Co-UDlabs

Report

Acoustic monitoring of suspended solids in natural and engineered systems

Co-UDlabs IWA/IAHR Webinar. 16/05/2023

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EDITION

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CAN ACOUSTIC TURBIDITY SENSORS OVERCOME THE SHORTCOMINGS OF TRADITIONAL OPTICAL TURBIDITY PROBES?

Although total suspended solids are relevant, there is a knowledge gap on the dynamics of processes, which is to some degree based on challenges associated with traditional optical sensors. Acoustic turbidity sensors are not impacted by biofouling or particle class changes, but face different challenges. Also, practical experience is lacking. In this Co-UDlabs training event, we discussed recent advances in particle-tracking sensors, inversion techniques and the relevance of particles and potential solutions.

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1. Introduction

Water quality is becoming increasingly important in natural and sewer environments due to sediment-related issues like erosion, transport, and deposition. These problems affect agriculture, engineering, and the environment by causing mechanical obstacles and pollutants to attach to sediments. Total suspended solids (TSS) is a crucial parameter to monitor pollutant levels, but few techniques offer real-time data. Traditional methods involve lab measurements or optical backscatter sensors that require significant calibration and maintenance. However, acoustic turbidity monitoring, based on acoustic backscattering, offers a modern approach to TSS monitoring that can be done using Acoustic Doppler Current Profilers, Acoustic Doppler Velocity Profilers, and Acoustic Doppler Velocimeters. This webinar will discuss the latest developments in TSS monitoring using acoustic backscattering methods, including fundamental principles, particle characteristics, instrument calibration, signal analysis, and inversion methods. Practical experiences from monitoring rivers and wastewater systems will also be shared.

On 16.05.2023, the Co-UDlabs project organized a training event on the acoustic monitoring of suspended solids in natural and engineered systems as a webinar. The Co-UDlabs is an EU project, INFRAIA H2020 program, aimed at building urban drainage laboratory communities through transnational access, networking and joint research activities. As acoustic monitoring in water systems is a very contemporary topic, the event was endorsed by the International Water Association (IWA) and the International Association of Hydro-Environment Engineering and Research (IAHR). The event brought together particle experts, sensor manufacturers, and individuals with practical experience in monitoring campaigns and projects. More than 100 participants registered for the event. Around 50 attendants were connected permanently. The webinar was divided into two main blocks of presentations, followed by group discussions. The initial presentations covered various aspects, including particle characterization, problem setting, theory, scattering, and scientific instruments. The second session focused on applications in urban and wastewater systems.

2. Particles: the overlooked pollutants

Prof. Peter Vanrolleghem from the University of Laval in Canada presented his research on the overlooked role of particles in pollution assessment. He emphasized the importance of continuously monitoring particles in urban drainage systems. Prof. Vanrolleghem discussed his early work on total suspended solids (TSS) in urban Danish systems, highlighting the variability of TSS levels during rain events and its impact on water quality. He explained that particles act as carriers for various pollutants, including organic matter, nitrogen, phosphorus, pathogens, heavy metals, and hydrophobic micropollutants. Furthermore, the presence of sand in the system can cause damage to pumps and equipment. Prof. Vanrolleghem stressed that monitoring particles is crucial for accurately assessing pollution, as particles behave differently from dissolved substances in sewer systems.

He discussed the measurement of TSS and its correlation with turbidity, which provides a visual indicator of particle concentration. He presented different principles of TSS measurement, including transmission shift, backscattering, forward scattering, and nephelometry. He mentioned the challenges of keeping sensors clean in wastewater systems due to pollution but highlighted the effectiveness of turbidity sensors when properly installed and maintained. Prof. Vanrolleghem shared long-term data collected in Denmark and Bordeaux, demonstrating the importance of high-frequency TSS monitoring. He discussed the benefits of such monitoring, including capturing dynamic behavior, understanding pollutant dilution during rain events, and optimizing facilities dealing with suspended solids. He also mentioned the use of models calibrated with turbidity measurements to describe TSS behavior.

