AquOculus: A Cost-effective Advanced Metering Infrastructure for Urban Water Distribution Systems

Matheus Pilotto Figueiredo, and Lizandro de Souza Oliveira

***Abstract*—Water consumption Automated Meter Reading (AMR) devices are fundamental to achieving sustainable management in Water Distribution Systems (WDS). However, available solutions are still relatively expensive, and don't feature adequate and synchronized network throughput to attain Leakage Detection and Localization (LDL). As a consequence, AMR installation isn't extended in most cities. As an alternative, we propose the so-called AquOculus Advanced Metering Infrastructure (AMI) system, intended to be a cost-effective solution. This article presents the first results obtained while developing the embryonic AquOculus AMR prototype, consistent with Technology Readiness Level (TRL) 3. It was based on an ESP32 microcontroller and communicated the correct consumed water volume to a remote application via Wi-Fi. An ordinary water meter was leveraged as the main reading instrument, coupled with the developed optoelectronic pulse counter. It doesn't require specific color, metallic, or magnetic parts on the monitored indicator, applying to a wider variety of water meter models. As the water volume counting is indirect, the measurement relies on the factory-calibrated water meter; so the initial validation setup was very simple, using a hairdryer to move the water meter mechanism. Sunlight sensitivity was observed, and the sensor positioning process was demanding. These issues were figured out and discussed for future work. Despite the TRL achieved, this article also addresses the main steps towards the complete AquOculus system. The cost-effective characteristics are expected to boost further studies to allow massive installations by water distribution companies. The developed software repository link was provided for reproducibility.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/10125

***Index Terms*—Sustainable Development Goals (SDG), Water Distribution Systems (WDS), Automated Meter Reading (AMR), Leakage Detection and Localization (LDL), Optoelectronics, Low-cost, ESP32, Wi-Fi**

I. INTRODUCTION

THE United Nations Educational, Scientific and Cultural Organization (UNESCO) defines the installation of Automated Meter Reading (AMR) devices as a fundamental step for Smart Water implementation in Water Distribution Systems (WDS) [1], an important step to attain the 6^{th} Sustainable Development Goal [2].

AMR devices register the customers' water consumption over time; data is usually collected by company personnel walking or driving by with data receivers; finally, data is transmitted to the company's main server.

The broader concept of Advanced Metering Infrastructure (AMI) embodies the endpoint AMR devices along with a telecommunications network so that data can be conveyed to the water company's main server automatically and bidirectionally, becoming accessible also to customers.

The most obvious advantage provided by the installation of AMR devices is that the monthly reading of consumed water by human work is dismissed, reducing costs and errors, especially when AMI is used. Online AMR data enables diagnostics of leakages in customer properties and consumption statistics, which can boost more conscious use of water. An underexplored feature is that such data allows real-time calculation of water loss and remote Leakage Detection and Localization (LDL) in WDS [1]–[5], which is a very challenging problem.

Nonetheless, the installation of AMR devices is rare, especially in developing countries, due to limitations in commercial solutions, such as relatively high cost (US$ 73.9 to US$ 229.80), the need to replace water meters or adapt hydraulic installations, low sampling frequencies related to battery power supply autonomy, and the requirement for additional telecommunication infrastructure. As a result, few studies have been conducted regarding the use of AMR data for LDL, while 126 billion m^3 of treated water are estimated to be lost each year [6].

To overcome such challenges, this work proposes AquOculus, as a cost-effective AMI solution. We focus on presenting our initial prototype, while also addressing general system features. AquOculus AMR device has low cost and leverages the original water meter dismissing replacement. Integration of the AMR devices between each other and with urban Wi-Fi networks reduces telecommunication infrastructure costs. Leveraging customer's electrical connection provides a robust power supply allowing high throughput for LDL. Provision of consumption flow and WDS infered pressure data along with the detection of reverse flow and violation are additional key feasible features based on the elementary AMR device.

This paper is organized as follows. In Section II we state the research problem. Then, in Section III, we present the solution

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[1]https://unesdoc.unesco.org/ark:/48223/pf0000367904
[2]https://sdgs.un.org/goals/goal6

guidelines. Section IV reviews existing academic and commercial AMR devices, comparing them to AquOculus. Section V presents the prototype hardware and electronic components. Section VI illustrates software functional characteristics using flowcharts. Section VII describes the experimental setup and observed prototype behavior. Section VIII addresses the complete frame overview of AquOculus, defines future work, and presents the estimated system cost. The main conclusions and data availability are discussed in Section IX.

