Evaluation of low-cost sensors for real-time water quality monitoring

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***Abstract*—Low-cost sensors have the potential to significantly reduce costs compared to reference devices. The problem, however, is that measurements from low-cost sensors can be unreliable when it comes to certifying water quality. This work investigates the possibility of using low-cost sensors to monitor water quality parameters and automate the monitoring process through the concept of the Internet of Things (IoT). The evaluation of the sensors was performed both in a controlled environment with standard solutions and in a real environment. The results show that the sensors provide readings that are close to reference values when tested in a controlled environment, but some challenges remain when tested in the real world.**

***Index Terms*—environmental monitoring, water quality, low-cost sensors, Internet of Things**

I. INTRODUCTION

Control and monitoring of the water quality parameters during the collection, treatment, and distribution processes is an essential task. The main parameters affecting water characteristics are dissolved oxygen, thermotolerant coliforms, the potential of hydrogen (pH), biological oxygen demand, temperature, total nitrogen, total phosphorus, turbidity, and total residue [1].

Information and communication technology has the potential to make water resource management more agile, modern, and efficient. The use of smart devices equipped with special sensors that can collect data and transmit them in real-time to the Internet is a solution with great potential to solve the problems of monitoring water quality, following the concept of the Internet of Things (IoT) [2].

The currently practiced method to measure water quality requires reference sensors in addition to the cost of logistics and trained personnel. A multiparameter reference sensor, e.g., Hanna HI9829, can cost around US$5,000 [3]. There are also sensors for measuring water quality on the market costing between US$4.00 and US$234.00, i.e., much less than professional or reference devices. But the reliability of low-cost sensors used in water quality measurement is unknown. It is also uncertain whether the characteristics of these sensors allow commercial and industrial use.

Several works have developed water quality monitoring solutions in the context of IoT for environmental monitoring [4]–[7]. These works are dedicated to the development of low-cost sensors [5], [7] or platforms equipped with low-cost sensors that can transmit measurements in real-time to the Internet [4], [6]. To our knowledge, the literature does not address whether low-cost sensors have sufficient accuracy and robustness to be used for water quality monitoring.

This work aims to present an evaluation of the performance of low-cost water quality sensors to build a water quality environmental monitoring network. The data obtained was provided in real-time over the Internet through a long-range, low-power network using LoRaWAN technology [8]. The water quality parameters, monitored by low-cost sensors, were turbidity, temperature, dissolved oxygen, and the potential of hydrogen. The sensors were evaluated in two scenarios: (a) in a controlled environment using standard solutions, and (b) in a real environment (an urban lake), comparing the sensors' measurements with those from a professional probe and water chemical analyses performed in a specialized laboratory.

The remainder of this paper is organized as follows. The methodology is presented in section II. In section III, the obtained results are presented and analyzed. Finally, in section IV the conclusion and future work are presented.

II. METHODOLOGY

The parameters selected for measurement are temperature, dissolved oxygen, pH, and turbidity, which are part of the Brazilian National Program for Water Quality Assessment (PNQA). They were chosen because there are low-cost sensors that are easy to find on the market and are also relevant water quality parameters. Table I shows the low-cost sensors evaluated in this work. The evaluation of the sensors can be divided into four parts. The first part is the calibration of the sensors. The second part is the evaluation of the low-cost sensors with standard solutions of known concentration. The third part is the comparison of the low-cost sensors with the reference instrument Hanna HI98194. These first three phases are performed in the laboratory. In the last phase, the sensors are evaluated in the field, under real environmental conditions, and their measurements are compared with water samples analyzed in a laboratory certified for water quality analysis.

TABLE I: Low-cost sensors evaluated

Sensor	Parameter	Price US$
DS18B20	Temperature Sensor	4.00
SEN0189	Water Turbidity sensor	9.90
ENV-50-DO	Dissolved Oxygen sensor	234.99
SEN0237	Dissolved Oxygen sensor	169.00
SEN0161-V2	Analog pH	39.50

A. *Sensor's calibration*

The pH, turbidity, and oxygen sensors have been calibrated based on the programming libraries and documentation provided in the individual sensor manufacturer's datasheets. The temperature sensor does not need to be calibrated.

