, rising gradually from 0.074 ppt to a peak of 0.269 ppt. In the absence of rainwater dilution, the inflow returned to its natural baseline dominated by baseflow and groundwater contributions, which naturally carry higher dissolved mineral loads. This upward trend during warmer, dry conditions was further reinforced by localized evapotranspiration within the catchment.

While baseline turbidity at the inlet remains low and stable (typically between 11 and 70 NTU), an isolated, extreme turbidity spike reaching 2078.7 NTU was recorded on June 22. Because zero rainfall occurred on this date, this localized event was driven entirely by natural physical disturbances within the stream or wetland channel - such as localized bank slumping, natural debris displacement, or animal movement stirring up benthic sediments immediately upstream of the sensor.

Statistical analysis of the inlet dataset yields a very weak correlation (r=0.112) between TDS and turbidity. This low value confirms that water clarity in the natural inflow is governed by insoluble, suspended organic and inorganic particles rather than dissolved ions or mineral salts. Consequently, physical sediment transport and chemical dissolution operate as independent processes within the catchment.

Toward the end of the monitoring period (June 23-26), TDS displays highly regular, rhythmic fluctuation cycles between ~0.05 ppt and ~0.11 ppt, while turbidity maintains a steady baseline around 68-72 NTU. In a natural system free of artificial pumping, these cyclic patterns are driven by diurnal environmental rhythms, including day-night water temperature fluctuations, evaporation rates, and natural interplay between shallow groundwater discharge and surface flow.

Conclusions

The laboratory analyses provide useful baseline information on water quality at the Söderhamnsporten pilot site, although the samples were not collected directly at the current site and the outlet was dry during the 2026 sampling events. The results show substantial seasonal variation. May samples indicated elevated colour, suspended solids, nutrients, iron, copper, zinc, and petroleum-related pollution, whereas June samples showed considerably lower concentrations for most parameters.

The results indicate that water quality is affected by both natural wetland processes and urban runoff. The main potential concerns are intermittent inputs of nutrients, metals, and hydrocarbons, while microbiological contamination remained relatively low. However, because outlet samples were unavailable, the data cannot be used to assess the treatment efficiency of the pilot system or determine whether the project targets have been achieved. Nevertheless, as the water was retained or infiltrated within the pilot area and no discharge was observed at the outlet during the monitoring period, no direct downstream transport of the measured pollutants to the Baltic Sea occurred under the observed conditions.

The real-time sensor data confirm a clear relationship between rainfall and water-quality conditions at the inlet. Rainfall caused rapid dilution of dissolved substances, while turbidity was generally independent of TDS and occasionally increased sharply without rainfall, indicating the mobilisation of suspended sediment within the channel or wetland. Continued monitoring at both the inlet and outlet, under dry and wet conditions, is therefore necessary to assess the system's actual performance and identify possible sediment or pollutant sources.

4.3.2. Broberg

Laboratory Water Quality Results

Broberg monitoring samples were also collected on May 5 and June 26, 2026, in the same manner as at Söderhamnsporten and are analyzed in a similar way. Unlike Söderhamnsporten, however, Broberg also has outlet data available.

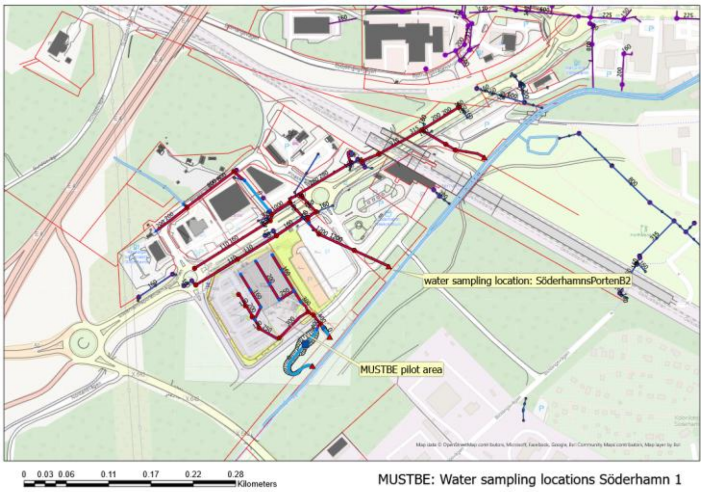


Figure 25. Broberg pilot site area shematic overwiew with sampling points, 2023

Analysis of the May samples reveals two contrasting trends between the inlet and outlet: a highly effective reduction in biological and nutrient pollution, alongside a noticeable decline in physical clarity and an increase in specific metal concentrations. On a positive note, the treatment or transformation process demonstrates exceptional efficiency in mitigating biological risks. Escherichia coli levels dropped significantly by 76.6%, decreasing from 470 to 110 MPN/100 mL, while total coliform bacteria at 35°C saw a substantial 47.1% reduction from 8700 to 4600 MPN/100 mL. This biological remediation is closely matched by an outstanding removal of biogenic elements, which is vital for preventing environmental eutrophication. Total nitrogen was cut by more than half, falling from 4.7 to 2.1 mg/L, driven heavily by an 88.5% plunge in nitrate and nitrite nitrogen, and a 55.0% drop in ammonium nitrogen. Phosphorus compounds followed a similar downward trajectory; total phosphorus decreased by 60.0% to 0.14 mg/L, while phosphate phosphorus dropped by 75.2% to a mere 0.067 mg/L.

Table 12. Broberg Water Analysis data, May 5, 2026

Parameter	Inlet	Outlet	Unit	Measurement Uncertainty
Microbiological Analysis				
Escherichia coli	470	110	MPN/100 mL	—
Coliform bacteria 35°C	8700	4600	MPN/100 mL	—
Physical & Chemical Analysis				
Water temperature at sampling	8.3	11	°C	—
Turbidity	5.8	29	FNU	20%
Color (410 nm)	100	340	mg Pt/L	25%
Suspended solids	11	28	mg/L	10%
pH	7.8	7.5	—	0.2
Temperature at pH measurement	21.9	21	°C	—
Alkalinity	160	140	mg HCO_3/L	10%
Conductivity	46	52	mS/m	10%
Ammonium nitrogen (NH_4^+-N)	1.2	0.54	mg/L	20%
Phosphate phosphorus (PO_4-P)	0.27	0.067	mg/L	20%
Nitrate + Nitrite nitrogen	2.7	0.31	mg/L	10% / 25%
Phosphorus (P)	0.35	0.14	mg/L	25%
Nitrogen (N)	4.7	2.1	mg/L	25%
Metals & Hydrocarbons				
Iron (Fe), digested	1.6	5.2	mg/L	25%
Lead (Pb), digested	0.00025	0.001	mg/L	20%
Cadmium (Cd), digested	0.000021	0.000015	mg/L	25%
Copper (Cu), digested	0.016	0.0062	mg/L	25%
Chromium (Cr), digested	0.00081	0.0019	mg/L	25%
Mercury (Hg), digested	< 0.00010	< 0.00010	mg/L	25%
Nickel (Ni), digested	0.0015	0.0022	mg/L	25%
Zinc (Zn), digested	0.024	0.014	mg/L	25%
Oil index	< 0.10	< 0.10	mg/L	40%

Conversely, the water's physical and aesthetic characteristics deteriorated markedly at the outlet. Turbidity surged fivefold, escalating by 400% from 5.8 to 29 FNU, and the water color value spiked by 240%, rising from 100 to 340 mg Pt/L. This visual degradation is corroborated by a 154.5% increase in suspended solids, which rose from 11 to 28 mg/L. Chemically, the water became slightly more acidic, with the pH shifting from 7.8 to 7.5, a change accompanied by a 12.5% reduction in alkalinity and a minor 13% increase in electrical conductivity.

This decline in physical clarity is directly linked to changes in metal concentrations, most notably a dramatic 225% spike in digested iron, which jumped from 1.6 to 5.2 mg/L. This massive influx of iron is the primary culprit behind the increased turbidity and the distinct yellow-brown discoloration at the outlet. Other heavy metals showed mixed behaviors; while copper, zinc, and cadmium concentrations decreased, lead levels rose by 300% - though remaining very low in absolute terms at 0.001 mg/L - and chromium and nickel experienced moderate increases. Mercury and the oil index remained completely unchanged, staying safely below detection limits at both sampling points. Ultimately, while the system successfully neutralizes organic and nutrient loads, the stark rise in iron, turbidity, and suspended solids suggests potential secondary contamination.

The samples collected on 5 May 2026 were taken shortly after rainfall, as confirmed by publicly available meteorological observation data. Windy conditions and relatively low water temperature were also present at the time. These conditions may partly account for the results, as they likely contributed to soil wash-off and elevated turbidity.

Later June 2026 samples indicate a different situation. While the system acts as a metal-retention zone, it is affected by pronounced microbiological deterioration, leaching of organic soil matter (iron/color), and nutrient transformation. Such a pattern is characteristic of a slow-flowing pond, wetland, or stagnant catchment undergoing summer organic decomposition.

The water quality undergoes severe microbiological deterioration as it passes through the system. Both E. coli and total coliform bacteria exhibit massive, order-of-magnitude increases from the inlet to the outlet. This pronounced bacterial surge points toward significant internal biological growth, stagnating warmer water zones, or an unmonitored influx of organic waste within the catchment area.

The physical clarity of the water degrades noticeably. The outlet exhibits heightened turbidity, a greater concentration of suspended solids, and a substantially darker, more intense coloration. This physical shift aligns with a sharp rise in digested iron. The co-occurrence of high iron, suspended particles, and heavy discoloration strongly indicates active sediment resuspension or the leaching of humic-rich wetland soils as water flows through the site.

The system acts as a site for intense nutrient transformation. While overall total nitrogen decreases across the system, there is a striking chemical shift. Oxidized nitrogen forms (nitrate and nitrite) drop precipitously, while ammonium levels rise significantly. This chemical fingerprint points to an oxygen-depleted, reducing environment between the points, driving denitrification alongside organic decomposition. Total phosphorus levels nearly double by the time the water exits the system, largely driven by the accumulation of decaying organic matter and bound particulates.

In stark contrast to the nutrient and bacterial trends, the system functions remarkably well as a natural sink for heavy metals. Key contaminants such as copper and zinc experience major reductions between the inlet and outlet, while nickel and cadmium drop near or below laboratory detection limits. This effective attenuation suggests that dissolved metals are successfully binding to vegetation or settling out with resuspended particles.

