Real-time monitoring of a roadside nature-based solution: Hydraulic behavior, inlet performance and system limitations

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Sammendrag

Sanntidsovervåkning av et veikantnært naturbasert overvannstiltak: Hydraulisk oppførsel, innløpsytelse og systembegrensninger. I dette studiet undersøker vi hvordan sensorteknologi og høyoppløselig overvåkingsdata kan forbedre forståelse av naturbaserte renseløsninger. Artikkelen dokumenterer utforming og etablering av et omfattende overvåkningsopplegg som samler hydrologiske og vannkvalitetsdata gjennom ulike sesonger fra et naturbasert overvannstiltak som renser veiavrenning. En kontrollert stresstest ble gjennomført for å simulere kraftig nedbør og vurdere systemresponsen. Testen avdekket flere designbegrensninger, blant annet utilstrekkelig vinkel på innløp og at vann renner umiddelbart overløp. Dette påvirker hydraulisk funksjon, flomhåndteringskapasitet og overvåkningsnøyaktighet. Selv om studien ikke vurderer renseeffekt, fremhever den sentrale utfordringer knyttet til overvåkning og gir innsikt som kan bidra til bedre utforming, drift og evaluering av blågrønn infrastruktur. Infiltrasjonssystemet fungerer som en referanselokalitet for fremtidige måle- og overvåkningsstudier av urbane overvannssystemer.

Summary

This paper examines the potential of enhanced monitoring to improve understanding of hydraulic behavior in nature-based solutions using sensor technology. The study documents the design and construction of a comprehensive monitoring setup deployed to capture high-resolution hydrological and water-quality data from a roadside nature-based solution treating road runoff. A controlled stress test was conducted to simulate intense rainfall and assess system response, revealing design limitations such as inlet bypassing and immediate overflow that influence hydraulic performance, flood-mitigation capacity and monitoring accuracy. Although the paper does not evaluate treatment efficiency, it highlights key challenges encountered during monitoring and provides insights to support improved design, operation and assessment of blue-green infrastructure. The infiltration trench serves as a reference site for future monitoring of urban stormwater management systems.

Introduction

Road runoff is a major source of environmental pollution (Winston et al., 2023). Stormwater and snowmelt flowing over road surfaces mobilize pollutants such as metals, hydrocarbons, tire wear particles and other microplastics, organic compounds, nutrients, suspended solids and pathogens (Charters et al., 2016; Gaggini et al., 2024; Helmreich et al., 2010; Johansen et al., 2014; Meland et al., 2024; Moazzem et al., 2024; Rødland et al., 2022), which degrade receiving aquatic environments (Meland et al., 2010). The need to manage road runoff pollutants has long been recognized (cf. Meland, 2016) and reinforced by regulatory frameworks such as the EU Water Framework Directive.

More recently, nature-based solutions (NbS) such as bioretention cells, constructed wetlands, detention basins, swales and raingardens have gained prominence for treating pollutants at their sources (Moazzem et al., 2024). Oslo municipality's planning documents (Asplan Viak, 2018; Oslo Kommune, 2020; Oslo kommune, 2014) demonstrate municipal support for integrating NbS into rehabilitated road corridors to enhance water quality, climate adaptation and urban greening.

Additional Norwegian experience with nature-based stormwater solutions is documented in studies and national guideline (e.g., Dalen et al., 2012; French et al., 2020; Hernes et al., 2020; Mengistu et al., 2022; Paus, 2020; Paus and Braskerud, 2014; Paus and Kazinic, 2023; Sivakumar et al., 2021; VA-Miljøblad 92, 2019). However, evaluating their real-world performance remains challenging due to the wide range of factors that influence how these systems function in practice.

One of the challenges is that NbS exhibit highly variable hydraulic behavior due to rainfall intensity, antecedent moisture, seasonal conditions and site-specific design factors. Field studies in cold climates show pronounced seasonal reductions in infiltration and retention during freeze–thaw (Balstad et al., 2018; Muthanna et al., 2008), and rainfall intensity strongly affects overflow, lag times and peak-flow attenuation (Amur et al., 2020; Kristvik et al., 2018). Studies further reveal that system aging, sediment accumulation and inlet performance progressively alter infiltration and increase bypassing (Dietz and Clausen, 2006; Jeon et al., 2021; McGauley et al., 2023), highlighting the need for continuous, high-resolution monitoring to understand NbS behavior under real conditions.