The manufacturer DFRobot of the turbidity sensor SEN0189 provides the sensor's response curve relating the output voltage (V) value to the turbidity value in NTU according to Equation 1, where the value of x represents voltage and y represents turbidity [9]. However, the response curve was not correct when tested with different turbidity samples. As a solution, we used the Equation 2 developed by Hakimi and Jamil [10], which showed a linear response of the sensor with a measurement range between 0 to 1800 NTU, where y represents the voltage value of the sensor output and x represents the turbidity value in NTU.

$$y = -1120.4x^2 + 5742.3x - 4352.9 \tag{1}$$

$$y = -0.0012x + 4.0769 \tag{2}$$

The maximum output voltage occurs when the turbidity value is 0 NTU and must be determined. The sensor used in this work presented an output of 4.804 V when not immersed in the water or when immersed in clean water (turbidity near zero). Therefore, the Equation 2 was corrected to the Equation (3).

$$y = -0.0012x + 4.804 \tag{3}$$

The relationship between the total amount of dissolved solids and turbidity is given by the Equation 4 [10], where *tb* is the turbidity value in NTU and *ts* is the total dissolved solids in mg/l.

$$tb = 1.873 + 0.518 \cdot ts \tag{4}$$

The SEN0161-V2 sensor requires two calibration points to obtain a linear response curve that calculates pH as a function of sensor output voltage. The two calibration points are the sensor output voltage for standard solutions pH 4 and 7. According to [11], the output voltages of pH 7 and pH 4 must be multiplied by 1000. Then the slope of the line is determined using the Equation 5, where *inc* is the slope of the line, *ts_ph7* and *ts_ph4* are the output voltage for pH 7 and pH 4, respectively. Then the intersection point *int* with the y-axis is determined by Equation 6.

$$inc = \frac{7.0 - 4.0}{\frac{ts\_ph7 - 1500}{3} - \frac{ts\_ph4 - 1500}{3}} \tag{5}$$

$$int = 7.0 - inc \cdot \frac{ts\_ph7 - 1500}{3} \tag{6}$$

The *inc* and *int* calculated before and the output voltage *ts* are used in Equation 7 to obtain the pH value.

$$ph = inc \cdot \frac{ts - 1500}{3} + int \tag{7}$$

In the calibration phase, the sensor output for the standard solutions pH 4 and pH 7 was 2 V and 1.49 V, respectively. Using the obtained values, Equation 8 represents the calibrated equation of our sensor.

$$ph = -0.0182 \cdot \frac{ts - 1500}{3} + 6.94 \tag{8}$$

The Atlas ENV-50-DO sensor provides an output voltage proportional to the amount of dissolved oxygen. When no dissolved oxygen is present, the sensor output voltage provides a constant value of 0 millivolts (mV). When exposed to an environment with an oxygen saturation of 100%, the sensor provides a value of nearly 60 mV [12]. The Gravity DO Meter V2.0 signal conditioning circuit receives the sensor voltage and provides the amplified and filtered voltage [12]. The calibration process consists of obtaining the voltage supplied by the conditioning circuit when the sensor is not immersed in the water. In this condition, the sensor response is considered the reference voltage for 100 percent dissolved oxygen saturation.

However, it was found that the probe did not provide a voltage of 0 mV when tested in a standard solution of zero dissolved oxygen (HI7040L, Hanna), and the output voltage reached 250 mV. Not immersed in the water, the probe provided voltages close to 450 mV. The measured output voltage shows an exaggerated error compared to the values of nearly 60 mV given in the sensor's datasheet. A detailed analysis shows that the container with the electrolyte and the sensor membrane changes the output voltage of the probe when it is screwed on clockwise. When the probe is fully screwed in, it has a minimum output voltage of more than 200 mV. If the probe is not fully screwed in, it is possible to achieve the output voltage of 60 mV specified in the datasheet, but the container is not fully fixed and can easily lose its setting.

The strategy used by the SEN0237 sensor for measurement and calibration is similar to that of the Atlas ENV-50-DO sensor. Calibration consists of storing the reference voltage when the sensor is exposed to free air or to a sample with a dissolved oxygen saturation of 100%. According to [13], two samples at different temperatures with saturated dissolved oxygen are required for calibration. It is recommended to stir the water sample manually or with a machine for 10 minutes.