In conclusion, Prof. Vanrolleghem emphasized that TSS carries over 50% of important pollutants in urban wastewater systems. He highlighted the need for high-frequency monitoring and modeling to effectively manage urban pollution. Therefore, the ideal TSS sensor should be easy to install, require minimal maintenance, provide fast and frequent measurements, have spatial resolution, remote operation, low power consumption, and be capable of measuring various particle sizes and types.

3. The fundamentals of acoustic turbidity are complex, therefore precise scientific instruments do not come with an inversion method

This presentation showed the application of acoustic scattering for particle analysis, focusing on the advances in environmental monitoring and research. The speaker, Dr. Stéphane Fischer, introduced Ubertone Company, a team of doctors and engineers based in Strasbourg (France), specializing in the development and manufacturing of acoustic profilers and sensors for scientific research and environmental monitoring. The presentation shows the promising advantages of acoustic turbidity in measuring suspended sediment concentration (SSC), highlighting its ability to work with wavelengths over 50 microns. In contrast, optical turbidity is sensitive to particle size.

He explained the basics of acoustic waves, including the emission and reception of signals using transducers. The emitted acoustic waves form an acoustic beam that propagates through the medium, interacting with suspended particles. As particles scatter energy in various directions, a portion of the energy is reflected back to the transducer. By analyzing the time delay and intensity of the returning waves, valuable information about the particle concentration and size distribution can be obtained. The speaker emphasized the importance of form functions, which determine the sensitivity of the measurement to different particle sizes and wavelengths. He also discusses the concept of acoustic turbidity as a representative measure of particle scattering in the medium. Stéphane Fischer further discussed the theoretical basis of acoustic scattering, including equations for backscattered intensity and attenuation. He explained the need for wideband transducers and accurate amplification to capture the wide variation in echo intensity over different distances. Inversion methods are mentioned as a means to derive particle concentration and size from the acquired data, with reference to the dual frequency method.

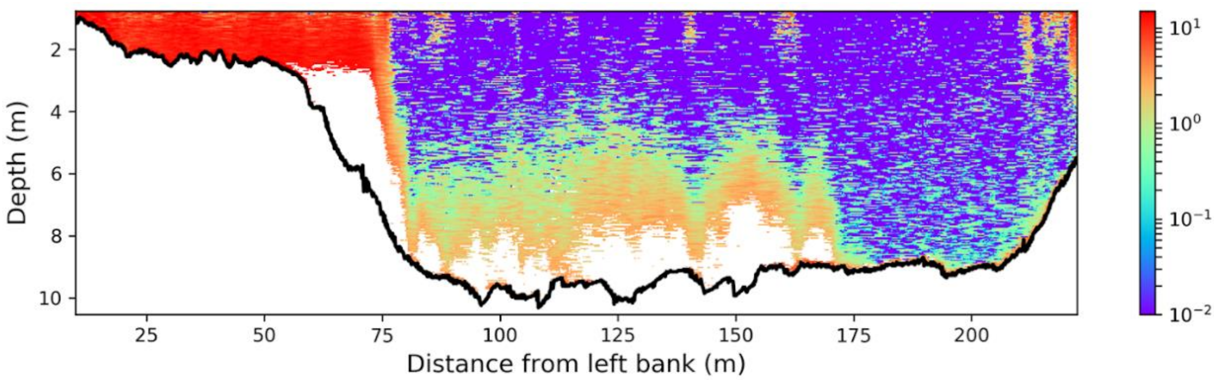
He also presented several practical applications from wastewater treatment plants, rivers, sewers, and beaches. These highlighted the ability to measure concentrations, detect sludge levels, monitor concentration changes during events, and even obtain velocity profiles. These examples showcase the versatility and potential of acoustic scattering for a wide range of applications. Inversion is currently the domain of specialized research groups.

4. Recent progress on inversion methods looks very promising by taking into account different fractions of suspended solids and their acoustic scattering characteristics

Dr. Celine Bernie is a research specialist in sediment transport at a public Research Institute in France, focused on the coherent and sustainable development of agriculture and the environment. Her work primarily involves laboratory experiments and acoustic techniques to study sediment transport and hydraulics. In her presentation, Celine discussed the experimental evaluation of hydroacoustic models and inversion methods for rivers. Rivers contain sediments that can be categorized into coarse particles near the bed and finer particles spread throughout the water column. Quantifying the suspended sediment fluxes, including both fine and coarse sediments, is crucial for understanding environmental impacts such as sedimentation, flooding, and pollutant transport. Previous studies have successfully applied acoustic inversion methods to determine sediment concentration for coarse sand particles. However, it remains unclear if these models can be applied to fine sediments found in rivers.