Another critical factor influencing NbS performance is inlet hydraulics. Nordic evaluations show that inlet geometry, placement and grading strongly affect hydraulic capture, with poorly configured or obstructed inlets causing bypass and uneven loading (Gómez, 2016; Paus and Braskerud, 2014). Cold-climate conditions further reduce inlet efficiency due to snow, sediment accumulation and winter maintenance practices (Haghighatafshar et al., 2014; Paus and Braskerud, 2014). Operational and installation challenges are also seldom discussed in detail. Although a few studies have conducted hydraulic stress-testing of NbS (e.g. Braskerud et al., 2012; Sivakumar et al., 2021), systematic stress-testing of NbS remains limited in the literature.

A further challenge is the limited availability of high-resolution monitoring data and the poor documentation of monitoring system configurations. High-resolution monitoring is necessary to understand real-world runoff dynamics in roadside environments because pollutant concentrations and compositions can vary rapidly over short timescales, and traditional low-frequency sampling often fails to capture the short-lived pulses that dominate pollutant loading (Helmreich et al., 2010; Winston et al., 2023). Although several NbS monitoring efforts have been reported, detailed documentation of monitoring system configuration (i.e., sensor placement, sampling strategies, dataflow architecture and site-specific operational constraints) remains scarce (Barkved et al., 2025; Jeon et al., 2021; McGauley et al., 2023). Many studies rely on low-frequency sampling or incomplete instrumentation, limiting their ability to capture short-duration fluctuations in runoff quality and hydraulic responses (Helmreich et al., 2010; Winston et al., 2023). This lack of methodological transparency makes it difficult to compare results across sites and to draw generalizable conclusions about NbS hydraulic behavior under different conditions (Barkved et al., 2025). Greater clarity in monitoring system design and reporting is therefore essential for building a more robust evidence base.

This paper introduces a real-time, sensor-based monitoring setup at a roadside NbS facility in Tåsenveien, constructed by Oslo Municipality to manage road runoff locally. It presents the monitoring site, describes the installed infrastructure and summarizes the continuous high-resolution hydrological and water-quality data collected. The paper focuses on system configuration, dataflow and limitations, along with practical challenges identified during field deployment and controlled stress testing. The aim is to provide a clear methodological reference for future NbS monitoring efforts seeking high-resolution datasets for evaluating hydraulic behavior and long-term system performance. Detailed assessments of treatment performance, pollutant dynamics and modelling results will be presented in future publications using the longterm dataset generated through the MULTISOURCE project (www.multisource.eu).

Methods

Site description

The monitored NbS facility is located in the northern part of Oslo (Norway), along a 730 m stretch rehabilitated road corridor extending from Tåsen Senter to the intersection with Stavangergata. The rehabilitation aimed to improve road safety, enhance climate resilience and reduce urban flooding. Due to space constraints, conventional stormwater infrastructure (sand traps and pipes) was installed in the northern segment, while the southern segment provided adequate space for multiple roadside NbS solutions designed to infiltrate and retain road runoff.

Runoff from the roadway is conveyed across the sidewalk into the NbS facilities, which Oslo Municipality refers to as “raingardens” (and henceforth are referred to as “infiltration trenches”) through channels whose inlets are positioned in line with the curbstones. The infiltration trenches were built by excavating native soil and separating the multilayered structure from the tree trench by lateral dividing

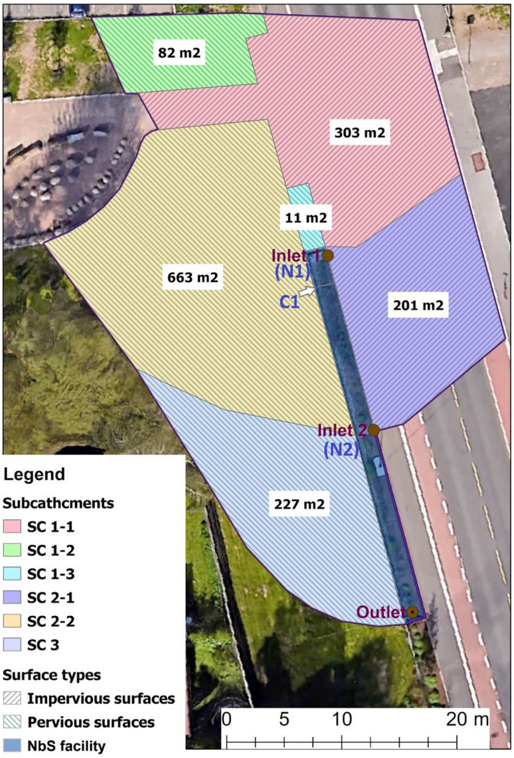

Figure 1. Layout of the pilot NbS facility’s catchment, sub-catchments, inlet and outlet locations, and land cover distribution.

wall and supporting stone structures B35 concrete. The surrounding terrain was reestablished to maintain landscape continuity.