To obtain two samples with different temperatures, one sample was cooled in a refrigerator while the other sample remained at room temperature. Then the two samples were stirred with a mixer for 10 minutes. In this way, the reference voltages for two saturated samples of dissolved oxygen at different temperatures were obtained. When tested with a calibration sample at a temperature of 16°C, the sensor provided 860 mV, and when tested with a sample at a temperature of

32°C, 1.5 V was measured. The voltage and temperature of the two samples are used to calculate the saturation voltage (Equation (9)), where *v_sat* is the saturation voltage, *CAL1_V* and *CAL2_V* are the reference voltages, and *CAL1_T* and *CAL2_T* are the temperature values for the calibration samples with the highest and lowest temperatures, respectively, and *temp* is the measured temperature value. Using the values of the calibration samples, the saturation voltage *v_sat* is shown in Equation 10.

$$v\_sat = (temp - CAL2\_T) \cdot \frac{CAL1\_V - CAL2\_V}{CAL1\_T - CAL2\_T} + CAL2\_V \quad (9)$$

$$v\_sat = 40 \cdot (temp - 16) + 860 \quad (10)$$

The amount of dissolved oxygen is determined using the saturation voltage in Equation 11, where *DO* is the amount of dissolved oxygen in μg/L, *vout* is the output voltage of the sensor and *temp* is the water temperature. The *DO_Table* term is an integer value that provides a constant based on temperature. The vector has 41 values that allow conversion of temperatures up to 41°C.

$$DO = vout \cdot \frac{DO\_Table[(int)\ \ temp]}{v\_sat} \quad (11)$$

B. Standard solution response

To evaluate the sensor's response after the calibration process the pH, turbidity, and dissolved oxygen sensors were tested with standard solutions in the laboratory. Measurements from the SEN0161-V2 sensor were compared to standard solutions pH 4, 7, and 9. The SEN0189 sensor was evaluated using a commercial certified turbidity solution from Specsol. The solution has a turbidity of 20 NTU with an uncertainty of 0.4 NTU. Dissolved oxygen sensor (SEN0237 and ENV-50-DO) measurements were evaluated using a zero dissolved oxygen solution diluted in water with sodium sulfite (Na_2 SO_3).

The three sensors (pH, turbidity, and dissolved oxygen) were tested according to a specific procedure:

1) When the system is set up and turned on, the data collected in the first 10 minutes are discarded due to the heating of the sensors.
2) Measurements are taken with standard solutions until the sensor reading stabilizes.
3) The sensor probe is washed with distilled water and dried with soft paper.
4) Step 2 is performed again. For each standard solution, the procedure is repeated five times for each sensor.

The room temperature was controlled to guarantee there was minimal variation during the tests.

C. Comparison with the reference device

The second test evaluated the behavior of low-cost sensors during immersion and compared the sensors' measurements with a reference device. The Hanna HI98194 multiparameter instrument and low-cost sensor probes were immersed in a container of water from Municipal Lake (Cascavel, Paraná, Brazil).

This test allows not only the comparison of measurements between a reference device and low-cost sensors but also the verification of the robustness of the sensors when submerged. The reference device Hanna HI98194 is robust and can be fully submerged. It allows measurement of pH, electrical conductivity, turbidity, temperature, dissolved oxygen, and oxidation and reduction potential (ORP) [14].

D. In field evaluation

In the last phase, the data measured by the device were evaluated in a real environment: the urban lake of Toledo (Paraná, Brazil). In addition to the data collected by the low-cost sensors in the field, three samples were collected from the lake and properly sent to the A3Q lab, a certified laboratory to obtain the physical-chemical parameters of the water so that the measurements provided by the low-cost sensors could be evaluated.

III. RESULTS

The results are divided into three parts: the use of standard solutions, the direct comparison between a reference probe and the low-cost sensors, and finally the field tests with the prototype in the urban lake of Toledo (Paraná).

A. Standard solutions

Fifteen tests were performed with the SEN061-V2 sensor using three typical pH standard solutions. Five of them were performed using an acidic standard solution (pH 4), another five tests were performed using a neutral standard solution (pH 7), and the last five tests were performed using an alkaline standard solution (pH 9). The interval between measurements was 8 seconds. The tests with the acidic standard solution gave a mean pH of 4.08 with a population standard deviation of 0.1 and a relative standard deviation of 2.46%. The average stabilization time between measurements was approximately 2.6 minutes. The average temperature remained at 27 °C during the first test.

The test with the standard neutral solution resulted in a mean of 7.08 with a population standard deviation of 0.24 and a relative standard deviation of 3.36%. The average stabilization time was approximately 1.2 minutes. The average temperature during the second test remained close to 26.2 °C. The test with the standard alkaline solution resulted in an average value of 8.79 with a standard deviation of 0.38 and a relative standard deviation of 4.32% with an average stabilization time of 1.3 minutes. The average temperature during the third test remained close to 25.3 °C. The three tests show that the SEN061-V2 sensor has higher accuracy for solutions with pH 4 and 7, with a lower standard deviation when tested with the more acidic sample (pH 4). The highest absolute error and standard deviation were found for the most alkaline sample (pH 9).