Table 13. Broberg Water Analysis data, June 26, 2026

Parameter	Inlet	Outlet	Unit	Measurement Uncertainty
Microbiological Analysis				
Escherichia coli	663	1782	MPN/100 mL	—
Coliform bacteria 35°C	1900	99000	MPN/100 mL	—
Physical & Chemical Analysis				
Turbidity	2.7	8.9	FNU	20%
Color (410 nm)	70	170	mg Pt/L	25%
Suspended solids	3.6	15	mg/L	35% / 10%*
pH	8	8	—	0.2
Temperature at pH measurement	22	22.2	°C	—
Alkalinity	200	320	mg HCO_3/L	10%
Conductivity	56	71	mS/m	10%
Ammonium nitrogen (NH_4^+-N)	0.47	2	mg/L	20%
Phosphate phosphorus (PO_4-P)	0.12	0.15	mg/L	20%
Nitrate + Nitrite nitrogen	4.5	0.34	mg/L	10% / 25%
Phosphorus (P, total)	0.16	0.29	mg/L	25%
Nitrogen (N, total)	6.4	3.9	mg/L	25%
Metals & Hydrocarbons				
Iron (Fe), digested	1.1	4.8	mg/L	25%
Lead (Pb), digested	< 0.00020	< 0.00020	mg/L	20%
Cadmium (Cd), digested	0.000016	< 0.000010	mg/L	25%
Copper (Cu), digested	0.016	0.00057	mg/L	25%
Chromium (Cr), digested	0.001	0.00064	mg/L	25%
Mercury (Hg), digested	< 0.00010	< 0.00010	mg/L	25%
Nickel (Ni), digested	0.0024	< 0.00050	mg/L	25%
Zinc (Zn), digested	0.013	0.0057	mg/L	25%
Oil index	< 0.10	< 0.10	mg/L	40%

When comparing the latest June results with the data from May 5th, the overall condition of the system has deteriorated significantly - particularly regarding microbiological safety and nutrient management. While the site performed well as a biological treatment system in May, warmer June temperatures appear to have turned it into a stagnant, organic-rich environment. Severe Microbiological Breakdown: In May, the system actively reduced bacterial concentrations from inlet to outlet. By June, this trend completely reversed, resulting in a severe bacterial surge where outlet E. coli exceeded EU safety limits and coliform levels spiked exponentially.

In May, the site effectively trapped phosphorus and nitrogen. In June, phosphorus retention ceased - leading to elevated outlet levels - while ammonium levels rose sharply, pointing to anaerobic decomposition within the system. Water clarity at the outlet improved slightly compared to May, with lower turbidity, suspended solids, and iron concentrations, though these physical parameters still remain elevated relative to the inlet. Heavy metal retention remained consistently strong across both months, with contaminants like copper and zinc continuing to be effectively filtered out.

Overall, while the site remains an effective trap for trace metals, it shifted in June from a functional biological filter into a stagnant source of bacterial amplification and nutrient release.

While several indicators deteriorate markedly from inlet to outlet, the overall changes remain less severe than the EU environmental quality standards indicate. The chemical and heavy metal status is satisfactory, with no evidence of hazardous contamination from heavy metals or petroleum products, suggesting that the system's decontamination mechanisms are functioning effectively in line with EQS requirements. In contrast, the microbiological and ecological status does not comply with EU standards: bacterial proliferation in the discharge exceeds the safety threshold under the EU Bathing Water Directive, and elevated phosphorus, nitrogen, and ammonium levels prevent attainment of "good ecological status" under the EU Water Framework Directive.

In evaluating the performance of the Broberg pilot site against the project's environmental target values, the May 5th sampling demonstrated strong overall treatment efficiency across most parameters, successfully meeting or exceeding the majority of reduction goals. The system functioned effectively as a biological filter for pathogens, achieving a 76.6% reduction in E. coli, which easily surpassed the project target of a 60% reduction. Nutrient removal was similarly efficient, with Total Nitrogen decreasing by 55.3%, well above the 30% target reduction. Heavy metal removal was also highly effective; copper levels dropped by 80.4% and zinc by 50%, both exceeding the 40% reduction target (though iron levels increased, as is typical in these wetland systems). Oil index concentrations remained safely below laboratory detection limits. The primary exception to this positive trend in May was Total Suspended Solids (TSS), which failed to meet the 60% reduction target due to an increase in organic matter and sediment suspension at the outlet.

By June 26th, seasonal shifts - particularly warmer temperatures and organic decomposition - altered the system's performance dynamics, leading to a more mixed outcome. While Total Nitrogen removal remained successful with a 39.1% reduction (still comfortably above the 30% goal), and heavy metal removal improved further (copper reduced by 96.4% and zinc by 56.2%, surpassing the 40% target), other indicators degraded. Warmer weather and potential water stagnation triggered internal bacterial growth, causing E. coli levels to increase significantly by 168.8% rather than achieving the targeted 60% removal. Similarly, TSS levels increased between the inlet and outlet, leaving the 60% reduction target unmet once again due to floating organic matter. Oil levels remained consistently low and within safe limits. Overall, while Broberg consistently met target reductions for nitrogen and heavy metals across both months, pathogen and suspended solid goals were strongly impacted by seasonal summer conditions.

Real-Time Sensor Monitoring Results

At Broberg, sensors were also installed at the pilot site to record different types of data. Clear correlations are visible in the data, for example between rainfall, TDS, and turbidity at the Broberg inlet.

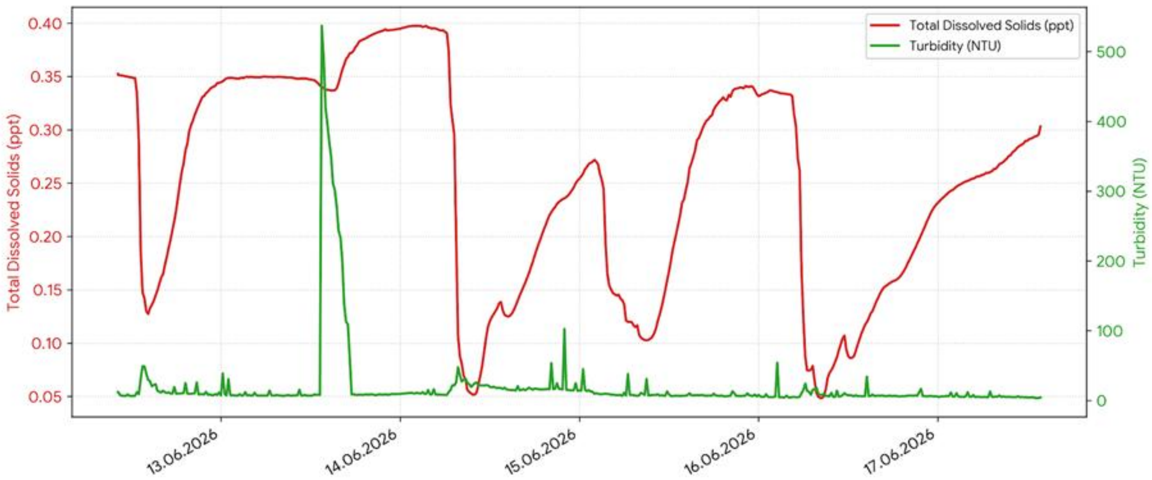


Figure 26. Total Dissolved Solids and Turbidity inlet, May 12 to May 17, 2026

The graphs demonstrate that the marked drops in TDS on June 12, 14, and 16 correspond directly with recorded precipitation events, with the sharpest decline matching the heavy 14 mm rainfall on June 14. This strongly validates the dilution effect, where incoming rainwater temporarily dilutes the concentration of dissolved ions in the water body before TDS levels gradually recover as dry conditions return.

The rainfall data correlate with the sharp turbidity spike observed on June 13, when turbidity reached 536.8 NTU. Because rainfall was recorded at 0 mm that day, weather-related erosion or surface runoff can be ruled out as the primary cause. Instead, the isolated increase in turbidity was most likely caused by a mechanical or physical disturbance, such as sediment resuspension or localized maintenance activity upstream.

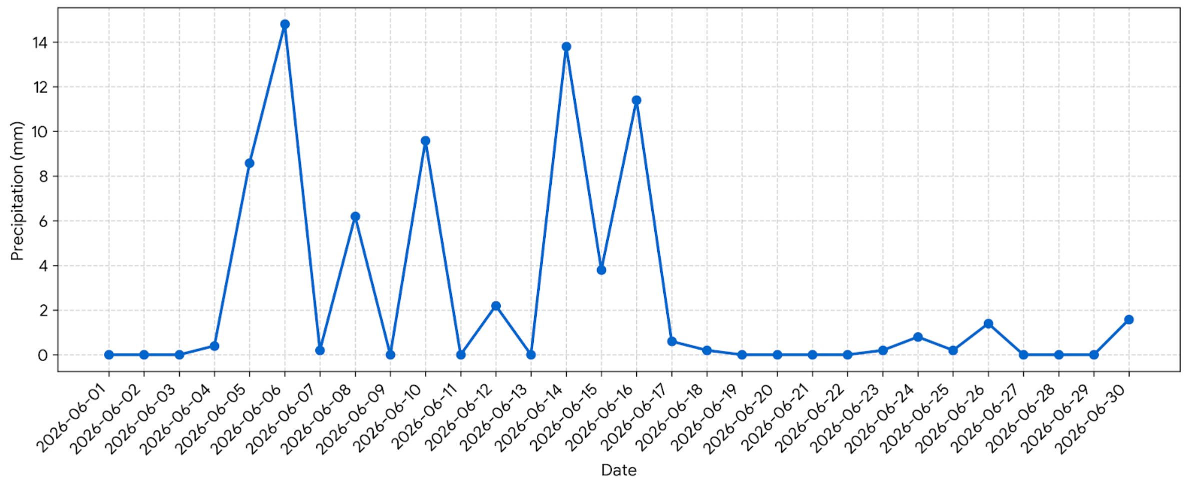


Figure 27. Hourly Precipitation in Söderhamn , June, 2026[8]

At the outlet point, TDS show a clear pattern of gradual accumulation over an extended period. Between June 18 and June 23, values steadily increased from approximately 0.31 ppt to 0.45 ppt. However, this gradual build-up is interrupted by periodic, sharp drops on dates such as June 14, 16, 23, 24, and 25, where TDS concentrations plunge to near-zero levels (0.02-0.06 ppt) within minutes. This profile is highly characteristic of systems experiencing periodic water exchanges, backwashing, or sudden freshwater/rainwater inflows that rapidly dilute dissolved salts and flush the system.