Celine Berni reported laboratory experiments using fine sediments from a river to investigate their acoustic behavior. By measuring sediment attenuation and backscatter, she compared the observed data with existing acoustic models developed for sand particles. The results showed significant discrepancies, suggesting that the previous models are not applicable to fine sediments. However, by adjusting the particle size distribution, a good agreement between measurements and modeling was achieved, indicating the potential for applying previous models to fine sediments. To validate these findings, field measurements were conducted in the Rhone River in France. The backscatter data collected from various frequencies were compared with the modeled backscatter using the previously calibrated models. The results indicated that while there was a good agreement for high frequencies, there were substantial differences for low frequencies, suggesting the presence of additional scatterers in the river. Possible explanations for the discrepancies between measurements and models include aggregates, turbulence, microbubbles, or microorganisms. Analyzing the slope of backscatter versus frequency, it was observed that sediments exhibited a frequency-dependent behavior, whereas bubbles showed a flat response. This suggests that microbubbles could be contributing to the backscatter signal near the surface of the river.

Despite the challenges in accurately modeling sediment response and the presence of other scatterers, Celine Berni highlighted that acoustic devices can still be used for sediment concentration measurements under certain conditions. These conditions include a sufficient proportion of sand or fines dominating the attenuation, homogeneity of grain size distribution, and variability of both sand and fines within the river section. To estimate sediment concentration and attenuation, Celine proposed a methodology involving acoustic backscatter measurements, near-bed samples with high sand concentration, backscatter modeling for sand-dominated regions, and applying frequency inversion methods. This methodology was validated through a case study of the Rhone River, where good agreement between acoustic and sample measurements was observed, providing a comprehensive overview of sediment distribution within the river cross-section. Ongoing developments, such as the software being developed to assist with inversion, aim to further improve the applicability and usability of these methods.



Inverse fine SSC outputs [g/L] from acoustic backscatter profiles in the confluence of Rhône and Isère rivers. Source: Vergne et al. (2020).

5. Commercial sensors for practical applications favor a practical approach to the inversion and have already been applied in various applications

Dr. Asmorom Kibrom presented the research and development work conducted at NIVUS, a market-leading flow metering company in Germany. The focus of the study is on the development and evaluation of a new sensor called PKM (Particle Concentration Measurement), designed to measure particle concentration and mass flow in sewer networks. The motivation behind this research was to overcome the limitations of existing optical spectrometer probes, which require high maintenance and are susceptible to drifting caused by optical path blockage.

The PKM sensor offers practical advantages in terms of ease of mounting, operation, and maintenance, along with the ability to scale up for industrial applications. NIVUS leverages its expertise in designing and fabricating related sensors, particularly in the field of flow measurement, to ensure accuracy and reliability. The sensor is capable of combining measurements of flow and Total Suspended Solids (TSS) to accurately determine mass flux in channels. The study involves testing the sensor's performance in different applications, including sewer networks and rainwater systems. Initial results from the research indicate the sensor's effectiveness in capturing concentration variations over time. Challenges observed in the study include sensor mounting, installation, and calibration. NIVUS addressed these challenges through their extensive experience in sensor design and mounting techniques.

The PKM sensor comprises various laboratory calibrations. NIVUS offers two sensor versions based on the required minimum water level (shallow: 7 cm, deep: 20cm). The study involves laboratory calibration for material parameter estimation and end-of-line calibration using a simple suspension setup. The data collected from the sensor shows promising results in capturing the dynamics of particle concentration and flow in sewer networks. Further research focuses on comparing the sensor data with traditional sampling methods, addressing the dependency of particle fractions on boundary conditions, and resolving particle size distributions across all fractions. NIVUS aims to continuously improve the measurement method, and calibration conditions for specific applications. Ongoing R&D projects in sewer networks provide opportunities for further development and refinement of the sensor technology.

