Capteurs propres, données fiables : développement et tests sur le terrain d'un nettoyage mécanique abordable de capteurs optiques en rivière

Clean sensors, happy data: Field test of low-tech wiper designs for optical sensors and river applications

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RÉSUMÉ

Le *biofouling* affecte considérablement la précision et la fonctionnalité à long terme des capteurs optiques de plus en plus utilisés pour surveiller la qualité de l'eau et des environnements aquatiques naturels. Cette étude examine les effets du *biofouling* sur la précision et l'exactitude des mesures de six capteurs de turbidité à faible coût sur une période de 11 semaines. Les données des capteurs ont été suivies deux fois par semaine à l'aide des solutions fait avec bentonite, de 0 et 1000 NTU). Le développement du *biofouling* a été quantifié par l'analyse d'images et un système d'évaluation visuelle qualitative. Les résultats montrent que le *biofouling* réduit progressivement la précision des mesures des capteurs, avec des effets significatifs après une exposition prolongée. Pour répondre à ce défi, un essuie-glace mécanique adaptable et open-source a été développé et testé, offrant une solution pratique pour limiter ce *biofouling*. Conçu pour être polyvalent, cet essuie-glace peut également être appliqué à d'autres types de capteurs optiques, élargissant ainsi son utilité au-delà de la mesure de turbidité. Ces résultats soulignent la viabilité des capteurs à faible coût pour une utilisation à court terme et mettent en évidence l'importance de stratégies d'atténuation intégrées pour les déploiements prolongés sur le terrain. Cette recherche offre des perspectives précieuses pour améliorer les performances des capteurs dans les applications de surveillance de l'eau et des milieux aquatiques.

ABSTRACT

Biofouling significantly impacts the accuracy and long-term functionality of optical sensors used to monitor natural water bodies. This study investigates the effects of biofouling on the measurement accuracy and precision in six low-cost turbidity sensors over the period of 11 weeks. The sensor output was monitored biweekly using fixed turbidity bentonite solutions (0 and 1000 NTU), while biofouling development was quantified through image analysis and data trends. Results show that biofouling progressively reduces sensor accuracy, with significant effects after prolonged exposure. To address this, an adaptable, open-source and affordable mechanical wiper was developed and tested, offering a practical solution to mitigate biofouling. The wiper's design is versatile and can be applied to other optical sensors, expanding its utility beyond turbidity monitoring. These findings emphasize the viability of low-cost sensors for short-term use and highlight the importance of integrated mitigation strategies for extended deployments. This research provides valuable insights into enhancing sensor performance in natural water monitoring applications.

MOTS CLÉS

Encrassement biologique ; nettoyage mécanique ; turbidité ; bas-cout ; science ouverte ;

biofouling; mechanical wiper; turbidity; open source; low-cost.

1 BACKGROUND

The growth of biofouling organisms in water bodies depends on environmental factors such as temperature, nutrient levels, and light availability (Gameiro et al., 2011). Warm, nutrient-rich water under high light exposure accelerates biofilm formation, fostering algae and diatom proliferation. Conversely, cooler or nutrient-poor conditions slow biofilm growth (Di Pippo et al., 2018). Even minimal biofilm presence can cause significant measurement errors in clear water by affecting light transmission and sensor accuracy (Austin et al., 2017). Strategies to mitigate biofouling include mechanical solutions (e.g., wipers, scrapers, pressure jets) and chemical methods such as biocides and non-stick coatings, applicable across various types of sensors.

Many existing antifouling solutions, both chemical and mechanical, are proprietary and tailored to specific commercial sensors, making them unsuitable for low-cost and open-source applications. There is a growing need for modular, replicable antifouling technologies that enable users to adapt and improve designs. Low-tech, open-source instruments have the potential to democratize water quality assessment, making it accessible to both scientists and community organizations. A low-cost, open-source approach is critical for expanding accessibility to environmental measurements like turbidity, improving spatial and temporal data resolution while reducing costs and fieldwork demands (Gillett & Marchiori, 2019; Downing, 2006; Langhorst et al., 2023). However, low-cost turbidity probes face similar biofouling challenges as commercial sensors. This paper presents the development and testing of an adaptable, low-tech mechanical antifouling solution for a low-cost turbidimeter based on light attenuation principles. Its performance was compared to a chemical solution (copper) and a system without antifouling measures, aiming to improve understanding and prevention of biofouling impacts on sensor reliability.