II. Problem Statement

The literature review article [6] is one of the most recent and complete when it comes to LDL. The author states that **"Until recently, online demand data using AMR has not usually been considered in the literature, as their installation on real WDNs is not currently extended"**. So it seems that existing solutions might not be sufficiently attractive for water companies. As a result, the use of such data is underexplored in the literature about LDL in WDS.

In fact, despite the current technological development, in most cities, especially in developing countries, not even the customers' monthly consumed water volume is automatic yet. The main limitations observed in existing AMR solutions constitute the assumed **problem guidelines**:

1) Relatively high costs for the AMR devices (US$ 73.9 to US$ 229.80), because they are prohibitive for cities with thousands or millions of inhabitants;
2) Necessity of water meters substitution or adaptations in the hydraulic installation, not only because of additional costs, but also for installation time, eventual insertion of hydraulic leakage, and environmental effects of discarding old water meters;
3) Focus only on water volume reading, as it limits the applicability of LDL algorithms;
4) Power supply and communications system design limited to low data throughput (monthly or daily readings), also for the reason of limited LDL applicability;
5) Necessity of additional network elements, once they represent installation time, system complexity and costs, or human drive-by to transmit data, which implies in monthly wages for several workers and the possibility of reading errors;
6) Inability to detect negative flows, as it implies eventual erratic consumption registration, and burdens the identification of abnormal WDS behaviors, such as leakages or pump operation failure;
7) Inability to detect water meter violation, which is essential for correct operation, system resilience and maintenance.

These limitations have hindered the widespread adoption of AMR devices, leaving their use for WDS management and LDL underexplored. To address these gaps, the following section proposes solution guidelines embodied in AquOculus.

III. Proposed Solution

AquOculus is an under-development system intended to encompass a set of technical solutions to implement a cost-effective AMI for WDS. The desired specific advantages to be offered to sanitation service managers and citizens constitute the **solution guidelines**, as follows:

1) Relatively low-cost for the AMR device, assuming large-scale installation, as the materials cost less than US$ 16.74 (roughly 23% of the cheapest consolidated commercial solution);
2) No need to change existing water meter or to adapt hydraulic installation, contrary to existing solutions, resulting in smaller environmental impact, cheaper and faster implantation, and maintaining original certified metrological features. This implies improved scalability and viability, especially for developing countries;
3) Broadened data, providing not only volume, as in most existing solutions, but also flow, and WDS pressure, which can be calculated indirectly based on flow for customers who dispose of particular tanks, increasing system utility for LDL;
4) Power supply leveraging customer electrical service connection, to allow data throughput high enough for LDL (5 to 15 minutes between readings [7]), without the need to trade-off throughput for battery autonomy, as in most existing solutions;
5) Usage of the very AMR devices to constitute an AMI, exploring their proximity and available Wi-Fi internet connections in urban environments, generating integrated and synchronized data to attain LDL, overcoming existing solutions, where individual AMR devices usually require human drive-by to gather data;
6) Detection of negative flows, avoiding read errors, allowing anomaly diagnostics, and eventual improvements in WDS operation, unlike existing solutions, in which this is not always offered;
7) Anti-tampering mechanisms for the detection of violation, using three wires and an analog signal from the sensor to the sealed processing unit, overcoming various existing solutions when it comes to data integrity, system resilience, and maintenance.

Such a cost-effective system, aggregating LDL compatibility features, addressing issues ranging from physical installation and maintenance, passing through power supply and data integration, could boost AMR installation, overcoming existing solutions towards the objective of sustainable water management. In the next section, we present the main features of existing academic and commercial AMR/AMI devices and systems while comparing to AquOculus.

IV. Commercial Solutions and Literature Review

In this section, we present Table I, in which commercial and academic solutions are summarized and compared against AquOculus based on the solution guidelines discussed in the previous section. Note that the Technology Readiness Level (TRL) of each product/prototype was indicated. Along the text, such solutions are described in more detail.

Unlike AquOculus, the available **commercial solutions** require the substitution of the existing water meter or hydraulic adaptation. They are ordered descendingly in relation to AMR device price, as follows:

TABLE I
COMPARISON OF AQUOCULUS TO EXISTING ACADEMIC AND COMMERCIAL SOLUTIONS

Solution / Technology Readiness Level (TRL)	1-Relative Low-Cost AMR device?	2-Substitution or Hydraulic Adaptation Dismissed?	3-Measured Variables V=Volume F=Flow P=Pressure	4-Power Supply and Communications Support LDL Necessary Throughput?	5-Additional network elements to transmit data to the water utility server are dismissed?	6-Negative Flow Detection?	7-Anti-Fraud Mechanisms?
(A) Commercial RF Ultrasonic AMR / TRL 9	✗ US$ 229.80 (13.7X)	✗	V, F	✗ battery	✗ requires LoRa gateways or personnel driving by	✓ inherent to ultrasonic sensors	✓ not described, but claimed by the manufacturer
(B1) Wi-Fi or LoraWAN telemeter + Magnetic (reed switch) Sensor Equipped Water Meter / TRL 3	✗US$ 85.65 (5.1X) or ✗US$ 107.49 (6.4X)	✗	V	✓ AC power or ✗ battery power supply	✗ requires Wi-Fi AP or LoRa gateways	✗ single on/off sensor	✗ on/off sensor, can be easily violated
(C) Commercial RF Inductive AMR / TRL 9	✗ US$ 73.99 (4.4X)	✗	V	✗ battery	✗ requires LoRa gateways or personnel driving by	✗ single on/off sensor	✗ measurements may be violated using magnets
(B2) Wi-Fi or LoraWAN telemeter + Hall effect sensor pulse counter (YFS201) / TRL 3	✗US$ 55.59 (3.3X) or ✗US$ 77.52 (4.6X)	✗	V, F	✓ AC power or ✗ battery power supply	✗ requires Wi-Fi AP or LoRa gateways	✗ single on/off sensor	✗ on/off sensor, can be easily violated
(D) Academic Camera Based AMR / TRL 3	-	✓ original water meter reading is monitored by image	V	-	✗ requires Wi-Fi cloud server access	✓ possible, using additional image processing	✓ in case of violation camera could detect background change
(E) Academic Optical Indicator Monitoring AMR / TRL 3	✓ probably US$ 16.74 (1X), or less, for materials	✓ calibrated indicator is monitored	V	✗ battery	✗ requires LoRa gateways	✗ sensor signal probably is symmetric	✓ microcontroller ADC could detect abnormal voltage range
(F) **AquOculus AMI System (This work) / TRL 3**	✓ probably US$ 16.74 (1X), or less, for materials (see Table II)	✓ calibrated dL indicator is monitored	V, F, P - deciliter indicator used to calibrate low-flow indicator	✓ AC power + battery	✓ implements AMI using the very AMR devices and customers' Wi-Fi as gateways	✓ sensor signature signal is asymmetric	✓ microcontroller ADC could detect abnormal voltage range

- (A) Ultrasonic automated water meters[3] are the most precise, but they are 11.3 times more expensive than the AquOculus AMR device. They require additional network infrastructure, representing an unviable solution for large-scale installation to monitor regular customers;
- Wi-Fi[4] or LoraWAN[5] telemeters are also available. Unlike AquOculus, which relies on monitoring the factory calibrated dL indicator of the certified water meter, these commercial solutions are based on pulses generated by an (B1) additional not certified hall effect sensor pulse counter (YFS201)[6] to be installed in series with the existing water meter, requiring adaptation of the customer hydraulic install and calibration. Another sensing alternative is to use a (B2) new water meter model equipped with a magnet fixed to the dL indicator, and a magnetic sensor (reed switch)[7], replacing the original one, however such a solution doesn't provide the ability to detect negative flows or violation as done by AquOculus. The commercial solution using the YF-S201 is similar to the one explored in a recent article [8];
- (C) RF telemeters based on inductive sensors[8] aren't

[3]Ultrasonic automated water meter - link
[4]Wi-Fi telemeter - link
[5]LoraWAN telemeter - link
[6]YFS201 flow sensor - link
[7]Magnetic reed switch equipped water meter - link
[8]RF telemeter based on inductive sensor - link

suited to provide small flow information for LDL, as they only monitor the dL indicator, which rotates slower; AquOculus, on the other hand, also monitors the low-flow indicator, which produces pulses with higher frequency. The manufacturer informs that the battery's theoretical lifetime is up to 15 years, but gives no guarantee nor relates such autonomy to data throughput, while AquOculus presents virtually infinite autonomy, as long as AC power is available, not limiting throughput.

The idea of reading ordinary water meters automatically, without the need for substitution, isn't new **in the academic literature**. A recent article [9] (D) proposes the development of a water volume AMR device based on the ESP32 CAM microcontroller platform, which processes photos to register water consumption. Ideas similar to this are presented in other papers [10], [11], [12], and [13]. However, these studies don't analyze their solutions regarding power sources, installation, integrated communication systems, flow measurements, and respective estimated costs.

Article [14] (E) also proposes an AMR device that dismisses the substitution of the existing water meter. It uses a TCRT5000 reflective optical sensor to monitor a half-plastic/half-metal indicator. AquOculus, on the other hand, fits much more existing water meter models, not requiring metallic or magnetic parts in the monitored indicators.