The facility drains a catchment of approximately 1,300 m², consisting of 26.5% impervious (roadways and sidewalks) and 73.5% pervious (lawn) surfaces. Runoff from both sides of the road is routed through two inlet gutters (20 cm × 15 cm) spaced 16 m apart (Figure 1): Inlet 1 drains 384 m² (78.7% impervious), while Inlet 2 drains 201 m² of impervious surface. An additional 838 m² of lawn contributes overland flow along the raingarden's length. The raingarden has a surface area of approximately 60 m² and provides about 19.6 m³ of surface storage along its 33.5 m length.

The system is bordered by 200 mm and 100 mm curb stones, which contain runoff and define facility edges. It consists of several functional layers (Figure 2):

- **Surface layer**: Intended for vegetation (although limited in practice), to enhance biodiversity, aesthetics, and pollutant uptake.
- **Filter medium**: A ≥ 500 mm layer of 50% sand, 45% compost, and 5% local topsoil that supports plant growth, infiltration and pollutant filtration.
- **Geotextile layer**: A fabric preventing mixing of the filter medium and the drainage layer.
- **Drainage layer**: 8 - 16 mm crushed stone surrounding a 160 mm diameter (potentially perforated) underdrain pipe.
- **Base layer**: Gravel and moraine stone for structural support and enhanced drainage.
- **Outlet system**: A downstream manhole storing and facilitating infiltration of the overland flow routed through the trench; standing water depth varies with runoff magnitude.

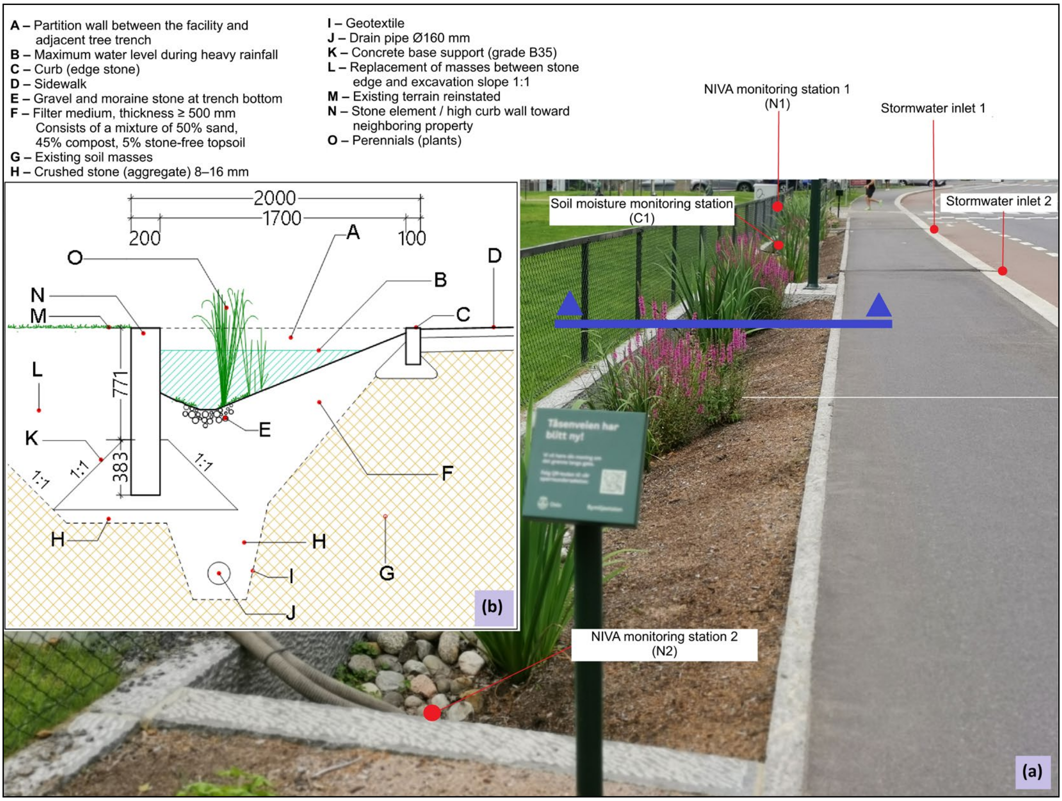

Figure 2. Locations of the monitoring stations N1, N2 (inlet/outlet) and C1 (soil moisture station). Background image source: Bymiljøetaten, Oslo kommune.