Unlike TDS, turbidity shows no gradual accumulation phase over time; under normal baseline conditions, it remains consistently low at approximately 10-35 NTU, interrupted only by acute, high-magnitude spikes. The dataset highlights two extreme periods: an extraordinary surge on June 13-14 peaking at 1.590 NTU, followed by a more sustained period of elevated turbidity between June 17 and June 18 fluctuating from 100 to 800 NTU. These brief, intense turbidity spikes point to mechanical disturbances or the resuspension of settled solids, which are typically triggered by pump activations, abrupt flow rate changes, or physical interventions in the system.

[8] www.open-meteo.com

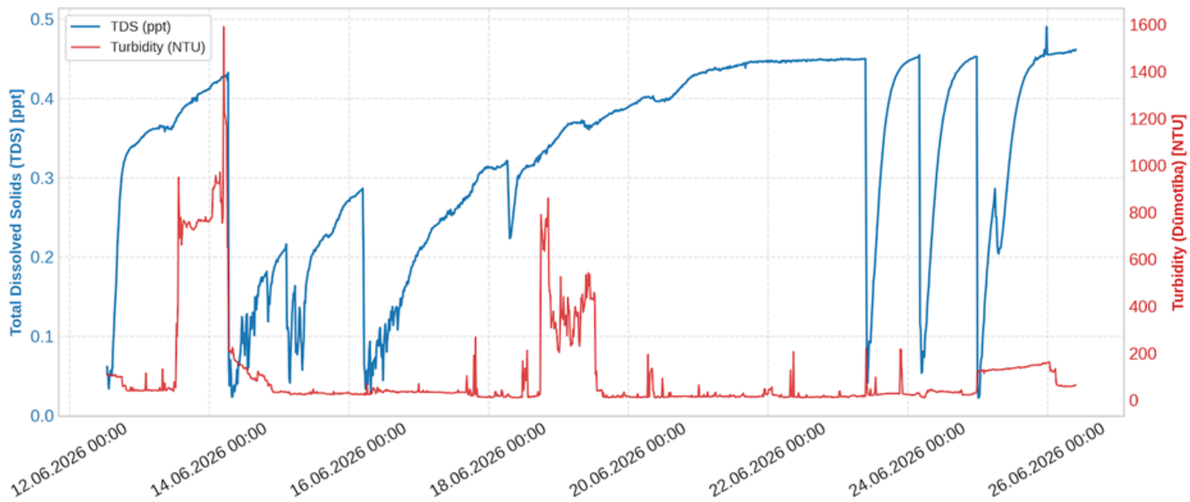


Figure 28. Total Dissolved Solids and Turbidity, outlet, June 12 to June 26, 2026

Although both TDS and turbidity serve as primary physical indicators of water quality, statistical analysis reveals a very weak positive correlation between them (r ≈ 0.114). This demonstrates that turbidity in the system is driven almost entirely by insoluble suspended particles rather than dissolved salts or minerals. Consequently, high turbidity events occur independently across both low and high TDS regimes without a direct causal link between the two parameters.

TDS exhibits a significant positive correlation with water temperature (r = 0.684), indicating that the two parameters are closely coupled throughout the monitoring period. During timeframes when water temperature rises, dissolved solids concentrations increase correspondingly. This relationship is likely driven by enhanced mineral solubility in warmer water alongside localized evaporation effects during warmer operational windows.

Following June 19, turbidity levels undergo a marked stabilization, remaining consistently low and generally staying below 20-30 NTU for the remainder of the observation period. Simultaneously, after June 23, the TDS fluctuations transition into highly rhythmic, predictable cycles. This dual stabilization suggests that the overall system reached an automated or well-regulated operational equilibrium toward the end of the monitoring window.

TDS profiles at both monitoring points mirror precipitation dynamics with exceptional precision. Heavy rainfall events on June 13-14 and June 16 triggered rapid, simultaneous plunges in TDS levels from baseline values of approximately 0.35-0.40 ppt down to 0.02-0.05 ppt at both stations. This immediate, synchronous dilution demonstrates that incoming rainwater rapidly mixes throughout the pilot system, causing the outlet station to respond without any noticeable lag. Following the precipitation events, during the drier period from June 18 to June 26, the outlet station records a steady, step-like recovery as TDS concentrations stabilize back up to approximately 0.46-0.49 ppt.

In contrast to TDS, turbidity exhibits marked differences between the two locations. Under calm, baseline conditions without rainfall, turbidity remains low at around 6–10 NTU at the inlet and 20-40 NTU at the outlet. However, heavy rainfall induces drastic peak amplification downstream. During the June 13-14 event, the inlet recorded a single pronounced turbidity spike of approximately 537 NTU that subsided rapidly, whereas the outlet experienced a surge peaking at 1.590 NTU. Furthermore, during the second rainy window from June 16 to June 18, outlet turbidity remained elevated between 400 and 800 NTU for an extended period, while inlet turbidity showed minimal increase.

TDS pass through the pilot site without significant retention or accumulation, as evidenced by the nearly symmetrical dilution profiles and virtually identical overall averages (~0.25 ppt vs. ~0.23 ppt). Conversely, water clarity deteriorates as flow traverses the system, leaving the site significantly more turbid than when it entered. High hydraulic inflows during storm events flush out previously settled benthic sediments and organic particles, transporting them downstream to create substantially higher turbidity surges at the outlet than at the inlet.

Conslusions

The Broberg pilot site demonstrated effective removal of several important pollutants during both sampling events. Total nitrogen and selected heavy metals, particularly copper and zinc, were consistently reduced, while petroleum products remained below the laboratory detection limit. These results indicate that the system functions effectively as a nutrient- and metal-retention zone.

However, the treatment performance varied with seasonal and hydraulic conditions. In May, bacterial pollution was substantially reduced, but turbidity, colour, suspended solids, and iron increased at the outlet. In June, the reduction of nitrogen and metals continued, but bacterial contamination, ammonium, phosphorus, iron, and suspended solids increased downstream. This suggests that warmer conditions, organic decomposition, stagnation, and sediment or soil mobilisation can negatively affect water quality.

The sensor data confirm a clear relationship between rainfall and TDS, with precipitation causing rapid dilution at both the inlet and outlet. Turbidity, however, was largely independent of TDS and showed pronounced peaks that are more likely related to sediment resuspension, hydraulic disturbances, or maintenance activities. Overall, Broberg shows promising treatment potential, but its performance is strongly seasonal and does not consistently improve all water-quality parameters.

Continued monitoring is therefore needed to assess long-term performance and to identify measures for controlling sediment mobilisation, stagnation, and internal nutrient release. Particular attention should be given to maintaining sufficient water circulation and monitoring microbiological and suspended-solid levels during warmer periods and after rainfall events.

4.4. Tallinn

The Tallinn pilot site is located in Tondimõisa Park (situated at Nõmme tee 107, spans 2.56 hectares), adjacent to Tammsaare Road, a densely built and heavily trafficked area that is prone to flooding due to an overloaded stormwater drainage system. The pilot site aims to mitigate flood risks and enhance water quality by constructing a stormwater retention and treatment facility that manages rainwater before it enters the urban drainage network.

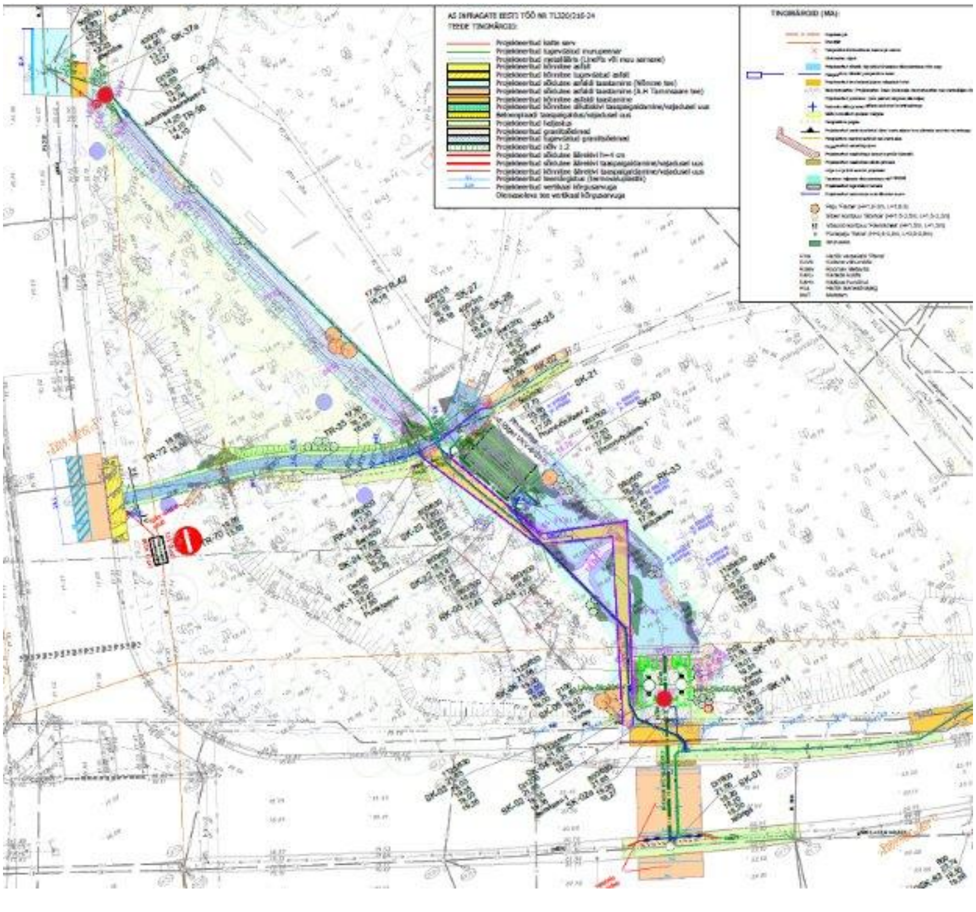


Figure 29. Tallin pilot site shematic overwiew

At the pilot site, the diversion chamber with its sluice is in place, leading into monitoring chamber 1, where turbidity, temperature, hydrocarbons, and nitrogen are measured. Downstream, the vortex separator removes oil, debris, and sediments before the flow enters two retention ponds of 125 m³ and 80 m³. This is followed by the soil filter pilot, which provides additional filtration through sample chambers installed before and after the filter. The regulation chamber, designed to adjust water levels in the ponds, leads to overflow and monitoring chamber 2, where peak flows can bypass while final quality control is carried out.