6. In practical comparative studies, acoustic sensors face serious challenges not only different particles, but also bubbles and other effects

Dr. Manuel Regueiro-Picallo discussed the possibility of using acoustic sensors to monitor suspended particle concentrations and particle sizes in water systems. He highlighted the importance of particulate matter and suspended sediment concentration as indicators of water pollution. The presentation focused on two experimental campaigns conducted in collaboration with Eawag during his PhD studies. In the first campaign, he used a small channel with a closed loop and introduced plastic particles and sand of various concentrations and sizes. They placed sensors and transducers inside the tank and measured the turbidity ratio profile using acoustic measurements. By analyzing the profile, they extracted two features: the slope and intercept of the linear relationship in the logarithmic domain. He observed that as the concentration and particle size increased, the response of the sensor became steeper and higher. However, he noticed differences in the results when comparing the mixing tank tests with the closed loop setup, which could be attributed to the presence of air bubbles in the closed loop configuration.

The second campaign took place in a flume test facility at a wastewater treatment plant. He measured the characteristics of particles in the wastewater inlet using acoustic profilers, optical turbidity meters, and autosamplers. He found good correlation between the acoustic results and samples in one case, while the optical turbidity results differed slightly. In the other case, the correlation was good with optical turbidity but poor with acoustic turbidity. Nevertheless, he calculated the same features from the acoustic turbidity profiles and found a strong correlation with mean grain sizes.

The overall results demonstrated the potential application of acoustic sensors for monitoring suspended particle concentrations and particle sizes in wastewater. He concluded with the need for local calibrations due to differences in test configurations and the presence of air bubbles.

7. In practical applications of pollution control acoustic sensors with virtually maintenance-free deployment could be a game changer for smart stormwater control solutions– despite biased measurements

Daniela Böckman from the consultant engineers Dr. Pecher AG, Germany, reported a pilot project in Emsdetten (Germany), where they acquired first experiences with the PKM sensor to survey stormwater sewers. The project, known as EM1, aimed to plan a stormwater treatment concept for a large catchment, based on pollution measurements to divert the most polluted flow to advanced treatment. The catchment included residential and industrial areas, as well as a main road, resulting in a mixture of runoff with varying pollution levels in the sewer system. The measurement site was located near the discharge point into the river. EM1 involved a measurement campaign with multiple sensors over several months. The collected data was analyzed and used for simulations of a treatment concept tailored to the pollution characteristics of the catchment. For monitoring total suspended solids (TSS), both an optical sensor and the acoustic PKM sensor were utilized simultaneously, allowing for a comparison of their performance.