Figure 3. Observed hydraulic behavior of the roadside NbS facility during an intense rainfall event associated with Storm Hans (07 August 2023, afternoon). (a) Runoff from the road surface and bicycle lane entering the system; (b) Inlet zone showing ponding and additional inflow from the adjacent lawn; (c) Mid-section illustrating conveyance of runoff along the trench with continued lateral inflow; (d) Downstream section showing temporary storage and flow routing within the system; (e) Outlet structure where runoff is discharged to the downstream manhole.

During the 7 August 2023 Storm Hans event, the intense rainfall revealed the system's behavior, with inlet inflow and lawn-generated overland flow loading the entire facility, causing ponding along the trench and rapid discharge downstream, as illustrated in Figure 3.

Monitoring systems and infrastructure

The monitoring system captures high-resolution hydrological responses and runoff contaminants. Sensor placement and logging frequency were determined to support detailed assessment of rapid pulses, bypassing, infiltration and delayed subsurface responses.

Monitoring stations

Three stations were established along the raingarden (Figure 2):

- **N1 (Inlet station)**: Located at the upper end, captures inflow water levels and water-quality parameters as runoff directly enters from the road.
- **N2 (Outlet station)**: Located at the downstream end, records outflow dynamics, delayed runoff, infiltrated responses and overflow behavior.
- **C1 (soil-moisture profile)**: Monitors subsurface moisture and temperature variations at multiple depths.

Instrumentation

At N1 and N2, NIVA installed sensors for: Water level (WIKA), Turbidity (AML), Electrical conductivity (Pyxis ST-720), and Temperature. Measurements were recorded at 5-minute intervals.

At C1, Cautus Geo installed Campbell Scientific CS655 probes measuring: Volumetric water content (VWC), Bulk electrical conductivity (EC), and Temperature. These were logged hourly at depths of 20, 33 and 72 cm.

Full technical specifications for all sensors are provided in Table 1.

Dataflow and cloud platforms

The digital infrastructure supporting the Tåsenveien pilot integrates several platforms for data management, visualization, and dissemination:

- **Cautus Web**: A cloud-based platform (https://cautusgeo.no/en/products/cautus-web/) for collecting, processing, and visualizing environmental monitoring data remotely. It supports real-time data acquisition from a wide range of sensors, regardless of manufacturer. In the Tåsenveien pilot, Cautus Web was used to manage data from soil moisture sensors installed at various depths within the raingarden.
- **NIVA Cloud**: A secure platform developed by NIVA for real-time environmental monitoring and data management. It supports automatic collection, storage, and visualization of high-frequency sensor data from various environmental monitoring stations. NIVA Cloud provides remote access to data through a secure cloud infrastructure, facilitating long-term environmental research, and informed decision-making for water management and pollution control. In the Tåsenveien pilot, access to NIVA Cloud data was provided through two open-source platforms, Grafana and Superset, tailoring access for different user groups:
    - **Grafana** (https://grafana.p.niva.no/): Used internally for quality control and operational oversight due to its flexibility to integrate various data sources and its powerful alerting capabilities.
    - **Superset** (https://superset.p.niva.no/superset/dashboard/multisource/): Used for broader public engagement enabling users to explore datasets through intuitive interfaces without requiring advanced technical skills.

Stress test procedure

A controlled hydraulic stress test was conducted on 23 October 2023 to simulate intense rainfall conditions. A fire department tanker truck discharged 9,000 liters of water upstream of the inlets in two phases:

Table 1. Technical specifications of sensors used at N1, N2, and C1.

