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Insights gained from a stormwater e-monitoring case study in Viimsi, Estonia

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Abstract The Baltic Sea is at risk from urban societies' diffuse pollution, which includes harmful substances, nutrients, and marine debris. Stormwater, the primary means by which these pollutants are transported, is typically evaluated through the collection and analysis of grab samples, which show the water quality at a particular moment in time. This method, however, is ineffective at capturing instances of high pollutant concentrations, which makes it more difficult to accurately assess the pollutant load or the impact of the pollutants on the environment. In order to better monitor fluctuations in stormwater quality, an e-monitoring station based on surrogate water quality parameters was built in Viimsi, Estonia. The developed system was based on variables such as pH, turbidity, dissolved oxygen, electrical conductivity, flow rate, and water level. The developed system was successful at capturing high frequency data (5-minute time step) over a three-month period, missing only 15% of the data collected and capturing extreme values that would otherwise not be captured (with traditional grab sampling). The gathered data opens up new avenues for stormwater management and investigations (such as identifying unauthorized connections), as having high frequency and real-time data is the first step towards creating a smart stormwater system that can be controlled in real-time in accordance with water quality criteria.

Keywords: e-monitoring, stormwater, surrogate parameters, water quality, smart cities

1. Introduction

The Baltic Sea is a semi-enclosed body of water that has slow water exchange with the global ocean, making it vulnerable to anthropogenic activities on land and at sea. It is widely known that pollutants like nutrients, hazardous substances, and sea litter harm it and to improve on the issue Helsinki Commission (HELCOM) was established in 1974 (HELCOM, 2023). Since the organization's founding, it has been gathering environmental monitoring data from all riparian countries and publishing Holistic Assessments (HOLAS) every five years to give member nations a thorough overview of the environmental health of the Baltic Sea (HELCOM, 2023).

The underlying premise of these reports is that the data reported to HELCOM is of high quality, meaning that it is accurate, reliable, and representative. It is, however, a difficult premise to validate due to the inherent variability of constituents between and within rainfall events. These changes in pollutant composition are influenced by catchment characteristics, stormwater system type (combined or separate), rainfall characteristics, and the length of the previous dry period, among other factors (Ackerman et al., 2011). Additionally, to maximize the effectiveness of sampling campaigns, time, logistics, and financial constraints must be balanced. Furthermore, data collection and analysis procedures must be standardized to ensure that the outcomes are comparable (Ackerman et al., 2011).

Investigations into non-point source pollution currently rely on taking samples from the environment and taking them to a lab for analysis. This method is used sporadically and only provides information after an event has occurred, leaving the environment's state before and after the measurement in doubt. Automatic samplers can help alleviate the problem by standardizing sample collection based on flow or volume (Behmel et al., 2016). However, relying on a low frequency sampling approach runs the risk of missing important changes in water quality, which could lead to an underestimation of the pollutant load entering the Baltic Sea and incorrect assessments of the sea's environmental status (Leigh et al., 2015).

Continuous monitoring using in-situ sensors could be used to increase the frequency with which stormwater quality is assessed. The method can be used to supplement or replace manual sampling and laboratory analysis, as well as to fill data gaps at higher frequencies to reflect more rapid changes in stormwater quality (Copetti et al., 2019). These sensors may be chosen based on their ability to identify specific chemical compounds (for example, nitrogen, different heavy metals, etc.) or on a surrogate relationship (for example, turbidity) that has been established with a variety of laboratory-based parameters (Leigh et al., 2019; Copetti et al., 2019).

As part of the Interreg Central Baltic CleanStormWater project, a first-of-its-kind stormwater quality and quantity monitoring system in the Baltics was built in Viimsi, Estonia. The new system was based on turbidity, electrical conductivity (EC), dissolved oxygen (DO), pH, flow, and water level sensors, and the system's performance and the value of continuous data collected during the first three months of operation were assessed. Going forward, it was anticipated that the continuous monitoring system would make stormwater management in Viimsi more knowledge-based, paving the way for the adoption of similar systems in other catchments.