Data acquisition is carried out using two network-powered sensors, which provide real-time monitoring and transmit data directly to AS Tallinna Vesi's SCADA system for internal access only. The setup includes In-Situ Aqua TROLL® Multiparameter Sonde units, 2260 Ultrasonic Level Transmitters, and FloPro XCi controllers.

Figure 30. In-Situ Aqua TROLL® Multiparameter Sonde units, 2260 Ultrasonic Level Transmitter[9], FloPro XCi controllers[10]

Real-time monitoring tracks pH, turbidity, conductivity, temperature, total suspended solids, total nitrogen, oil products, and water levels using dedicated sensors, complemented by manual sampling of key parameters - such as nutrients, suspended solids, and BOD - to assess improvements in water quality status. This real-time data will also drive automated water flow regulation, optimizing downstream water quality.

[9] www.in-situ.com
[10] www.macemeters.com

Table 14. Tallin pilot site baseline and target values

	Suspended solids, mg/L	Total Nitrogen, mg/L	E-coli, CFU/100 ml	Hydrocarbons, mg/L	Metals, µg/L
Baseline values	98	1,8	*4700**	*0,002**	*93,4**
Target values	**39**	**1,2**	**1880**	**0,001**	**56**

Water quality sampling and online monitoring were conducted under two distinct hydrological conditions: a dry-weather campaign (relatively little rainfall, possible changes were neither drastic nor long-lasting) on 10 June 2026 and a rainfall-event campaign on 6 July 2026. In total, four grab samples were collected, covering both influent and effluent streams for each monitoring event. Laboratory analyses have been completed, and continuous online sensor readings from inlet and outlet monitoring points have been compiled into hourly datasets.

Operational challenges were identified at the outlet monitoring location. Accumulated sediment in the ditch downstream of the soil filter was transported into the outlet monitoring well. This sediment buildup adversely affected the outlet online sensor readings - specifically turbidity - and resulted in sediment deposition around the sensor array and within the outlet pipe.

To mitigate this issue during the rainfall-event monitoring on July 6, the effluent grab sample was collected directly after the filter field (upstream of the ditch) rather than from the monitoring well. Consequently, while the laboratory grab sample reflects the direct discharge from the filter, the outlet online sensor remained situated in the downstream monitoring well, creating a minor spatial discrepancy between the physical samples and the online sensor measurements for that event.

To prevent future sediment transport from the ditch into the monitoring well and ensure data consistency, a revised technical solution is currently underway. Reconstruction of the problematic outlet section is scheduled for completion.

Real-Time Sensor Monitoring Results

However, despite these limitations, an analysis of the sensor data indicates that, on June 10, for example, a pronounced turbidity peak observed at the outlet between 04:00 and 11:00 (reaching a maximum of 1,257 NTU) directly contrasts with the low, stable turbidity levels at the inlet. This empirical trend may confirm the underlying technical issue: elevated flows caused sediment present in the downstream ditch to be transported back into the outlet monitoring well. Consequently, the continuous online readings from the outlet sensor reflect ditch contamination rather than the true filtration efficiency of the soil filter.

A distinct physical-chemical interaction is also evident during this high-turbidity period. Between 04:00 and 09:00, petroleum product readings at the outlet unexpectedly dropped to zero. This anomaly suggests that the heavy accumulation of suspended solids physically obstructed or coated the sensor's optical interface, resulting in false zero values until the flow stabilized later in the day.

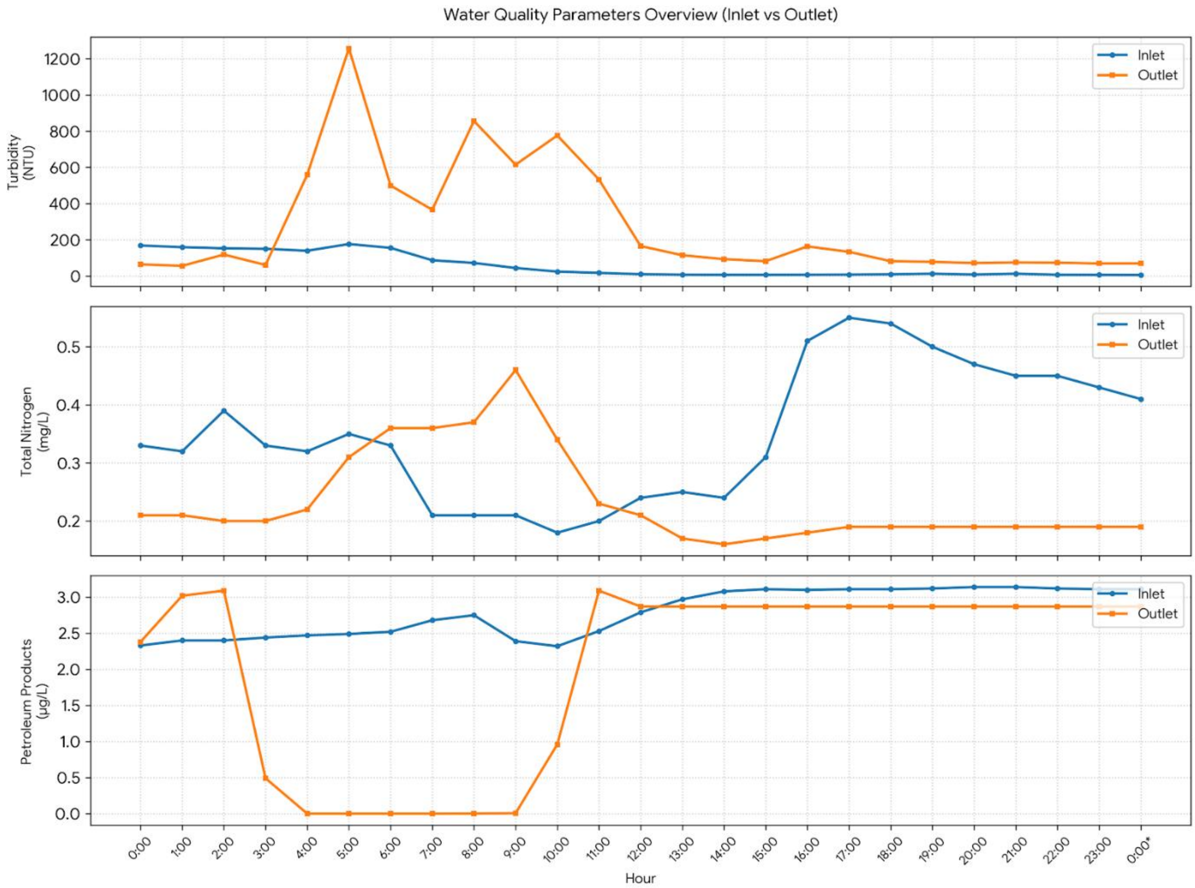


Figure 31. Water Quality Parameters Overview, Inlet vs Outlet, June 10, 2026

The total nitrogen dynamics further illustrate the filter's baseline performance versus the impact of external contamination. During the morning hours (05:00 to 09:00), an elevated total nitrogen concentration at the outlet coincided with the turbidity spike, indicating that organic nitrogen bound to ditch sediment was introduced into the monitoring well. However, once the ditch influence subsided after 12:00, inlet TN levels rose above 0.5 mg/L while outlet concentration remained low and stable at approximately 0.19 mg/L, proving that the soil filter successfully removes nitrogen under normal operating conditions.

Ultimately, these combined datasets demonstrate that the current monitoring well setup downstream of the ditch yields distorted environmental data. The poor outlet water quality observed during relatively dry weather may reflect sensor uncertainty, as noted above, or the inflow of lower-quality water from the surrounding edges rather than through the inlet wells, if such inflows are present. Therefore the planned engineering reconstruction of the outlet section is essential to isolate the filter discharge, eliminate sediment backflow, and ensure reliable data collection.

The sensors remained operational throughout July, including on July 6, following slight to moderate rainfall since the previous day. Because the sensors remained in their original locations, the measurements represent the full treatment cycle of the pilot solution.

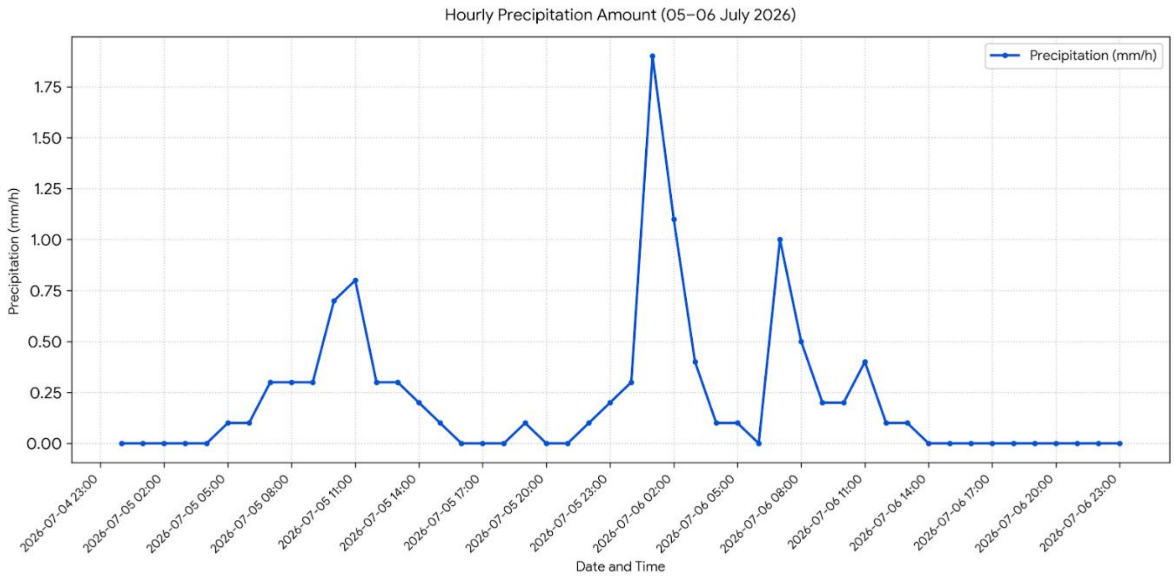


Figure 32. Hourly Precipitation in Tallinn, July 5 to July 6, 2026[11]

Comparing rainfall intensity with continuous online monitoring reveals a significant hydrologic lag time through the system. The primary precipitation peak occurred early in the morning at 01:00 (1.9 mm/h), followed by a secondary surge at 07:00 (1.0 mm/h), with rainfall completely subsiding by 13:00. Despite these early precipitation events, the pronounced turbidity peak at the outlet - reaching a maximum of 902.8 NTU – did not register until between 13:00 and 15:00. This 11- to 12-hour delay demonstrates the soil filter's substantial hydraulic retention capacity, as infiltrating water requires considerable time to percolate through the filter medium before exiting via the drainage layer.