	Turbidity	Water depth	Conductivity	Soil Moisture
Sensor brand	AML	WIKA	PYXIS	Campbell
Sensor model	Turbidity eXange with wiper with MicroX sensor head	LH-20 with ventilated cable	ST-720	CS655
Measurement unit	NTU	bar	µS/cm	VWC: m^3/m^3 EC: dS/m T: °C
Measurement range	0-3000	0-0.4	1-100 000	VWC: 0 - 0.7 EC: 0 - 8 T: –40 - +60
Calibration	Factory-calibrated (checked by means of Formazin dilution and a HACH lab turbidimeter)	Factory-calibrated	Factory-calibrated	Factory-calibrated

- **Phase 1:** Approximately 3,000 liters were discharged over 12.5 minutes, corresponding to a flow rate of about 250 liters per second. After releasing about 1,000 liters of water, a barrier was installed at Inlet1 to redirect the flow into the NbS unit.
- **Phase 2:** The remaining 6,000 liters were released over approximately 6 minutes, with the hose positioned directly into Inlet1 channel.

Observations focused on flow paths, bypassing, inlet capture, overflow timing, infiltration signals and travel time from N1 and N2. Sensor responses were reviewed afterwards.

Results and Discussion

Monitoring-based characterization of system response

Continuous monitoring of the Tåsenveien pilot revealed highly dynamic runoff conditions, characterized by pronounced temporal variability in both hydraulic and water-quality parameters.

Figure 4 provides an example of the monitored time series. At the inlet (N1), turbidity and electrical conductivity showed strong event-driven fluctuations, with short-duration peaks indicating rapid mobilization of sediments and dissolved constituents during rainfall events. These patterns illustrate the variable nature of

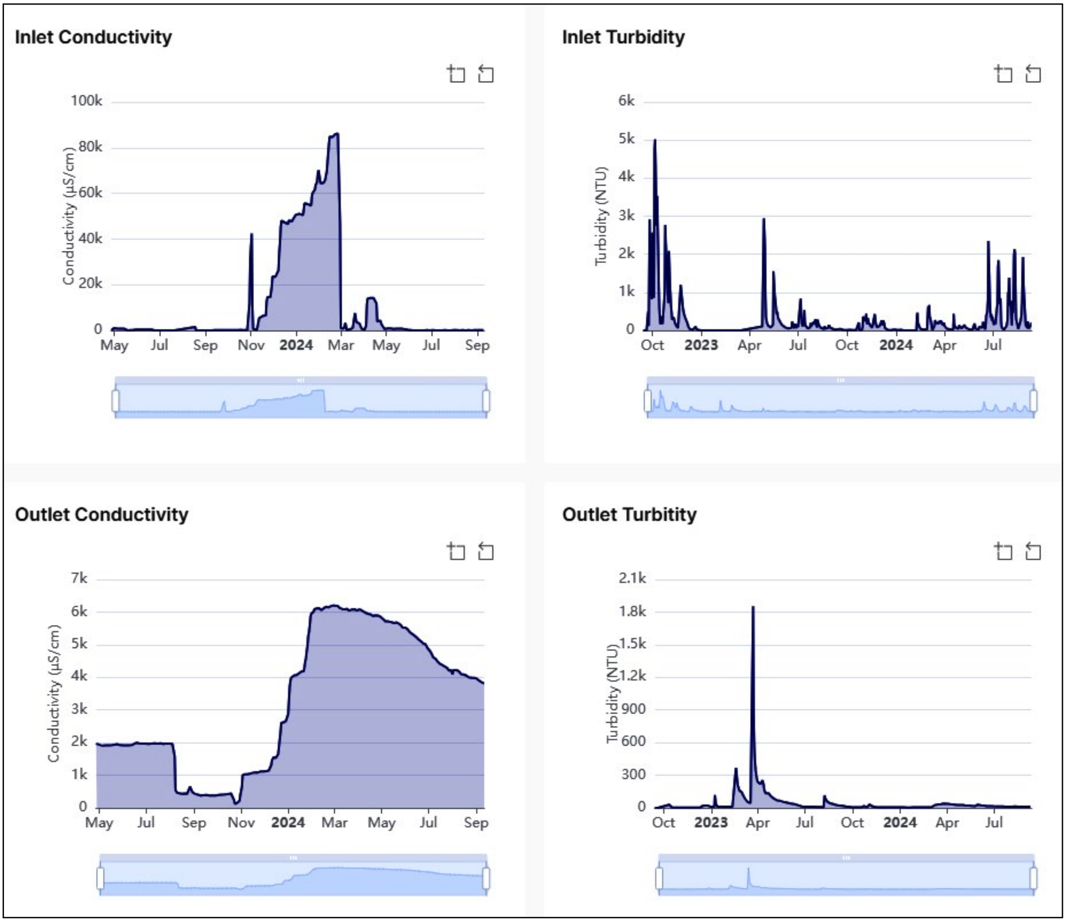

Figure 4. Example of long-term monitoring data from the Tåsenveien facility showing electrical conductivity (µS/cm) and turbidity (NTU) at the inlet (N1) and outlet (N2). The time series illustrate strong event-driven variability at the inlet and attenuated but still variable responses at the outlet.

road runoff, where pollutant loads occur in short, intense pulses.