2. Materials and methods

Three monitoring stations were installed at the stormwater catchment in Viimsi, Estonia, as a part of the CleanStormWater project (Figure 1) (CleanStormWater, 2023). The placement of these stations was based on the characteristics of the catchments (e.g., land use and nearby anthropogenic activities).

Figure 1 Green arrows indicate stormwater monitoring stations (Muuli (1), Sõpruse (2), and Karulaugu (3)), white arrows indicate grab sampling locations, and the red arrow indicates the location of the weather station (WS).

The newly constructed e-monitoring system is comprised of water quality sensors, flow measurement device, and a weather station (Table 1).

Table 1 Key attributes of sensors (temperature sensor integrated into pH sensor).

Sensor	Working principle	Operating range	Precision
EC	Four electrode amperometry	0 – 200 mS/cm	**1%**
pH	Combined electrode	0 - 14	**0.1**
DO	Optical fluorescence	0 – 20 mg/L	**0.1**
Turb	Infrared Nephelometry	0 – 4000 NTU	**<5%**
Flow	Radar	0.15 m/s – 10 m/s	**5%**
Weather station	Precipitation measurements (rain gauge), temperature sensor, wind direction measurement, humidity sensor		

The first monitoring station (Muuli) was built at the stormwater outfall. Here parameters such as EC, pH, DO, turbidity, temperature, and flow are measured. Aqualabo (PONSEL) water quality sensors are used in all monitoring stations, and NivuFlow 550 and NivuMaster equipment are used to detect flow and water level, respectively.

The second monitoring station (Sõpruse) was installed before the inlet of a newly built oil/grit separator. The station measures DO, temperature, turbidity, and EC.

The third monitoring station (Karulaugu) was built in a residential area surrounded by private homes and shopping malls. A “smart” trash screen was installed in this location and water quality parameters such as temperature, EC, and turbidity are measured.

The collected data from all monitoring stations is sent to the e-monitoring system (VAAL) at 5-minute intervals (VAAL, 2023). A graphical user interface is available on the platform for viewing and interacting with data. The data can be viewed graphically or tabularly, and the timeframe or time step at which the data is viewed can be adjusted. Users can also configure alarm thresholds and view basic statistics.

Surrogate parameters had to be established in order to assess the data collected by the monitoring system. Thus, between June and September 2022, a sampling session was held during which 28 samples were collected. The grab samples were collected at four different locations (outfall, culvert, pond, and ditch) and analyzed in an accredited environmental laboratory within 24 hours of sampling (Figure 1). A linear regression model between turbidity and total suspended solids (TSS) was developed based on the results.

3. Results

The Viimsi stormwater system's outfall is governed by an environmental permit, which requires the municipality to keep the TSS below 25 mg/l. TSS is an important parameter to monitor because it has a high affinity for binding and/or transporting pollutants like phosphorus, heavy metals, organic pollutants, microplastics, and pathogens far away from their original sources (Copetti et al., 2019). Turbidity was chosen as a surrogate to track TSS in real-time, and a site-specific relationship ($y = 1.5566x + 7.4087$, $R^2 = 0.89$) was established (Figure 2).

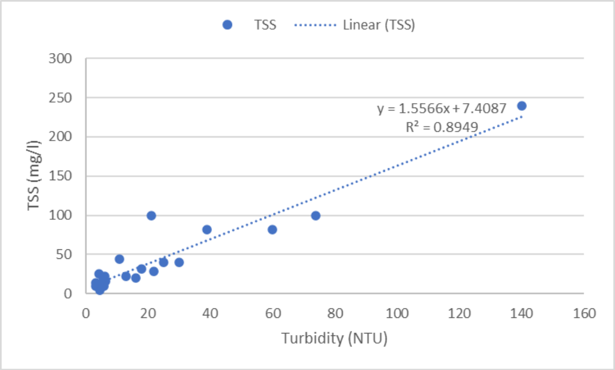

Figure 2 The relationship between TSS and turbidity in the Viimsi catchment (x-axis represents TSS (mg/l), y-axis turbidity (NTU)).

It was anticipated that by establishing such a relationship, TSS could be estimated in real time without the need for samples to be sent to a laboratory (Leigh et al., 2019). Assuming the surrogate relationship shown in Figure 2 held true, TSS exceeded threshold values 37% (9517/25920) of the time between December 2022 and March 2022 (Figure 3).