Crucially, because the effluent sampling point for this event was relocated directly downstream of the soil filter (excluding ditch sediment backflow), the afternoon turbidity spike reflects internal filter

[11] www.open-meteo.com

dynamics rather than external contamination. Given that overall rainfall remained light to moderate, this indicates that even modest hydraulic loads are sufficient to induce a filter flushing effect, mechanically mobilizing fine particles and colloids from the filter matrix itself. Conversely, the earlier, smaller turbidity and nitrogen fluctuations observed at the inlet between 08:00 and 11:00 responded almost immediately to the 07:00 rainfall surge, proving that surface runoff quickly transports catchment-level wash-off into the system inlet.

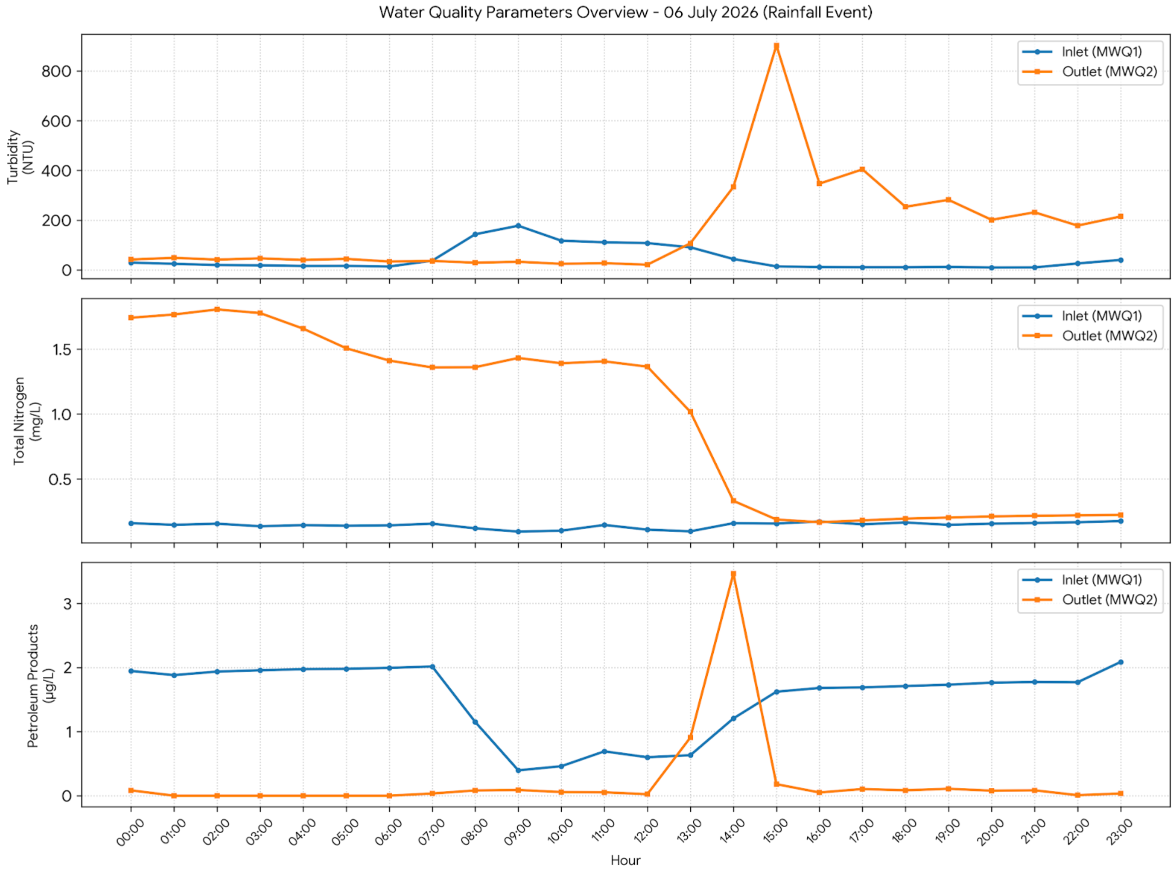


Figure 33. Water Quality Parameters Overview During the Rainfall Event, Inlet vs Outlet, July 6, 2026

Despite the internal release of suspended solids, the soil filter demonstrated excellent chemical treatment performance once fully engaged by the runoff volume. During the initial phase (00:0 - 12:00), elevated total nitrogen concentrations at the outlet (1.3-1.8 mg/L) reflected the flushing of stagnant water accumulated from prior dry periods. As the main body of low-concentration rainwater percolated through after 13:00, it effectively displaced and diluted this residual water, driving effluent total nitrogen levels down to a stable ~0.19 mg/L - well below the target threshold of 1.2 mg/L.

Similarly, hydrocarbon retention remained highly effective. Petroleum product concentrations at the outlet stayed near zero (≤ 0.1 µg/L) throughout the day, interrupted only by a brief system-flushing peak of 3.47 µg/L at 14:00 that coincided with the onset of high turbidity. Overall, coupling the rainfall temporal profile with the revised sampling location confirms that the soil filter functions effectively as a chemical sink for nitrogen and hydrocarbons, while highlighting that even moderate precipitation triggers a distinct hydraulic lag and temporary internal sediment flushing.

Laboratory Water Quality Results

The chemical analyses indicate a different picture on June 10: water quality in the system is deteriorating. While the incoming water at the inlet starts exceptionally clear with negligible suspended solids, it suffers a severe degradation as it flows through the system, resulting in a dramatic 19-fold spike in particulate matter by the time it reaches the outlet. This intense increase in turbidity directly correlates with a substantial accumulation of chemical and heavy metal pollution. Notably, total phosphorus levels surge nearly nine-fold, and TN shows a marked increase, signaling a significant nutrient load accumulation that elevates downstream eutrophication risks. This deteriorating trend extends directly into the chemical and heavy metal profile of the water; metals such as nickel and lead experience dramatic multi-fold increases, while copper, zinc, chromium, and cadmium all show noticeable accumulation. Furthermore, while petroleum products remain entirely undetectable at the system's entry point, they emerge in measurable concentrations at the outlet.

Table 15. Tallinn Pilot Site Water Analysis Data During Dry period, June 10, 2026

June 10, 2026	**Dry period**		
Parameter	**Inlet**	**Outlet**	**Unit**
Physical & General			
Water temperature	12	15	°C
pH	7.9	7.8	—
Electrical Conductivity	830	630	µS/cm
Dissolved Oxygen (O_2)	10.5	9.6	mg/l
Suspended Solids	3	56	mg/l
Nutrients			
Total Phosphorus (P)	0.021	0.18	mg/l
Total Nitrogen (N)	1.5	2.3	mg/l
Metals & Hydrocarbons			
Copper (Cu)	2.3	8.8	µg/l
Zinc (Zn)	22	40	µg/l
Nickel (Ni)	0.9	9	µg/l
Lead (Pb)	0.12	3.3	µg/l
Chromium (Cr)	0.5	3	µg/l
Cadmium (Cd)	< 0.01	0.024	µg/l
Petroleum Products (C_{10} - C_{40})	< 20	40	µg/l

Additional analyses were carried out on July 6, 2026, following slight to moderate rainfall that had occurred since the previous day. The laboratory results from the grab samples provide valuable information on the treatment efficiency under the prevailing rainfall conditions. However, the samples were collected directly downstream of the soil-filter field and upstream of the ditch. Therefore, the results reflect the performance of the soil filter only and should not be interpreted as representing the treatment efficiency of the entire system.

Table 16. Tallinn Water Analysis Data During the Rainfall Event, July 6, 2026

July 6, 2026	**Rainy period**		
Parameter	**Inlet - before retention ponds**	**After filter field, before ditch**	**Unit**
Suspended solids	10	18	mg/L
Total phosphorus	0.042	0.096	mg/L
Total nitrogen	1.3	<1	mg/L
Cadmium	<0.01	<0.01	µg/L
Chromium	1.1	2.9	µg/L
Nickel	0.65	3.8	µg/L
Lead	0.27	0.41	µg/L
Zinc	44	8.6	µg/L
Copper	2.7	2.8	µg/L
Petroleum products	<20	<20	µg/L
Conductivity	500	340	µS/cm
Dissolved oxygen	9.6	9.1	mg/L
pH	8.0	8.1	
Water temperature	15	16	°C

The analytical data confirm that the soil filter operates effectively during rainfall events, achieving high removal efficiencies for several primary contaminants. Total nitrogen decreased from 1.3 mg/L at the inlet to <1 mg/L post-filter, successfully meeting the target performance threshold (≤1.2 mg/L). Similarly, zinc (Zn) levels dropped by approximately 80%, from 44 µ/L to 8.6 µ/L demonstrating strong heavy-metal attenuation within the filter media. Electrical conductivity also declined from 500 to 340 µ/cm, directly reflecting the beneficial dilution effect caused by the incoming moderate rainfall. Furthermore, both cadmium (0.01 µ/L) and petroleum products (20 µ/L) remained below detection limits at both sampling locations, confirming no hydrocarbon or cadmium discharge occurred.