The academic and commercial solutions presented here have limitations that we propose to overcome with the AquOculus system. First of all, differently from commercial solutions, water meter substitution, adaptations in hydraulic installation and hydraulic calibration aren't required. The Aquoculus AMR device materials cost roughly 23% of the cheapest consolidated commercial solution. Additional infrastructure to transmit data is dismissed. Autonomy isn't a problem, as in most solutions, that depend on batteries, so throughput isn't limited by such a factor. AquOculus is also capable of detecting negative flows and violations. And finally, based on the measured flow, AquOculus integrated data framework shall also provide WDS pressure measurements, contributing to a high degree to attain LDL algorithms.

In the next section, we present the embryonic AquOculus prototype hardware.

V. AquOculus Hardware

AquOculus is intended to work on the various types of ordinary water meters existing in most cities, disregarding particular features such as specific color, the existence of magnets, or metallic parts on the rotating indicators. Electrical energy was thought to be supplied from the customer's electrical service entrance, which is usually near the water meter and the residence Wi-Fi Access Point (AP), representing a robust source.

The AquOculus AMR device's first prototype hardware was composed of the following elements:

1) One optical sensor with separated and 45º angled IR 940 nm LED (TIL32) and phototransistor (TIL78) is fixed directly over the x0.0001 (dL) indicator (see Fig. 1 and Fig. 2). This sensor is responsible for volume reading, providing the same original accuracy parameters up to the scale of liters (one full revolution corresponds to 1 L). A plastic part holds the optoelectronic emitter and receiver approximately 1 cm distant from each other, so that the perfect reflection point is obtained when the sensor is positioned 0.5 cm from the white water meter background. Note that such distance from the acrylic cover and the background may vary according to the water meter model.
2) One optical sensor similar to the previous one installed on the low-flow indicator. Such an indicator rotates faster than the dL indicator, varies in format from one model to another (some look like gears, others look like double axes), and isn't calibrated, so it would be responsible for flow reading after a calibration process using the dL indicator as a reference.
3) The main board with input connections to the two sensors above and equipped with an interface circuit to treat the signals and an ESP32 module to store, process, and transmit data using Wi-Fi (see Fig. 3 and Fig. 4)
4) A common smartphone 5 V power source, connected to an AC outlet.

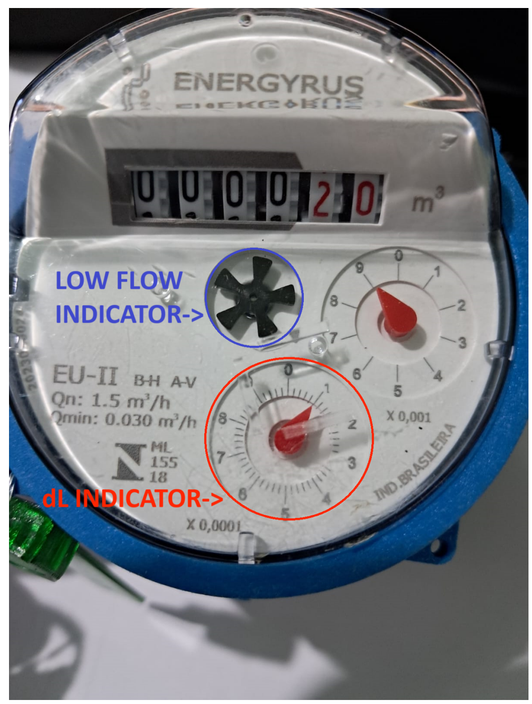

Fig. 1. Ordinary hydraulic water meter - dL and low-flow indicators.

Experiments have shown that the optoelectronic elements must be angled at 45º because, under such an arrangement, they work more as a through-beam sensor than as a retro-reflective sensor. In fact, the indicator and background surfaces present similar reflective behavior, producing a better signal excursion for the through-beam arrangement, in which the IR emission is cut twice per revolution (see Fig. 5 and 7).

Another important design choice was the utilization of an inverting Schmitt Trigger circuit. Not only does it condition the phototransistor signal voltage levels to be readable by the ESP32, as logic high and low, but it also provides immunity to noise.