The SEN0189 sensor tests were performed using a commercial standard solution with 20 NTU turbidity formazine and 0.4 NTU confidence interval. The tests were performed in quintuplicate with a time interval of 8 seconds between measurements. The experiments were performed at an average temperature of 22.3 °C. The stabilization time of the measurements was about 1.7 minutes. After stabilization of the measures, the tests resulted in mean turbidity of 18.9 NTU with a population standard deviation of 3.16.

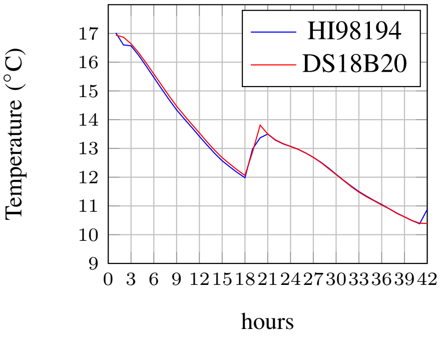
Experiments with the SEN0237 dissolved oxygen sensor were also performed in quintuplicate with an 8-second interval between measurements. As described in section II-B, an oxygen-free solution containing anhydrous sodium sulfite (Na_2SO_3) diluted in water was prepared for the tests. The average temperature during the tests remained at 19.1 °C. All five tests reached a value close to 0 mg/L at some point. The measurements stabilized at 0.04 mg/L after an average time of 2.1 min.

B. Intercomparison

Comparison tests between the reference multiparameter device (HI98194) and the low-cost sensors were performed for 42 hours without interruption. The interval between measurements was set at 1 minute, and the data were grouped into hourly intervals by taking the arithmetic mean between the 60 values of each hour. During the experiment, there was a malfunction of the dissolved oxygen probe of the HI98194 device, so the dissolved oxygen data of the device were discarded.

In this experiment, the water was taken from the Municipal Lake (Cascavel, PR, Brazil). The water sample was placed in a container so that the sensors and the probe of the reference instrument could be submerged. After 18 hours, the water was discarded and a new water sample was taken and placed back into the container. The plots showing the temperature measurements of the DS18B20 sensor and the reference sensor (Figure 1) show that there are no significant differences between the two sensors and that the response curve of the sensors changes when the water was changed after 18 hours.

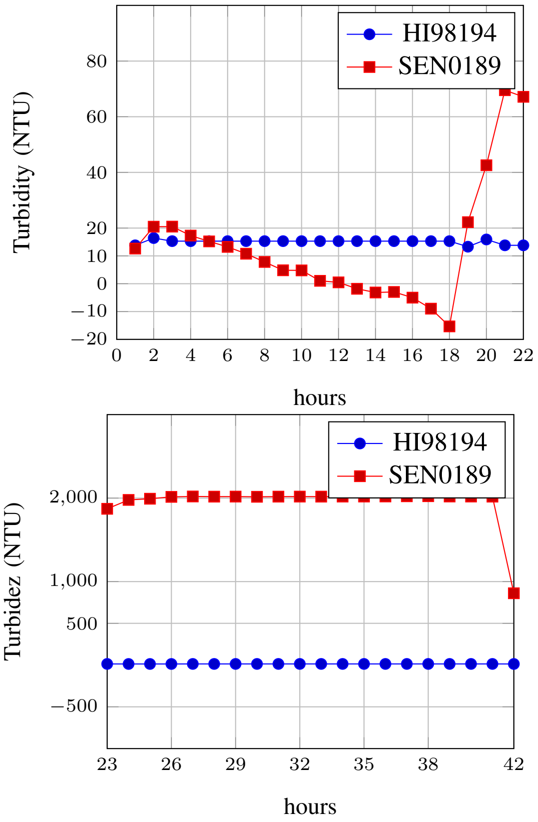
Fig. 1: Intercomparison between DS18B20 and HI98194 (reference) temperature sensors



The response curve of the SEN0189 turbidity sensor (Figure 2) can be divided into two moments: before the 22 hours of testing, when the sensor showed measurements that were relatively close to the reference sensor HI98194, and after the 22 hours of testing, when the measurements showed a significant error due to water penetration into the electronic circuits of the SEN0189 sensor, leading to its malfunction. The low-cost sensor survived the immersion and provided results close to those of the reference sensor during the 8-hour test period. After this period, the difference between the response curves of the two sensors continuously increases. When the water is changed (18 hours), the error increases significantly. The seal and the mechanical structure of the SEN0189 sensor are not prepared for immersion. The structure was adapted and sealed for the tests with hot glue, silicone adhesive, adhesive tape, and insulating tape.