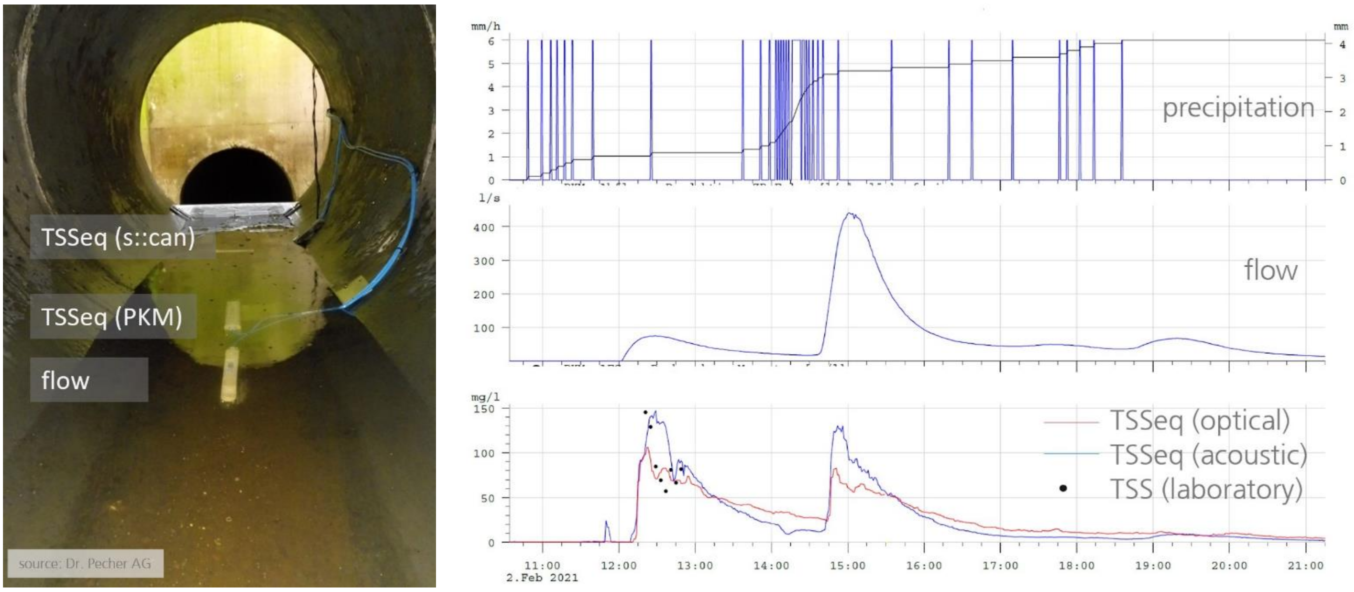
The measurement setup consisted of creating a minimum water level of 0.2 meters to ensure adequate sensor operation. The optical sensor was positioned first, followed by a section for sampling and then the acoustic sensor with a flow meter installed behind it. Regular maintenance visits occurred every two weeks, primarily focusing on cleaning the optical probe to prevent blockages, while the acoustic sensor required less frequent maintenance. Data was collected over a six-month period, including information on precipitation from rain gauges, water levels, flow rates, and hydrographs of TSS concentrations measured by both the optical and acoustic sensors. The laboratory analysis results for TSS concentrations were represented by black and gray dots on the graphs.

Analyzing individual events revealed a consistent pattern where TSS concentrations rapidly increased with rising flow and then gradually decreased. Both the optical and acoustic sensors captured this characteristic, although there were differences in absolute concentrations. The acoustic sensor also provided the capability to examine particle size, as demonstrated by the TSS63 hydrograph. Significant variations were observed, with the laboratory TSS63 concentrations falling within the concentration range of the entire TSS measurements but higher than the TSS fraction captured by the acoustic sensor.

In another event, while the rapid increase and slow decrease in concentration were similar, the concentrations were relatively low and slightly underestimated compared to the laboratory analysis. The optical measurement was closer to the laboratory analysis in this instance. Differences between the sensors and laboratory analysis were also observed in additional events. One event involved composite sampling, resulting in a medium concentration over a half-hour period. The TSS63 fraction from the acoustic measurement was closer to the laboratory analysis than the total TSS concentration.

Overall, the optical measurements tended to align more closely with the laboratory analysis than the acoustic measurements, but the reasons for this discrepancy were unclear. The positioning of the measurement areas and sampling point may have influenced the results. The acoustic sensor demonstrated less disturbance and required less maintenance, although a minimum water level of 0.2 meters was necessary.

The data collected during the pilot project was used to fulfill its mission of planning a stormwater treatment concept. A model of the catchment was constructed using software called SWMM. The model was calibrated using the precipitation data and the flow and pollution data from the measurement campaign. Simulations were conducted to evaluate the treatment concept, with high-polluted flow separated for treatment and low-polluted flow discharged directly. The simulations indicated that a threshold of 45 mg/L for TSS concentration was suitable for flow separation. Over several years of simulation, it was found that treating only 14% of the flow with high efficiency achieved the required overall efficiency for the discharge, demonstrating the ecological and economic advantages of adapting stormwater treatment plans to site-specific conditions.



Measurement campaign in a storm sewer (left) and data from rain intensities, flow rates and TSS concentrations comparing acoustic, optical and laboratory measurements (right). Source: Daniela Böckmann (Dr. Pecher AG).