2 METHODS

To test two antifouling methods and a control, six shells were mounted on a stainless-steel base: two with chemical protection, two with mechanical protection, and two controls. The setup excluded electronics to enable full submersion and biofilm formation, with a single turbidimeter used biweekly for consistent measurements. Waterproof neoprene sealed the inside of the shells, secured by a steel bar with bolts. For measurements, the bar and neoprene were removed and later reattached, minimizing out-of-water time to 1 hour per cycle (or up to 2 hours during maintenance). Copper sensors were wrapped in copper tape around the plastic cap, avoiding contact with metal components. The entire setup was placed in a pond in the Burnley gardens in Melbourne (Australia) during a 11 week period in the spring and summer time.

The low-cost SEN0189 (DF Robot, 2007) sensor was used to measures turbidity using the light attenuation principle with a wavelength of 940nm. Originally enclosed in a 3D-printed case and a Polypropylene (PP) shell, the case was removed to use a single probe across all tested shells, ensuring consistent comparisons. For each measurement, the sensor was inserted into each shell, with the closed side submerged in one of two bentonite solutions, for two-minutes. This process was repeated for all six shells twice every week, allowing time for the biofilm to develop. To track turbidity changes during the test, only two standard solutions (0 and 1000 NTU) were used, this way we aimed to isolate biofouling effects from natural turbidity fluctuations.

2.1 Mechanical wiping system

The mechanical system operates based on Pascal's Principle, using a 150N actuator to transmit pressure through a water-filled PVC tube connected to two syringes: one attached to the actuator and the other, in the end of the tube, to a nylon brush. The brush, positioned at the sensor shell gap, activates hourly for a 10-second cleaning cycle.

The electronics, including the actuator, PCB, battery, and solar panel, are housed in a protected, dry enclosure (that remains outside the stream) to ensure reliability and prevent water damage. Only durable components like PP, PVC, and stainless steel are submerged, avoiding the need for water shielding.

The system is energy-efficient and powered by a solar-recharged 4000 mAh battery, allowing the small solar panel to maintain battery levels above 80% throughout the experiment, ensuring continuous operation with minimal energy demands.

3 RESULTS

The performance differences among the three shell types are supported by quantitative trends. Sensors 1 and 2, with mechanical protection, exhibited slower slope values, indicating minimal decay and greater longevity. For instance, Sensor 1 at 1000 NTU maintained stable readings with a high p-value of 0.889, confirming the effectiveness of mechanical mitigation. In this context, a high p-value indicates that the sensor's readings over time show no statistically significant trend of decline, suggesting stability and resilience to biofouling. This, coupled with visual inspections, validated the quality of these solutions. Sensors without protection or cleaning showed very strong biofouling and served as a reference. This observation was further confirmed through visual analysis with microscopes, where biofouling was highly evident and clearly visible to the naked eye.

In comparison, the chemically protected shells, such as Sensor 5, showed moderate performance with slower slopes but slightly more variability. Meanwhile, control sensors 3 and 4 displayed significant downward trends, with low p-values at 0 NTU (e.g., $p = 0.000359$ for Sensor 3), reflecting a steady decline in accuracy due to biofouling accumulation.

Overall, all sensors displayed a gradual decline in performance over time, particularly the controls, reflecting an initial clean phase followed by degradation due to biofilm buildup.

4 OUTLOOK

While wipers are not a new concept for mitigating biofouling and maintaining sensor accuracy (e.g., Strom et al., 1994), designing an adaptable, affordable, open-source wiper system for attenuation turbidity sensors posed unique challenges. These sensors have intricate geometries that require cleaning systems capable of maintaining functionality without obstructing light paths or causing misalignments. Our mechanical brush design addresses these issues with a simple, robust solution that avoids in-water electronics, making it more reliable and easier to implement.

The key innovation of this system lies in its adaptability to various optical sensor types, recognizing that each sensor has specific requirements. The wiper axis can be modified to accommodate different diameters, angles, materials, and cleaning objectives, ensuring flexibility across diverse applications. This modularity simplifies integration and enhances the potential for broader adoption.

To support open science and collaborative improvement, the design documents for both the wiper system and the low-cost turbidimeter are freely available on our page (https://github.com/mariagisi/Turbidity_01) on GitHub. This approach aims to make biofouling mitigation more accessible and adaptable, fostering innovations in water quality monitoring across a range of low-cost sensor technologies.

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