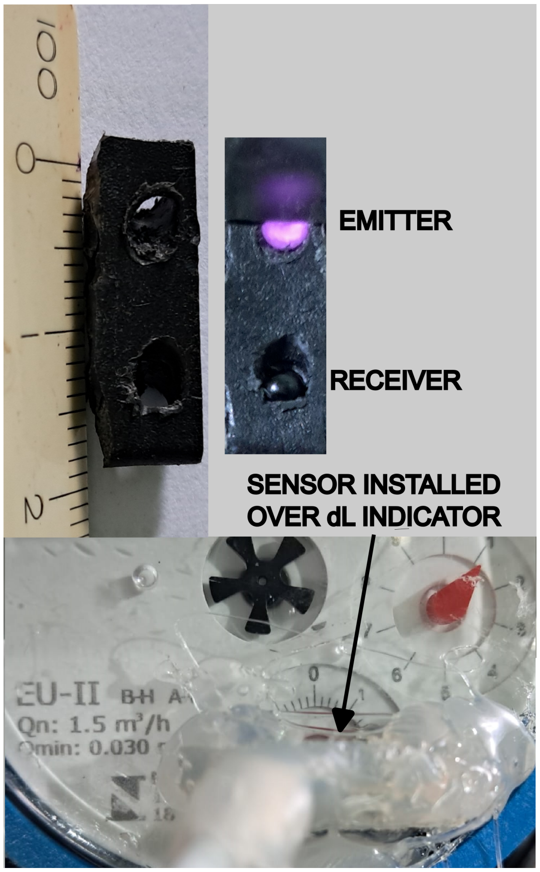

Fig. 2. AquOculus sensor.

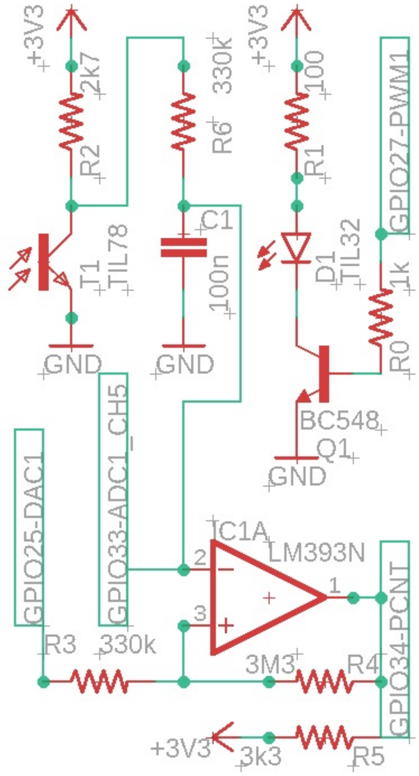

Fig. 4. AquOculus signal treatment circuit diagram - identical for both monitored indicators (dL and low-flow), but using different GPIOs of the ESP32.

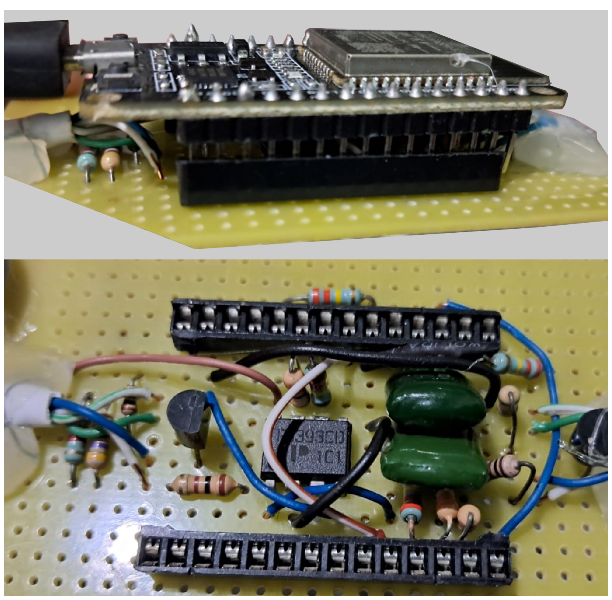

Fig. 3. AquOculus main board - signal treatment circuits and ESP32 30 pins DOIT kit.

Additionally, as the ESP32 Digital-to-Analog Converter 1 (DAC1) is wired to the inverting Schmitt Trigger circuit (see Fig. 4), a suitable comparison voltage can be set according to the voltage bias and excursion range generated by the phototransistor.

To do so, a calibration process is executed right after installing the sensor, where the ESP32 Analog-to-Digital Converter 1 (ADC1), channel 5, reads the signature signal generated by the phototransistor (see Fig. 5) while the dL indicator rotates for some time, completing at least a full revolution. Such a mechanism provides robustness because the DAC1 voltage is defined automatically, no matter if the phototransistor voltage swings from 2 V to 3 V or from 0.3 V to 0.9 V, for example. Note that such variations in the excursion range are related to the acrylic transparency and background reflectivity, which may vary depending on the water meter model and age.

In this work, the comparison voltage is calculated as the minimum voltage of the signature signal, added to 150 mv. To better explain how the phototransistor signature signal is generated, Fig. 7 illustrates the path of the dL indicator under the IR beam, showing four key characterization points according to Fig 5.