Conversely, the data highlight a minor internal mobilization of particulate matter driven by hydraulic loading. Suspended solids increased from 10 mg/L at the inlet to 18 mg/L after the filter. Because ditch-sediment backflow was physically excluded from this sampling point, this elevation confirms that percolating rainwater causes a slight mechanical flushing of fine particles from the filter matrix itself. Slight increases in total phosphorus rising from 0.042 to 0.096 mg/L, chromium (from 1.1 to 2.9 µ/L) and nickel (from 0.6 to 3.8 µ/L) correlate directly with this process, as these substances are naturally bound to the washed-out fine particulates.

Importantly, despite this localized flushing effect, the effluent suspended solids concentration of 18 mg/L remains well within the regulatory compliance target (≤39 mg/L). This proves that the soil filter itself operates within design parameters during rainfall events, and that previously observed severe turbidity spikes were entirely attributable to downstream ditch sediment.

It should be noted that, based on the analysis results available up to June 10, the initially defined objectives have not yet been achieved. The July 6 results are not considered suitable for assessing the performance of the entire system, as the samples were collected downstream of the soil-filter field and therefore reflect only the performance of that component. Water quality is expected to improve once the system has been repaired.

Conclusions

The Tallinn pilot site shows that the soil filter has the potential to improve water quality, particularly by reducing nitrogen and hydrocarbons under normal operating conditions. However, the current monitoring setup is affected by sediment transport from the downstream ditch, which distorts the outlet sensor readings and limits the reliability of the data. The July 6 grab-sample results confirm that the soil filter itself performs well during rainfall events, but they do not represent the entire system because the sample was taken downstream of the filter field and upstream of the ditch. Overall, the pilot site is not yet fully operational, and the measured results indicate that further technical reconstruction is needed before the system can be properly assessed as a whole. Once the outlet section is repaired water quality is expected to improve further.

4.5. Rīga

The Rīga pilot site focuses on an approximately 800-metre section of the Šmerļupīte stream, where rainwater from a 20 km² catchment area from Mežciems, Pļavnieki, and Dreiliņi neighbourhoods is discharged. The stream has been artificially modified and is partially channelised underground. The incoming stormwater contains high levels of total nitrogen, ammonium, total phosphorus, and organic contamination (BOD_5), as well as elevated levels of lead and copper, indicating possible illegal domestic sewage connections. This pollution degrades the ecological condition of Šmerļupīte and negatively affects the recreational value of the surrounding green zone, which is used by residents for leisure. It also impacts water quality downstream, particularly along the southern shore of Lake Ķīšezers.

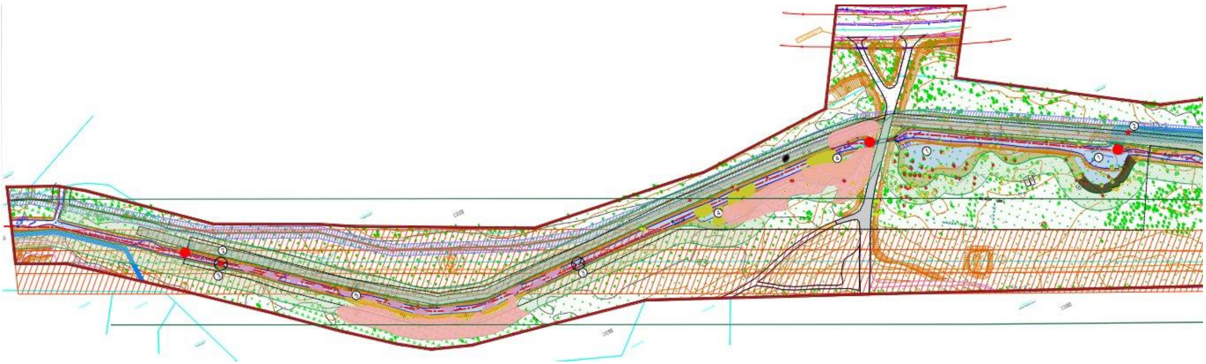


Figure 34. Šmerļupīte pilot site area shematic overwiew with sampling points

Figures 35 and 36. Šmerļupīte Pilot Site during construction

The solution divides the area into two functional zones - stormwater treatment zone, which includes sedimentation ponds and reed filtration beds, and renaturalisation zone, features meandering stream paths, wet meadows, and phytoremediation vegetation.

Figure 37. Project Information Board at the Pilot Site

Figures 38. Šmerļupīte Pilot Site after construction

Sedimentation and filtration ponds are designed to slow water flow and promote pollutant removal. Vegetation includes species such as Lolium perenne, Cirsium arvense, Festuca rubra, Trifolium pratense etc. Wet meadows and two-level riverbanks enhance biodiversity and water quality. For monitoring purposes, real-time sensors for pH, electrical conductivity, temperature, turbidity, and flow velocity is foreseen with telemetry systems for data transmission and integration into online platforms. Manual sampling is planned for comprehensive water quality analysis. Design ensures access to sediment removal and streambed cleaning.

The system monitors biochemical and physical water quality parameters through sensors tracking water level, pH, electrical conductivity, temperature, turbidity, flow velocity, flow rate, dissolved nitrogen, oxidation-reduction potential, and total dissolved substances. Grab sampling for nutrients, suspended solids, pathogens, metals, and hydrocarbons.

Table 17. Rīga pilot site baseline and target values

	Suspended solids, mg/L	**Total Nitrogen,** mg/L	**E-coli,** CFU/100 ml	**Hydrocarbons,** mg/L	**Metals,** µg/L
Baseline values	80	3.5	4700*	*<0.02*	25
Target values	**30**	**1.4**	**1880**	**<0.02**	**15**

The "Willsensors" system stores data in the Rīga Municipality data warehouse, with Power BI dashboards available upon request for internal purposes and the option to publish to the open data portal if needed; transmission frequency ranges from 1 minute to 7 days. It features In-Situ VuLink CI + AquaTroll 800 Multiparameter Sonde units (monitoring temperature, conductivity, pH/ORP, turbidity, nitrates, ammonium, dissolved oxygen, and hydrostatic level), alongside Macemeters with Mace FloSeries3 + Doppler card + WebComm 4G, including HVFlo XCi + Doppler + PolyMount components.

Figure 39. In-Situ VuLink CI + AquaTroll 800 Multiparameter Sonde[12] and Macemeters with different components[13]

Figure 40. Sensor Power Connection and Monitoring Well

Real-Time Sensor Monitoring Results

Although the acquisition and visualisation of sensor data is still being refined, basic measurement data are already being transmitted and collected. This enables preliminary comparisons of water-quality parameters between the inlet and outlet monitoring points. The water quality monitoring data directly reflects the hydrological dynamics of the surrounding environment and the immediate impact of rainfall events. The measured parameters include total dissolved solids, turbidity, and nitrates.

[12] www.in-situ.com
[13] www.macemeters.com

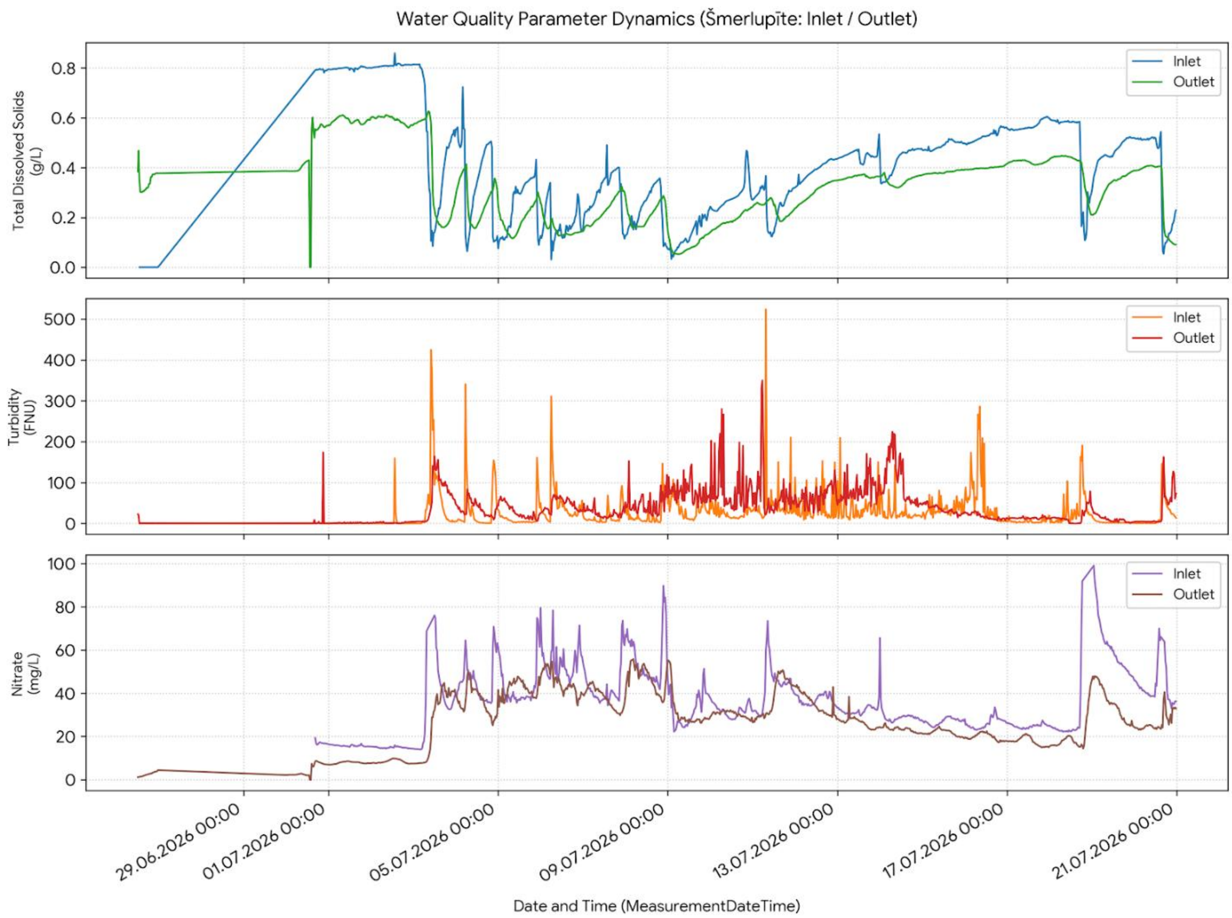


Figure 41. Water Quality Parameters Overview Inlet vs Outlet, June 29 to July 21, 2026