Outlet measurements (N2) exhibited more attenuated responses, with lower peak magnitudes and more gradual temporal variation. The differences between inlet and outlet signals indicate that the system modifies incoming runoff through a combination of surface storage, mixing and subsurface flow processes, although the persistence of temporal variability at N2 suggests limited buffering capacity under dynamic loading conditions.

Overall, these monitoring observations show that the system is frequently subjected to highly variable inflow conditions while providing only partial attenuation of hydraulic and water-quality signals. This characterization forms an important basis for interpreting the hydraulic behavior observed during the controlled stress test.

Hydraulic response under controlled stress testing

The controlled stress test revealed hydraulic performance patterns that highlight key hydraulic behaviors at the site. The hydraulic loading was lower than in the hydrant-based test at Deichmans gate (Sivakumar et al., 2021) due to tanker-truck limitations; nevertheless, the test still exposed several of the same inlet- and routing-related constraints.

- **Inlet capture efficiency and bypass behavior.** A substantial portion of inflow bypassed the inlet openings during the initial stress test phase. However, the degree of bypass at Tåsenveien was more pronounced, likely due to the combination of slope geometry, lack of sediment trap and a sharp 90° angle into the inlet channel. When water was manually directed into the inlet during Phase 2, the system accepted flow more effectively, reinforcing inlet geometry and hydraulics as the primary constraints. This behavior is consistent with field observations during the Storm Hans event (Figure 3), where runoff was observed to bypass inlet openings and substantial amounts of water entered the system as distributed surface flow from the lawn.
- **Overflow response and surface storage limitations.** At the downstream end (station N2), overflow occurred almost immediately once water reached this point due to limited surface detention capacity. Compared with typical configurations, the Tåsenveien overflow elevation offers limited opportunity for attenuation causing outlet hydrographs to respond rapidly to incoming flow. However, the overflow response at Tåsenveien was more severe due to the overflow being positioned exactly at the soil-surface level, which limits temporary storage. Similar patterns were observed during the Storm Hans event, where rapid downstream conveyance and absence of meaningful surface storage resulted in immediate discharge at the outlet.
- **Flow routing and subsurface pathway uncertainty.** A travel time of approximately five minutes between the inlet station N1 and the outlet station N2 was observed for the first flash, indicating temporary retention or delayed movement within the system. The distributed inflow and overland flow observed during the Storm Hans event further support the interpretation that multiple flow pathways exist within the system. Infiltrated water may follow multiple possible routes within the facility, i.e., vertical movement toward the longitudinal underdrain or lateral movement toward the downstream manhole. Because the stress test was short and underdrain flow is not monitored, the relative proportions and timing associated with each pathway remain uncertain. Overall, the hydraulic patterns suggest that subsurface drainage at Tåsenveien may operate differently than implied by the design drawings and warrant further investigation.
- **Sensor-based characterization of hydraulic and water quality responses.** The monitored responses were consistent with field observations from the Storm Hans, particularly with respect to rapid flow

propagation and limited detention within the system. Figure 4 shows the recorded sensor responses. The key patterns observed are:

- Rising and falling limbs of water-level hydrographs at N1 and N2, reflecting the rapid inflow and short-delay outflow characteristic of road-runoff pulses.
- Sharp increases in turbidity during initial flow pulses, consistent with mobilization of road-deposited sediments and tire-wear particles.
- Conductivity variations reflecting entrained road salts and dissolved constituents.
- Soil-moisture responses at all three depths, showing rapid near-surface wetting and progressively delayed responses at deeper layers.