The inverting Schmitt Trigger comparator functioning can be analyzed using the superposition theorem and its output behavior is defined by Eq. 1. Note that the LM393 comparator integrated circuit has an open-collector transistor output, so R5 serves as a negligible resistance pull-up resistor. Also, observe that the hysteresis voltage is $k_2 \cdot 3.3 \approx 330\ mV$.

$$V(t) = \begin{cases} LOW, & \text{if } V_{pt} > k_1 \cdot V_{DAC1} + k_2 \cdot 3.3 \\ HIGH, & \text{if } V_{pt} < k_1 \cdot V_{DAC1} \\ V(t^-), & \text{if } V_{pt} \geq k_1 \cdot V_{DAC1}, \\ & \text{and } V_{pt} \leq k_1 \cdot V_{DAC1} + k_2 \cdot 3.3 \end{cases} \quad (1)$$

where,
$V(t)$ is the comparator output voltage
V_{pt} is the phototransistor output voltage, which is applied to the inverting input of the comparator
$k_1 \cdot V_{DAC1}$ is the comparison voltage, which depends on the voltage set to DAC1
$k_1 = (R4 + R5)/(R3 + R4 + R5) \approx 0.91$
$k_2 = (R3)/(R3 + R4 + R5) \approx 0.1$
$V(t^-)$ is the comparator output voltage previous value

The behavior defined by Eq. 1 can be interpreted along with Fig. 5 (phototransistor signature signal) and Fig 6(inverting Schmitt Trigger comparator output). The circuit output (green line in Fig 6) will switch to low logic level (representing that the indicator is passing through the IR beam), immediately when the phototransistor voltage (blue line in Fig. 5) exceeds the comparison voltage + hysteresis voltage (yellow line in Fig. 5). However, after that, the output only returns to high logic level when the phototransistor voltage becomes inferior to the comparison voltage (red line in Fig. 5). So, there is a window between these thresholds (difference between yellow and red lines) equivalent to the hysteresis voltage, thus small signal variations relative to noise can't cause the output to change its logic level, avoiding erroneous pulse counting.

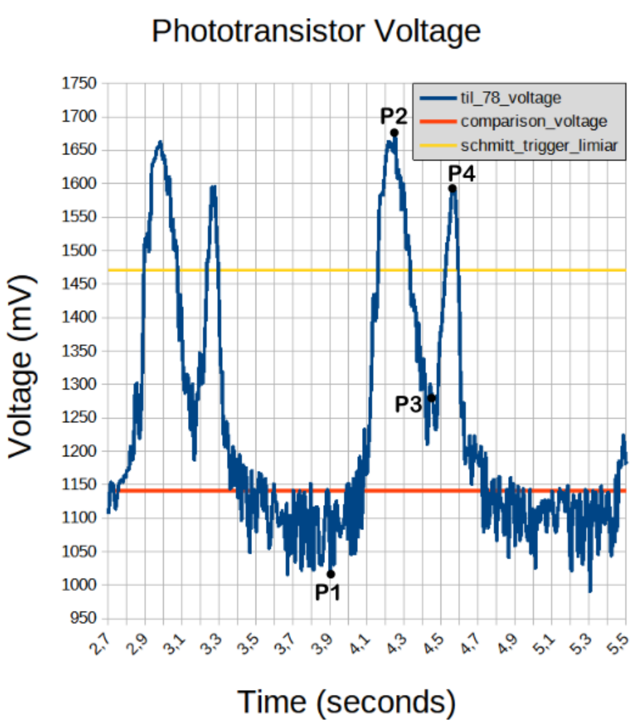

Fig. 5. Data from calibration process - Phototransistor voltage pattern (blue); ADC1 comparison voltage (red) and Schmitt Trigger limiar voltage (yellow).