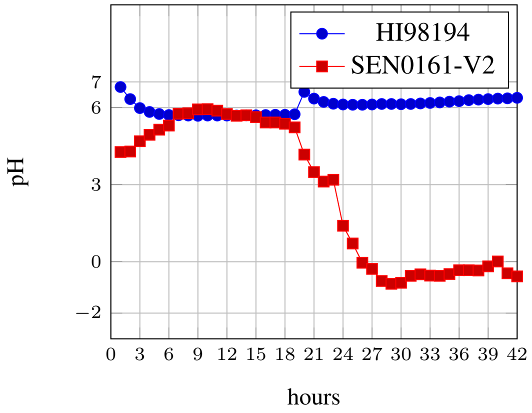
Considering only the first 8 hours of the test, the average turbidity measured by the SEN0189 sensor was 13.65 NTU with a standard deviation of 5.37. While the reference sensor recorded an average turbidity value of 15.3 NTU with a standard deviation of 0.66. The standard deviation shows that the measurements of the HI98194 sensor remained constant, while the measurements of the SEN0189 sensor fluctuated more during the same period.

Fig. 2: Intercomparison between SEN0189 and HI98194 turbidity sensors



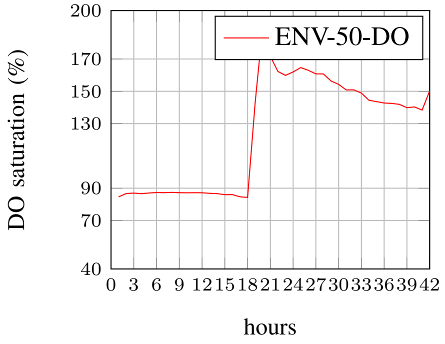
The low-cost pH sensor showed a similar response curve to the reference sensor (Figure 3) during the 20-hour test period. The pH sensor, like the turbidity sensor, has no mechanical structure prepared for immersion. However, the pH sensor survived an extended period of testing before showing significant failures. During the first 20 hours of the experiment, the SEN0161 sensor recorded an average pH of 5.23 with a standard deviation of 0.67. The reference sensor, HI98194, recorded an average pH of 5.88 with a standard deviation of 0.33. After 20 hours of testing, the differences between the sensor measurements increased significantly.

Fig. 3: Intercomparison between SEN0161-V2 and HI98194 pH sensors.



For the dissolved oxygen measurement test, the output voltage of the Atlas ENV-50-DO sensor had to be carefully adjusted due to the sensor calibration issues described in Section II. The output voltage of the sensor was set to approximately 57 mV using a multimeter. During the period when the sensor did not lose its adjustment and calibration (initially 18 hours), the mean dissolved oxygen saturation (DO) remained at 89.5%. After the water change (18 hours), the sensor lost its adjustment and gave dissolved oxygen saturation values greater than 130%.

Fig. 4: ENV-50-DO Sensor Dissolved Oxygen Measurements



C. *Field test*

The prototype was anchored on one of the shores of the urban lake and remained in place for 13 hours. The interval between measurements was set at 5 minutes. The sensors were not completely immersed in the water. An acrylic plate held in place by two threaded rods allowed the sensors to be submerged only to the necessary depth. During the same test period, three samples were taken from the lake and analyzed by the A3Q lab.

During the test period, the SEN0161 pH sensor had a mean of 5.7 and a standard deviation of 0.2. The sensor response curve (Figure 5) shows that the measurements stabilized between 5.5 and 6 most of the time. The dissolved oxygen sensor response curve SEN0237 (Figure 6) gave a mean value of 7 mg/l with a standard deviation of 0.79. Samples analyzed by the A3Q laboratory gave a pH of 6.85 and a dissolved oxygen value of 7.85 mg/l.

The DS18B20 temperature sensor remained at an average temperature of 21.3 °C during the experiment (Figure 8). The readings from the SEN0189 turbidity sensor (Figure 7) can be divided into two periods with different behavior. During the first 16 measurements (1.3 hours test duration), the sensor showed an average turbidity value of 39.2 NTU with a standard deviation of 3.56. The laboratory report indicates turbidity of the lake of 57.04 NTU. After 1.3 hours of testing, the sensor lost its setting and remained out of the water until the end of the test, resulting in a turbidity value of nearly 0 NTU.