The hydraulic behaviors observed at Tåsenveien (i.e., inlet bypass under steep approach conditions, limited surface detention associated with low overflow elevation, rapid conveyance of surface water during intense loading, and uncertainty in subsurface routing) are broadly consistent with patterns described in previous evaluations of raingardens and bioretention systems. Earlier studies highlight the influence of inlet configuration and approach flow on capture efficiency (Gómez, 2016; Paus and Braskerud, 2014), the importance of overflow elevation for enabling meaningful detention and attenuation (Dietz and Clausen, 2006), and the role of internal drainage layout in shaping lag times and complicating pathway interpretation (Jeon et al., 2021; McGauley et al., 2023). While the drivers at Tåsenveien are site-specific, the overall responses align with established observations from other roadside and cold-climate NbS installations.

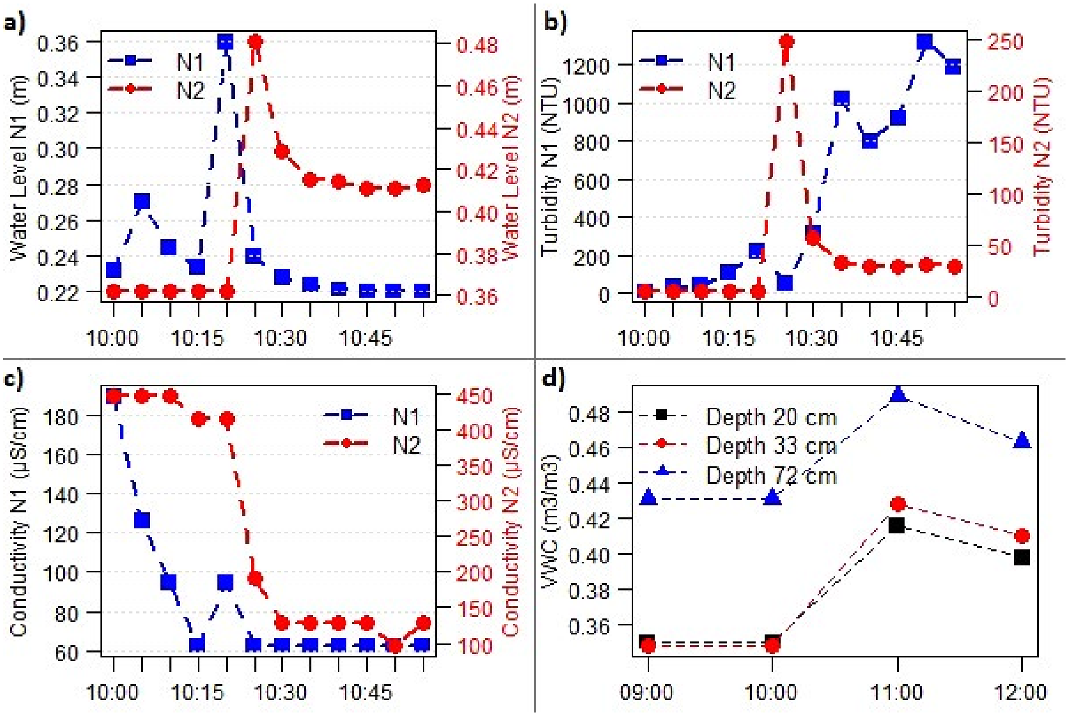

Figure 5. Time series plots of monitored parameters during the stress test on 23 October 2023. (a) Water level (m) at stations N1 and N2. (b) Turbidity (NTU) at stations N1 and N2. (c) Electrical conductivity (µS/cm) at stations N1 and N2. (d) Volumetric water content (VWC, m^3/m^3) at soil depths of 20 cm, 33 cm, and 72 cm – station C1.

The observed flow pathways and system response during the test are illustrated in Figure 6.

Maintenance requirements for improved NbS performance

The monitoring dataset and field observations highlighted two factors that could reduce the hydraulic and treatment efficiency of the NbS facility over time.

- **Debris accumulation at inlets.** Accumulation of debris, particularly leaves and sediment at inlet structures, was observed to reduce hydraulic capture efficiency and influence both runoff conveyance and monitoring reliability. This is consistent with studies showing that sediment, leaves and winter debris reduce NbS performance (Haghighatafshar et al., 2014; Paus and Braskerud, 2014).
- **Vegetation and surface clogging.** Limited vegetation cover on the filter surface exposes the underlying media to clogging over time, potentially reducing infiltration capacity. This contracts with vegetated raingardens described by (French et al., 2020), which maintained higher infiltration rates until sedimentation became severe.