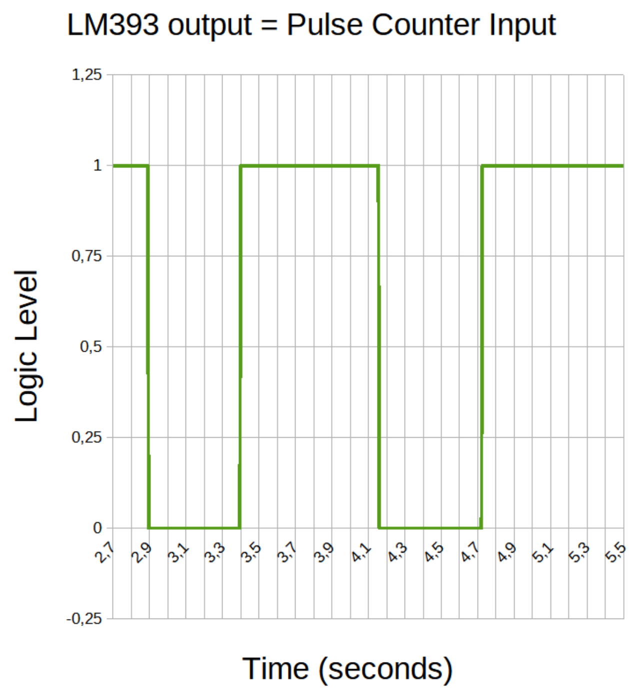

Fig. 6. Schmitt Trigger output goes to logic level "0" when the phototransistor voltage exceeds the comparison voltage by 330mV and goes to logic level "1" when it falls below the comparison voltage.

Observe that the comparator output pulses are registered by the ESP32 pulse counter module PCNT, on GPIO34.

Although ADC1 was used in this prototype only for calibration of the comparison voltage, it is fundamental for flow direction inference and violation detection, thus attaining solution guidelines 6 and 7, described in Section III. The mechanisms to implement such features will be discussed in Section VIII.

The low-pass filter and transistor Q1 were added for further experiments using a bigger IR LED current, along with Pulse Width Modulation (PWM) signal. In this initial prototype, the resistor was chosen to get around 20 mA LED current, and GPIO27 was fixed with high-level voltage.

As we have presented, the AquOculus AMR device is quite simple in terms of the basic components used, aiming for low cost. Nonetheless, the manner in which such components are disposed and connected was carefully decided to obtain the maximum possible benefits, such as compatibility with most existing water meters and the ability to allow future improvements, leveraging the ESP32 capabilities. Now that the hardware is described and illustrated, we can move on to the next section, where software functioning is depicted.

VI. AquOculus Software

Two software programs were developed to test the system, focusing on the implantation procedures that a technician would conduct: sensor installation, calibration, setting of initial water meter reading, and functional assessment. The first software is run on the AMR ESP32 microcontroller, and the second on the technician's notebook or smartphone.

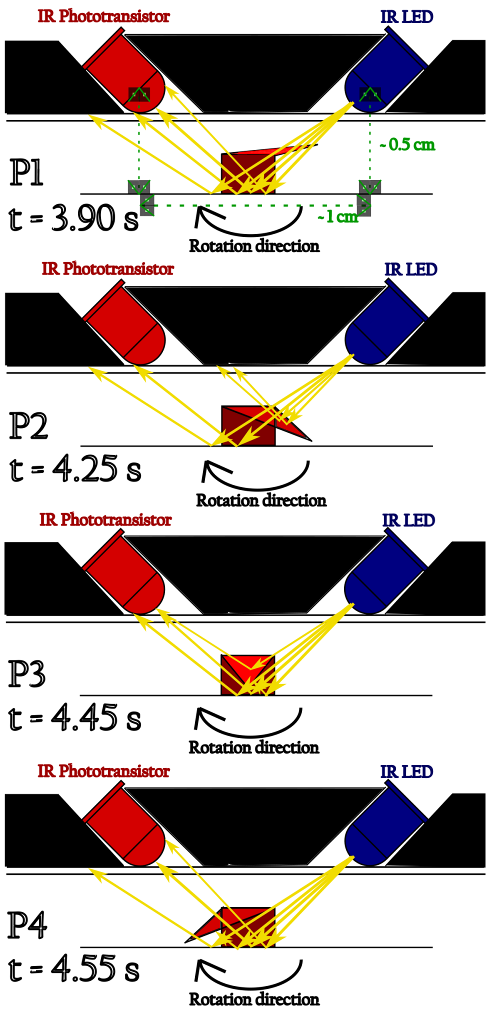

Fig. 7. Illustration of indicator path over IR beam along time instants, according to Fig. 5, where key points were inserted.