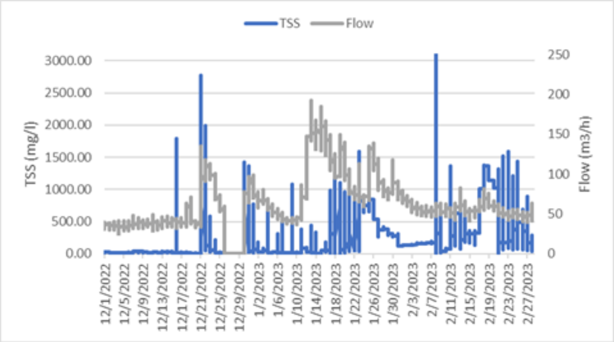

Figure 3 Total suspended solids in mg/l (left axis) and flow measurements in m^3/h (right axis) at 5-minute intervals from December 2022 to March 2023.

Continuous monitoring also aids in identifying the highest concentrations. TSS, as shown in Figure 3, can multiple times exceed the values expected by national authorities (25 mg/l). A single grab sample is unlikely to capture such conditions during a storm event, and even if it does, it cannot be determined whether or not it was the maximum value. This may result in an underestimation of pollutant loads and, as a result, a failure to implement appropriate environmental management strategies. The Minnesota Pollution Control Agency, for example, stated in their Stormwater Manual (Minnesota Stormwater Manual, 2023) that TSS values above 1000 mg/l are frequently observed at construction sites, and according to Figure 3, such conditions prevailed in Viimsi approximately 4.4% of the time, or for more than 4 days. As a result of these high TSS events, the risk of human-pathogen contact is high in catchments such as Viimsi, where the outfall is near a public beach.

There is value to be extracted from real-time monitoring data sets even if some data is missing or corrupted. Data loss can occur due to a variety of factors, including debris clogging, sensor drift, fouling, water level dropping below the minimum level, and so on. However, by identifying systematic problems, choosing appropriate trigger values, and making sure that e-monitoring system maintenance takes place even on weekends and holidays, the data loss can be minimized. A larger data set, even with some missing data, gives us the ability to more precisely estimate monthly and yearly TSS loads as it contains more extreme values. Another advantage of e-monitoring is that its high frequency allows us to identify areas where pollutant streams should not be present. For example, an investigation in the summer of 2022 uncovered an unanticipated source of pollution between the measurement stations Muuli and Karulaugu. Table 2 displays the changes in water quality that were noticed over the summer.

Table 2 Results from water quality grab sampling undertaken between June 2022 and September 2022. For sampling locations refer to Figure 1.

Parameter	Min.	Max.	Avg.
Site 1 (outfall)			
EC (µS/cm)	990	1400	1130
TSS (mg/l)	4	22	11.3
E. coli (Count/100ml)	400	2800	1600
Enterococci (Count/100ml)	4280	4800	4540
Site 2 (culvert)			
EC (µS/cm)	950	1917	2900
TSS (mg/l)	32	44	38.7
E. coli (Count/100ml)	1800	3700	2750
Enterococci (Count/100ml)	2260	10190	6225
Site 3 (ditch)			
EC (µS/cm)	740	770	757
TSS (mg/l)	20	240	120
E. coli (Count/100ml)	1400	1700	1550
Enterococci (Count/100ml)	308	866	587
Site 4 (pond)			
EC (µS/cm)	700	890	820
TSS (mg/l)	10	25	16
E. coli (Count/100ml)	40	70	54
Enterococci (Count/100ml)	9	69	140

The samples indicated that primary pollution between sites 3, 4, and 2, and that dilution occurred between sites 1 and 2 (Table 2). The sampling session resulted in the discovery of another catchment, but the sources of pollutants became clear only after the installation of the Sõpruse monitoring station. The EC of this station (Figure 4) is several orders of magnitude higher than that of the other monitoring stations. The maximum electrical conductivity measured at Sõpruse monitoring stations was 29312 µS/cm, while Muuli was 2405 µS/cm and Karulaugu was 3866 µS/cm. According to Göbel et al., the typical EC in the urban environment ranges from 500-2000 µS/cm. The observations collected over the three months confirmed this number, indicating that EC is below it 90% of the time (Figure 4).