Together, these factors influence key hydraulic processes such as inflow capture, surface storage, infiltration and pollutant retention, thereby reducing overall system effectiveness. Therefore, regular maintenance, removal of accumulated debris at inlets, restoration of vegetation cover, and periodic inspection of the filter media is essential. These observations, and the maintenance needs identified at Tåsenveien, are consistent with earlier findings that emphasize

Figure 6. Photographic documentation of the 23 October 2023 stress test showing inflow at Inlet 1 (a), mid-section flow conveyance (b), approaching flow near the outlet (c) and discharge into the downstream manhole (d).

the importance of sediment control and vegetation management for sustaining performance of NbS facilities in roadside environments exposed to high sediment and debris loads.

Data interpretation limitations and future modelling needs

Beyond the practical maintenance issues described above, several fundamental limitations remain in interpreting the hydrological behavior of the system from monitoring data alone. Although the monitoring setup successfully captured clear hydraulic responses at both the inlet and outlet, key uncertainties emanate from the internal configuration of the installation. Internal flow paths between the gravel zones, the underdrain and the downstream manhole cannot be distinguished in terms of whether infiltrated water is conveyed vertically through the underdrain or laterally through subsurface pathways toward the manhole. Similar hidden or undocumented subsurface routing has been highlighted as a key challenge in interpreting field-scale NbS performance, where complex drainage layouts can obscure or confound the relationship between measured inflows, storage, and outflows (Jeon et al., 2021; McGauley et al., 2023).

These uncertainties affect understanding of the lag times, infiltration signals and storage–release dynamics. As a result, particular hydrograph features cannot be reliably attributed to specific subsurface pathways as discussed in section 3.2. More specifically, the absence of sensors on the underdrain prevents quantification of the relative contributions of infiltration, preferential pathways and vertically drained infiltrated water, and prevents determining what proportion of infiltrated water leaves the system through the underdrain rather than laterally toward the manhole.

To address these limitations, future work will incorporate targeted hydraulic and hydrological modelling. Previous studies have shown that modelling can clarify subsurface processes that are not directly measurable in the field and can distinguish between structural routing and true infiltration and drainage mechanisms (Muthanna et al., 2008; Paus and Braskerud, 2014; Paus and Kazinic, 2023). Integrating monitoring data with modelling will therefore be essential for resolving internal flow pathways, evaluating long-term performance and determining the relative contributions of infiltration, retention and conveyance under different seasonal and hydraulic conditions. Such modelling can also guide improved monitoring configurations in future installations by identifying where instrumentation is needed to discriminate overflow, laterally routed infiltrated water reaching the manhole, and vertically routed infiltrated water draining into the underdrain.

Implications for NbS design and operation

The monitoring results and stress-test findings indicate several practical design considerations for roadside NbS in cold climates based on the hydraulic responses observed in this study:

- Inlet geometry should be improved to enhance hydraulic capture and reduce bypasses.
- Overflow structures should be elevated to enable surface ponding and attenuation.
- Maintenance-friendly configurations are needed to limit sediment-induced clogging and preserve infiltration capacity.
- Monitoring should distinguish lateral from vertical drainage, since laterally routed infiltrated water reaches the manhole and is measured, while vertically drained infiltrated water enters the underdrain and leaves the monitored system.

These lessons provide clear guidance for improving hydraulic performance and interpretability in future raingarden installations.

Conclusion

This study presents a real-time, sensor-based monitoring setup implemented at a roadside NbS facility in Tåsenveien, Oslo, and documents its design, installation and operational performance under real-world conditions. Continuous high-resolution measurements, together with a controlled hydraulic stress test, demonstrated the value of detailed monitoring for identifying inlet-related constraints, flow path uncertainties and other hydraulic challenges that influence system behavior. The sensor configuration, dataflow design and field deployment and shortcomings identified provide a practical reference for future monitoring programs seeking to generate reliable datasets for evaluating NbS hydraulic performance.

By systematically documenting monitoring system configuration and reporting the challenges encountered during operation, this study addresses a recognized gap in NbS monitoring practice and offers guidance for improving inlet design, overflow configuration and maintenance strategies in roadside installations. While this paper focuses on hydraulic understanding and system behavior, planned future work will assess pollutant treatment performance, pollutant dynamics and modelling outcomes using the long-term dataset generated through the MULTISOURCE project (www.multisource.eu).

Acknowledgements

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