8. Optical methods to the rescue – advanced optical monitoring with time of flight resolutions

Dr. Anne Pallrès, a researcher from Strasbourg University, and her team have been working on Acoustic solid measurements in Wastewater for approximately 20 years. They compared these measurements to Optical data used in wastewater treatment and observed significant differences. To understand these differences, they developed a new technique called Time Resolved Optical Turbidity (TROT). TROT is a promising real-time technique that is still under development, with two working prototypes.

The development of TROT became possible due to the progress in affordable electronics, which enabled the use of medical technology in the field. The concept of TROT involves an optical probe consisting of four fiber optics, which are connected to homemade ultra-fast electronics. The goal is to obtain real-time turbidity and velocity measurements. In TROT, short light pulses (100 picoseconds) are emitted from one fiber, and the information is captured by the other fiber, depending on the movement of light between them. By analyzing the arrival times of the photons, a Time Point Spread Function (TPSF) is created, which is a histogram representing the number of photons as a function of their arrival time. This technique utilizes time-correlated single-photon counting. TROT provides additional information beyond optical turbidity, such as an exponential tail of the spectrum and the mean time of flight of photons. The combination of these measurements offers more insights than traditional optical turbidity alone. The experiments conducted with TROT on water suspensions of various concentrations and particle sizes demonstrated its capabilities.

Comparisons were made with optical turbidity and acoustic backscattering, using different types of particles such as kaolin, wet stock, and chiselgur. Kaolin and chiselgur are hard mineral particles that reflect acoustics well, while wet stock represents soft particles with different acoustic behavior. Optical turbidity showed a linear relationship with particle concentration until a plateau was reached at higher concentrations, leading to a dysfunction of the turbidity meter. Acoustic backscattering exhibited linear behavior for larger particles but had unstable measurements due to the proximity to the signal-to-noise level.

TROT measurements of normalized photon counts demonstrated similar behavior for kaolin and wet stock particles. However, by considering additional information such as the mean time of flight, it was possible to distinguish between different concentration levels. TROT also showed promise in being insensitive to biofouling, a common issue with optical devices in wastewater. Preliminary results indicated that TROT could accurately determine concentration levels even in the presence of biofouling.

9. The future – combining optical and acoustic methods, open datasets and flexible software to develop custom inversion methods for specific applications

The following are the take-home messages that the speakers highlighted in this webinar:

- Acoustic turbidity monitoring presents important advantages over traditional optical turbidity methods for measuring suspended sediment concentration. In practical application, it is less affected by biofouling. The effectiveness of acoustic scattering has been demonstrated in various applications, such as rivers, beaches, hydropower facilities, as well as wastewater treatment plants and sewers. The various scientific sensors, which are commercially available, do not come with built-in inversion methods to compute levels of solid concentrations or turbidity. In contrast, the newly available heavy-duty industrial sensors require (strong) assumptions on the scattering properties of the solids, which can differ from the conditions in the field.
- Continuous TSS monitoring, enabled by high-frequency monitoring and modeling, not only acknowledges the important role of particles in pollution assessment, but also opens opportunities for effective solutions. In practical applications, for example, real-time control to improve the effectiveness for stormwater pollution, the virtually maintenance-free operation of acoustic sensors can outweigh the lack in precise measurements.
- Optical turbidity sensors are effective for monitoring small particles and perform poorly at high concentrations, while acoustic turbidity sensors are more sensitive for large particles and perform poorly at low concentrations. Therefore, the complementary nature of optical and acoustic techniques was highlighted, with many participants advocating for their integration to advance suspended solids monitoring. This integration, as showcased with the work on Time Resolved Optical Turbidity (TROT), can provide real-time turbidity data, differentiate particle concentrations, and offer potential resistance to

biofouling in wastewater monitoring. Also, gathering and re-analyzing available datasets with novel inversion methods seems very promising.

Building Collaborative Urban Drainage research lab communities: https://co-udlabs.eu/

The Co-UDlabs project aims to establish a community in urban drainage by providing research infrastructure and networking opportunities. This webinar is part of a series of training events organized under this project. Additionally, the project provides free-of-charge access to 17 facilities of relevant scientific and technical excellence. The access to the facilities is open to the international community through Transnational Access (TA) projects. A workshop on the TA call will be held at the NOVATECH conference to facilitate idea sharing and utilization of the facilities.