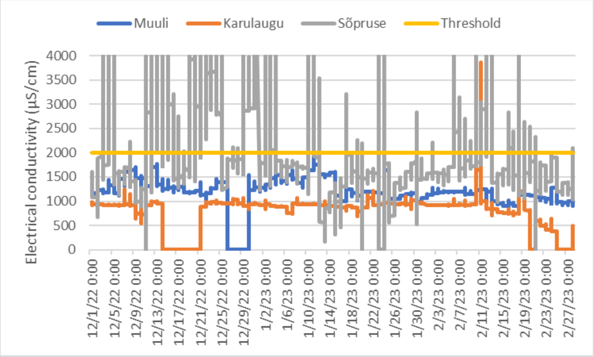

Figure 4 Electrical conductivity across monitoring stations. The maximum values for the x-axis have been removed to improve readability.

The developed system in Viimsi performed well in general, with data being provided approximately 85% of the time. Regular maintenance (6 times in 3 months) contributed to this relatively high availability, and providing such data using only grab sampling would be difficult and costly.

4. Discussion and conclusions

The primary goals of monitoring and managing nonpoint source pollution are to determine pollutant loads and fluxes. To be successful with this complex issue, it is necessary to monitor both pollutant concentration and flow in real time. The typical approach, grab sampling, represents the water quality at a single point in time (discrete), and it is critical to collect a sufficient number of samples at the appropriate time to properly characterize the loads. This, however, is costly and time-consuming.

Instead it is possible to leverage surrogate water quality parameters, modern sensors and information and communication technologies (ICT) to increase the sampling frequency. Continuous data collection provides a detailed profile of non-point source pollutant flow, which is necessary for taking appropriate action to reduce pollutant input into the Baltic Sea. However, increasing the frequency with which data is collected is only part of the solution. The more challenging task is ensuring that the data collected is meaningful (accurate and precise) and developing data analysis guidelines. This necessitates the creation of protocols for regular sensor calibration, maintenance, and data analysis.

The newly built continuous monitoring system was the first of its kind in the Baltic countries, and it meets its primary goal of providing data well (85% of the time). The collected data may be considered sufficiently reliable because a maintenance service, which included cleaning and calibrating the sensors, was acquired during the tendering process. Furthermore, the measurements were validated by laboratory-based measurements during startup, and the service provider performed maintenance six times during the data collection period.

The installed sensors vividly demonstrated that when water quality in a separate stormwater system (in our case, with an existing baseflow) is monitored over time, spikes that would otherwise go unnoticed by grab sampling are registered. These extreme conditions detected through monitoring are representative of real-world conditions, which can result in both acute and long-term negative environmental impacts. Despite previous years' grab samples demonstrating adherence to national environmental threshold values, the newly built system revealed that during the winter the TSS exceeded it 37% of the time. The relatively high TSS concentrations could be attributed to the catchment's relatively mild winter conditions, which included many freezing-thawing cycles, as well as construction activities. The measurements show that 75 mm of rain fell and that temperatures were above zero 45 percent of the time.

Furthermore, electrical conductivity measurements revealed abnormally high levels for an urban environment, with highest values occasionally resembling seawater at highest EC level reaching 29895 µS/cm at Sõpruse station, which was approximately 10 times higher than at the outfall or at the other station. Because this happened during the winter, it was most likely caused by municipal road salting. However, because summertime measurements revealed significant amounts of pathogens and hazardous substances from around the same catchment, there might be a significant pollutant source nearby. However, the higher pollutant concentration could also be attributed to the monitoring station lacking baseflow, resulting in little to no dilution in comparison to the other monitoring points.

Overall, the developed system provides new opportunities for studying stormwater in the catchment and detecting upstream pollution sources, but various hypotheses can only be tested and validated through laboratory-based measurements. Furthermore, if the ultimate goal is to integrate the system's measurements into a smart stormwater management system, where control devices are regulated in real time or near real time based on water quality criteria, the collected data quality should be improved, as should procedures for data quality control and maintenance.

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