Fig. 5: SEN0161-V2 pH sensor field measurements

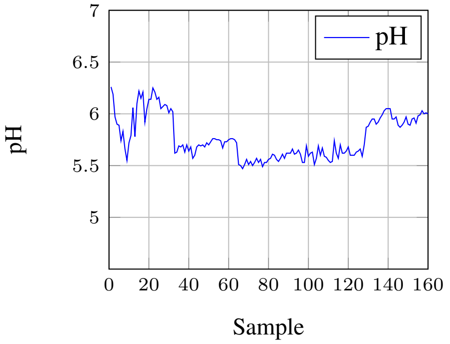
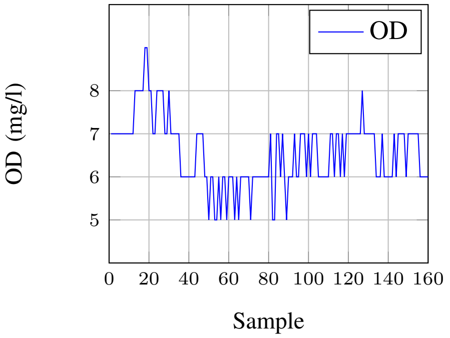


Fig. 6: SEN0237 dissolved oxygen sensor measurements



IV. CONCLUSION

This work was devoted to evaluating the performance of low-cost sensors, costing between US$4.00 and US$234.00, to measure physicochemical parameters of waters that determine their quality. The low-cost sensors were connected to an electronic device that measures the water quality parameters and

Fig. 7: SEN0189 turbidity sensor measurements

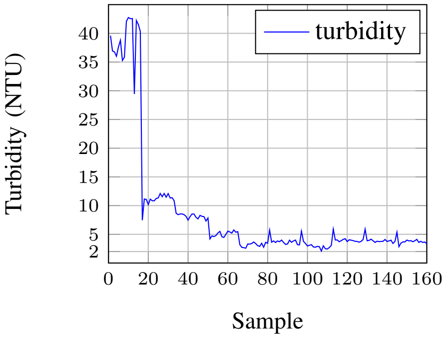
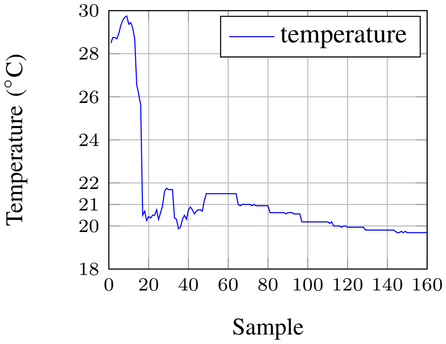


Fig. 8: DS18B20 temperature sensor measurements



transmits them in real time to the Internet. The sensors showed accurate results when tested in a controlled environment, while errors increased significantly when tested in the field under natural environmental conditions or fully submerged. It is also important to note that the measurements from the low-cost sensors showed greater variability than the measurements from the reference instruments.

It can be argued that this work is the beginning of a longer investigation into the behavior and performance of low-cost sensors that can be used for water quality monitoring. The work can be extended and improved on several fronts, as there is a large gap in the development of low-cost devices for water quality monitoring of water bodies (urban lakes, rivers, reservoirs).

In general, the mechanical structure of the low-cost sensors proved to be vulnerable in both the comparison test and the field test. In particular, the turbidity sensor did not provide adequate protection for uncontrolled environments. A future task is to investigate and develop mechanical structures that will allow the low-cost sensors (i.e., those used in this work) to remain in aggressive environments for extended periods of time. Another potential improvement is to automate the cleaning of the sensors. When the sensors are used in rivers and lakes, debris accumulates which can lead to erroneous readings.

Further, to obtain a robust evaluation of the performance of low-cost sensors for water quality monitoring, tests with standard solutions, comparisons with reference devices, and field tests should be later applied to other brands and models of sensors. Finally, another meaningful change for future field tests is to extend the test period to observe and detect sensor wear and measurement errors over time. The analysis of measurement errors and the study of sensor wear can open up a range of applications where artificial intelligence can correct low-cost sensor readings.

V. ACKNOWLEDGEMENTS

We thank the Municipality of Toledo, Paraná, Brazil, the company Overtech Technologic Solutions, and the Research Foundation of São Paulo (FAPESP), process 20/05135-5, for research support.

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