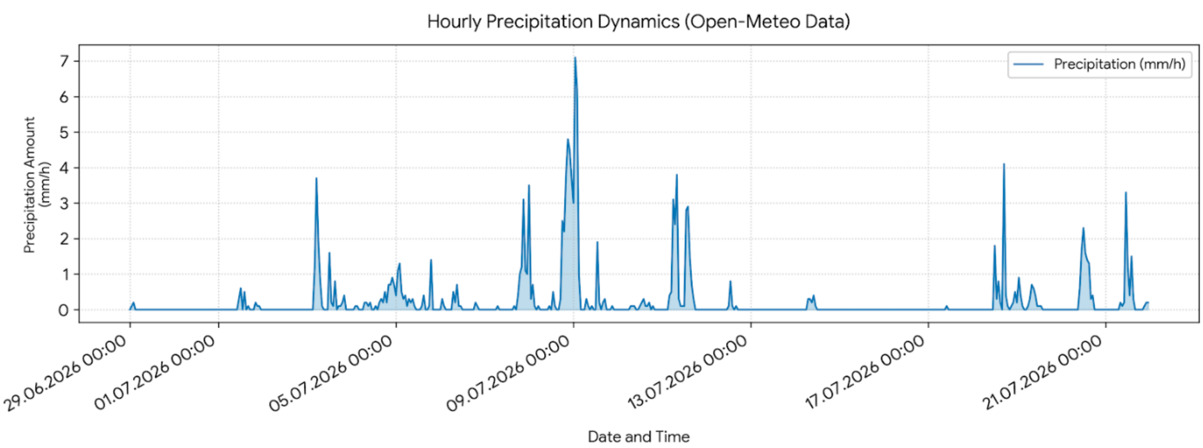


Figure 42. Hourly Precipitation in Rīga, July 5 to July 6, 2026 [14]

Under baseflow conditions, TDS levels in the stream remain stable around 0.4 to 0.8 g/L. However, rainfall events trigger a sharp decline in concentration, showing a negative correlation of -0.37 with a

[14] www.open-meteo.com

roughly 5-hour lag. The rapid influx of soft, low-mineral rainwater dilutes the natural ion and salt concentrations within the watercourse.

Regarding turbidity, levels remain consistently low at below 10 FNU during dry spells, such as July 13 to 18. Conversely, major precipitation peaks - such as the intense storm on July 9 reaching 7.1 mm/h cause immediate turbidity spikes at the inlet exceeding 500 FNU due to soil erosion and the flushing of sediment and organic matter into the stream. At the outlet, this peak is noticeably attenuated and delayed, demonstrating the system's capacity to buffer suspended solids.

As for Nitrates, concentrations exhibit a strong positive hysteresis with a correlation of 0.32 and a 3- to 4-hour time lag relative to rainfall onset. As rainwater infiltrates the surrounding catchment soils, it mobilizes accumulated nutrient reserves, pushing inlet nitrate levels up to 70–90 mg/L following heavy rains.

The observed 1- to 5-hour time lag between peak rainfall and parameter response corresponds to the catchment response time required for surface runoff to enter the stream channel. Precipitation acts as the primary hydrological driver - simultaneously diluting dissolved minerals (reduced TDS) while washing suspended sediments and nutrients into the system (increased turbidity and nitrates).

Sensors installed in the Šmerļupīte stream record water depth and flow rate, both of which are closely coupled with precipitation patterns. Beyond merely confirming that rainfall increases water depth and current velocity, these monitoring data provide deeper insights into the catchment's hydrological behavior.

The catchment exhibits a notable hydrological lag time between discharge and water storage. The net flow rate responds almost instantaneously to precipitation events, as indicated by sharp, immediate peaks. In contrast, the water depth reaches its maximum with a distinct time lag. This is most prominent during the heavy rainfall event around July 9–10, where the flow rate peaks immediately, whereas the peak water depth remains elevated for more than a full day.

Furthermore, the recession curve illustrates substantial hydraulic retention within the drainage catchment or green infrastructure solution. The falling limb of the water depth hydrograph following a peak - for instance, between July 10 and July 14 - exhibits a gradual and prolonged decline. This demonstrates that the system successfully buffers peak runoff and releases stormwater slowly downstream rather than draining immediately.

During extended dry spells, such as the period from July 14 to July 19, the water depth stabilizes at a steady baseline of approximately 0.15 m, accompanied by a near-zero net flow rate. This represents the natural baseflow regime of the system under dry-weather conditions.

Finally, the data highlights the critical influence of antecedent soil moisture conditions on peak runoff generation. A comparison between the rainfall events on July 4 and July 9–10 illustrates the strong effect of catchment saturation. The high-intensity rainfall on July 9–10 occurred when the soil and storage capacity were already saturated from preceding rain on July 8, triggering a disproportionately sharp surge in water level exceeding 1.25 m alongside a major peak in net flow rate.

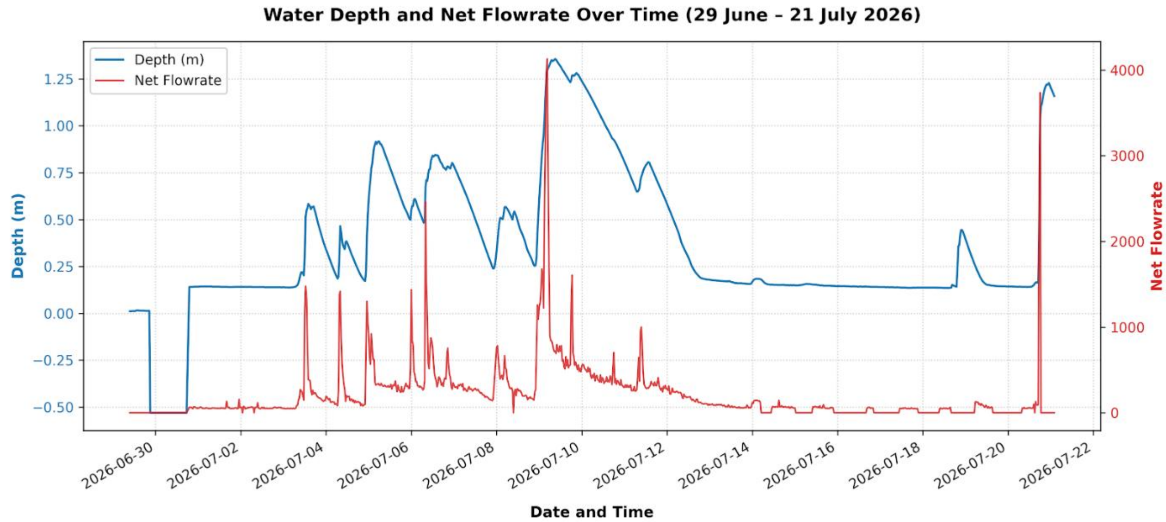


Figure 43. Water Depth and Net Flowrate Over Time, June 29 to July 21, 2026

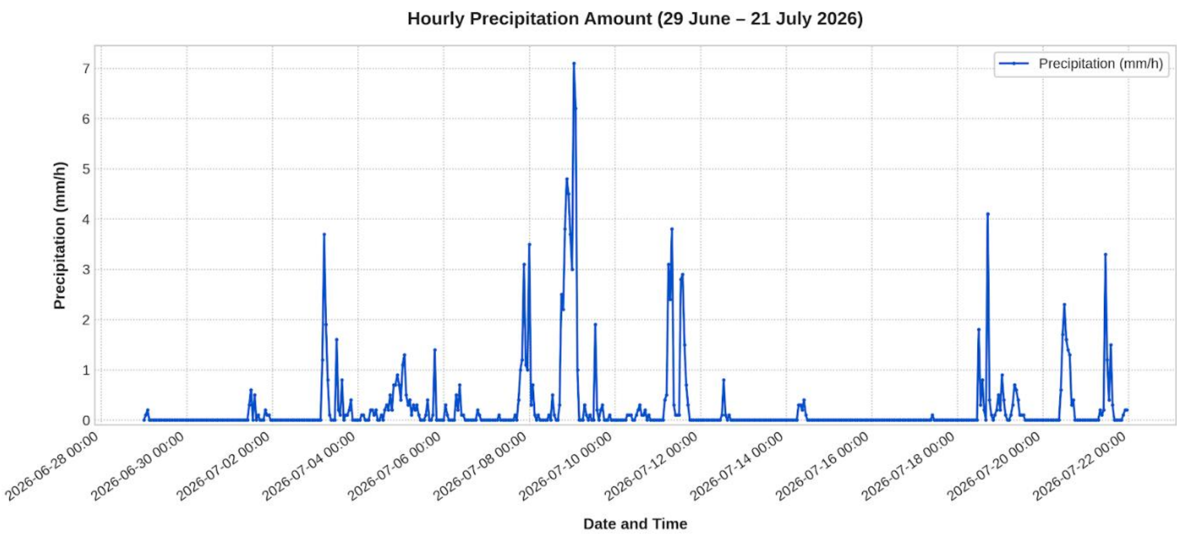


Figure 44. Hourly Precipitation in Rīga, June 29 to July 21, 2026[15]

[15] www.open-meteo.com

Laboratory Water Quality Results

Prior to NBS construction, water samples were collected from the Šmerļupīte river on June 21, 2023; July 7, 2023; and December 21, 2023. Sampling occurred during both dry periods and post-precipitation events. Results show that precipitation worsened some indicators (e.g., total suspended solids, NH_4) while others remained unaffected. Several parameters fell within regulatory limits, but others exceeded them, indicating poor baseline water quality. The project aims to improve these indicators and identify key correlations.

Repeated water samples were collected on March 9, 2026, during the river straightening and transformation phase. None of the measured indicators exceeded the project's initial target values. However, E. coli bacteria were detected, suggesting possible direct inflow of domestic wastewater into the pilot river section. This is supported by the absence of E. coli in the upstream sample. Notably, bacterial levels remained below target thresholds.

Table 18. Šmerļupītes Pilot Site Water Analysis Data During Dry Period, March 9, 2026

March 9, 2026	**Dry period**			
Parameter	**Unit**	**Inlet**	**Middle**	**Outlet**
Suspended solids	mg/L	<2	3	10
Total Nitrogen, Ntot	mg/L	0.555	2.22	1.66
Hydrocarbon Oil Index (HOI)	mg/L	<0.02	<0.02	<0.02
E-coli	KVV/100 mL	0	1600	1400
Cadmium, Cd	µg/L	<0.12	<0.12	<0.12
Chromium, Cr	µg/L	<2	<2	<2
Copper, Cu	µg/L	<0.8	1.44	2.77
Mercury, Hg	µg/L	<0.08	<0.08	<0.08
Nickel, Ni	µg/L	<2	<2	<2
Lead, Pb	µg/L	2.04	2.81	<0.9
Zinc, Zn	mg/L	<0.04	<0.04	<0.04

An evaluation of the water quality monitoring data collected on 20 July, 2026 - following a period of rainfall - reveals mixed system performance between the inlet and outlet sampling points.

Overall, the treatment path demonstrates positive physical filtration and nutrient reduction capabilities. Suspended solids dropped by 12.5%, decreasing from 40 mg/L at the inlet to 35 mg/L at the outlet, indicating effective settling or physical trapping of particulate matter. TN saw a modest reduction of 8.5%, moving from 1.88 mg/L to 1.72 mg/L. Furthermore, several key pollutants remained exceptionally low across both sampling points; Hydrocarbon Oil Index (HOI) levels were consistently below the detection limit (<0,02 mg/L), as were concentrations of chromium, mercury, and zinc.

Table 19. Šmerļupītes Water Quality Laboratory Measurements, July 20, 2026

July 20, 2026	**Rainy period**		
Parameter	**Unit**	**Inlet**	**Outlet**
Suspended solids	mg/L	40	35
Total Nitrogen, Ntot	mg/L	1.88	1.72
Hydrocarbon Oil Index (HOI)	mg/L	<0.02	<0.02
E-coli	CFU/100 mL	230	270
Cadmium, Cd	µg/L	<0.12	0.221
Chromium, Cr	µg/L	<2	<2
Copper, Cu	µg/L	39.3	41
Mercury, Hg	µg/L	<0.04	<0.04
Nickel, Ni	µg/L	<2	2.38
Lead, Pb	µg/L	33.2	38.2
Zinc, Zn	mg/L	<0.04	<0.04

However, the post-rainfall conditions also highlight notable secondary mobilization risks within the system. Microbial contamination increased at the outlet, with *E. coli* levels rising by 17.4% (from 230 to 270 CFU/100 mL), which is a common occurrence during high-flow events due to surface runoff or local soil wash-off. Additionally, heavy metal concentrations showed an upward trend downstream: Lead (Pb) increased by 15.1% (from 33.2 to 38.2 µg/L) Copper rose by 4.3% (from 39.3 to 41.0 µg/L) and trace amounts of Cadmium (0.221 µg/L) and Nickel (2.38 µg/L) emerged at the outlet after being undetected at the inlet.

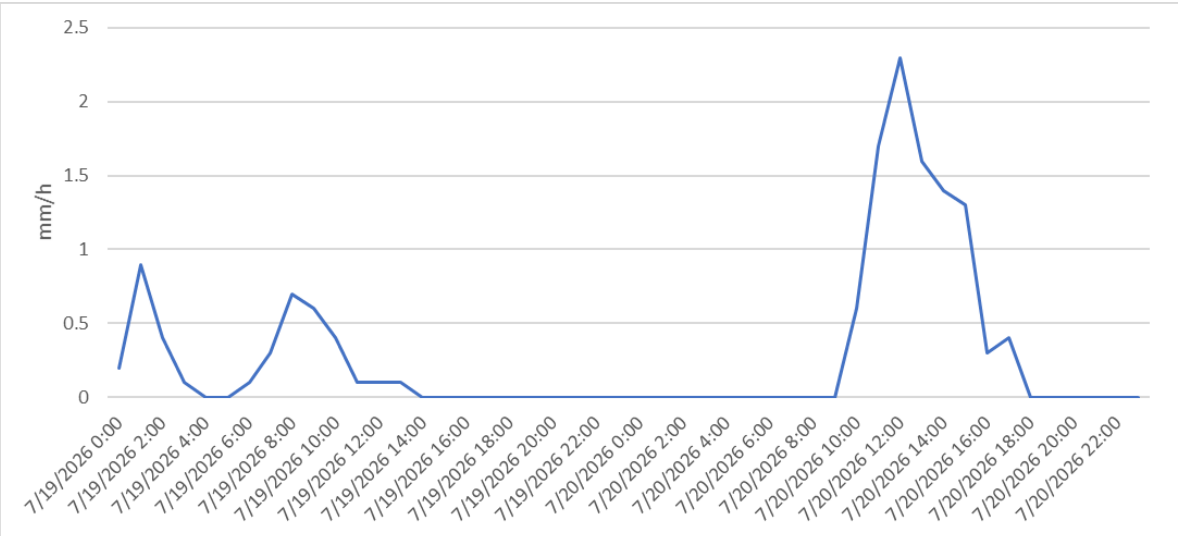


Figure 45. Hourly Precipitation in Rīga, July 19 to July 20, 2026

This increase in heavy metals and bacteria downstream strongly suggests that high storm flushes are triggering the resuspension of previously settled bed sediments or causing localized bank erosion between the inlet and outlet monitoring points.

The comparison of the results of the dry March and July rains shows that metal concentrations in July's rainwater runoff are significantly higher than in March. This is explained by rainwater washing off and carrying previously accumulated metals from roads, roofs, and urban surfaces into the river (for example, from vehicle brake dust and tire wear).

Suspended solids are substantially higher in July (35 mg/L vs. 10 mg/L in March) due to erosion and strong water flow.

In March, a very large bacterial spike was observed at the outlet (jumping from 0 at the inlet to 1,400 CFU/100 mL at the outlet), whereas in July, although E. coli was 230 CFU/100 mL at the inlet, it increased only slightly at the outlet (up to 270 CFU/100 mL).

The continuous operation of the sensor network successfully demonstrates real-time telemetry, data transmission, and collection capabilities, allowing for effective comparative analysis between the inlet and outlet monitoring points.

Furthermore, the sensors exhibit high sensitivity to environmental dynamics, accurately capturing both steady baseflow conditions during dry periods and immediate parameter shifts triggered by rainfall events.

The monitoring system effectively captures critical peak values and system response delays ranging from 1 to 5 hours. This highlights distinct physical and chemical mechanisms, such as immediate turbidity surges contrasted with the more gradual dilution of total dissolved solids and nutrient leaching of nitrates.

Finally, the clear differentiation between inlet and outlet sensor readings—most notably the attenuation of turbidity spikes—validates the utility of the monitoring setup in assessing the system's buffering and pollutant retention capacity.

In conclusion the Rīga pilot system demonstrated moderate treatment performance during the rainfall event, with improvements in suspended solids and total nitrogen. Hydrocarbons and several metals remained below the detection limits, indicating that the system provides some water-quality treatment.

However, increases in certain heavy metals and E. coli concentrations were observed at the outlet. This may indicate the resuspension of deposited sediments, local bank erosion, or the mobilisation of pollutants during rainfall and high-flow conditions.

Overall, the system shows potential for reducing selected pollutants, but its performance remains mixed. Continued monitoring under both dry-weather and rainfall conditions is needed to assess its long-term effectiveness and identify any additional measures required.

Conclusions

The Rīga pilot system shows that the sensor network and grab sampling together can reliably capture how rainfall events affect both hydraulics and water quality along the Šmerļupīte stream. Real-time data demonstrate clear time lags and correlations between precipitation, flow, water depth, TDS, turbidity, and nitrates, confirming that the system buffers peak flows and slowly releases stormwater downstream rather than draining it immediately. At the same time, the laboratory results indicate that the system provides only moderate treatment performance during rainfall, with some reduction in suspended solids and total nitrogen and consistently low levels of hydrocarbons and several metals. However, both sensor and laboratory data point to secondary mobilisation risks under high-flow conditions. After rainfall, E. coli and several heavy metals (lead, copper, cadmium, nickel) tend to increase at the outlet, likely due to sediment resuspension, bank erosion, or wash-off from urban surfaces. Comparisons between dry-period and rainy-period sampling further show that summer rainfall substantially increases suspended solids and metal loads entering and passing through the system.

Overall, the Rīga pilot demonstrates that the NBS and monitoring setup are functioning and that the system can attenuate certain pollutants and hydraulically buffer stormwater, but its water-quality performance remains mixed. Continued monitoring under both dry and wet conditions, with attention to sediment dynamics and local pollution sources, is needed to evaluate long-term effectiveness and to determine whether additional design or management measures are required.

5. Conclusions

The MUSTBE pilot sites demonstrate that nature-based stormwater solutions effectively support flood management, attenuate peak runoff, and improve overall water quality, while highlighting how performance uniquely adapts to local site conditions, weather patterns, and system designs. Across the report, combining laboratory analyses with real-time sensor data proved to be a highly effective approach for gaining comprehensive insights into both hydrological responses and pollutant dynamics.

Several sites are already delivering clear positive outcomes. In Pori, the Central Square solution successfully achieved key project targets by retaining the majority of stormwater, while the wetland contributed to stabilizing hydrology, enhancing acidity levels, and reducing specific metal concentrations, providing a strong baseline for further seasonal adaptation. In Viimsi, real-time monitoring effectively captured clear, rainfall-driven dynamics in water level, conductivity, and dissolved oxygen, establishing a solid foundation for long-term evaluation as the site continues to mature.

In Söderhamn, the implemented solutions are progressing well and performing as intended, demonstrating encouraging improvements in nutrients, metals, and microbiological indicators. While the dry conditions at the Söderhamnsporten outlet present an opportunity for future flow evaluation, the Broberg site already showcases impressive pollutant removal capacity, offering valuable insights into seasonal shifts and temperature-related dynamics. Together, these results illustrate the rich operational versatility of green infrastructure even within the same municipality.

The pilots in Tallinn and Rīga further reinforce the functional strong points of these systems while offering useful operational learnings. In Tallinn, the soil filter serves as a effective treatment component, with initial sediment observations providing clear guidance on how to optimize future monitoring setups. In Rīga, the system successfully buffers peak flows and lowers pollutant levels, while also revealing important insights into rainfall-triggered mobilization patterns that will help fine-tune future catchment management.

Overall, the report confirms that NBS provide meaningful, long-term stormwater treatment benefits. As these young ecosystems continue to settle, sustained monitoring and targeted site refinements will play a key role in maximizing their efficiency, perfecting design strategies, and fully realizing the long-term potential of green infrastructure across Baltic urban landscapes.