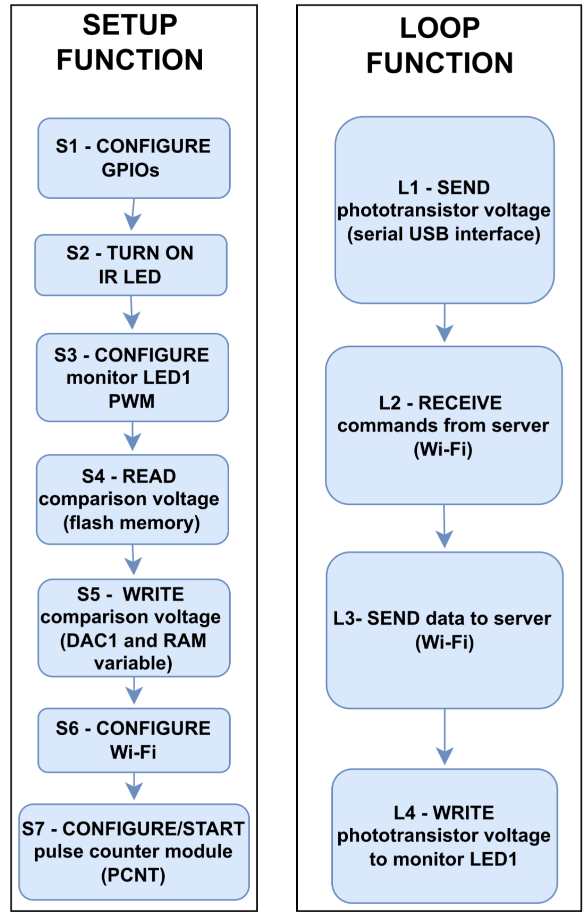

Fig. 8. ESP32 SETUP and LOOP routines.

The communication logic is very simple. The server provides a Wi-Fi AP to which the AMR device connects. LED1 serves as an auxiliary visual tool to position the sensor during installation. Then the technician can demand the AMR to execute the calibration process. After that, he visually reads the water meter and sets the initial read value on the server application. Finally, AquOculus AMR device counts the dL indicator pulses and sends the count to the server application to be summed to the initial read, so the functional assessment can be executed, observing if the hydraulic water meter and the server application register the same volume.

The microcontroller was programmed using the Arduino IDE (C++ language) for simplicity and reduced development time. It is responsible for the tasks indicated in Fig. 8. Tasks S1 to S7 are executed inside the SETUP function, which occurs only once at system power-up. After that, the LOOP function repeats as long as there is a power supply, executing tasks L1 to L5.

Below we detail the microcontroller tasks:

- S1 - Defines each General Purpose Input/Output (GPIO) port as input or output;
- S2 - As explained in the previous section, the IR led is actuated through a transistor connected to a PWM port, for future experiments; however, in this initial prototype, we set the port to be continuously at high logic level;
- S3 - ESP32 development kit LED1 PWM is set to use 10 kHz frequency and 12 bits resolution;
- S4 - After the sensor calibration process, the comparison voltage is calculated and stored in flash (non-volatile) memory;
- S5 - Comparison voltage is applied to DAC1 and saved to a variable in RAM to be used afterward in the LOOP function;
- S6 - Wi-Fi is configured with fixed IP address, using HTTP protocol. The microcontroller is set as a client and connects to the server;
- S7 - To save processing time, the PCNT hardware pulse counter module of the ESP32 is used. It was configured to count on rising edges, that is, just after the dL indicator ends its way through the path of the optical sensor (see Fig. 5);
- L1 - In each iteration of the LOOP function, the phototransistor voltage is sent using the ESP32 serial USB interface, which was used as a debugging tool while developing the prototype software;
- L2 - The microcontroller receives three possible command requests from the server:
  - enable/disable LED1, to confirm connection status;

- perform sensor calibration;
- reset pulse counter to zero, which is done whenever the technician resets the water meter reading in the server;

- L3 - Data sent to the server:
  - current pulse count;
  - phototransistor voltage;
  - comparison voltage, defined in the last calibration;
- L4 - Current phototransistor voltage is applied to LED1 PWM interface. This is used as an indirect means to monitor the phototransistor voltage through brightness variation, facilitating installation and maintenance.

As Arduino IDE was used, data transmission reliability and performance aren't strong, and could be improved using the Espressif IDE. For that reason, performance metrics, such as response times, transmission frequency, error rate, and maximum communication distance, weren't assessed yet, as we intend to change the IDE and respective libraries for future work.

A notebook with mobile hotspot feature represents the installer technician's computer or smartphone, which is configured as an HTTP server. A Windows Form application was developed using Visual Studio 2022 (VB.NET language). The functionalities are (see Fig. 9):

1) connects or disconnects to the AMR device;
2) enables or disables LED1, to save energy when not in use;
3) displays the current phototransistor voltage value, so the technician can observe its variation as the indicator passes under the sensor;
4) demands the AMR device to execute the calibration process;
5) displays the current comparison voltage value, to allow the technician to ratify that the last calibration was successful, and to diagnose eventual problems;
6) allows the installer technician to set the initial water meter visual reading into the application. This process also sends a command to the AMR device to reset the ESP32 pulse count to zero;
7) continuously shows the system volume reading (L), which corresponds to the sum of the initial water meter visual reading with the current EsP32 pulse count;
8) allows the technician to select the water meter model, which is useful to get its working parameters, such as maximum and minimum flow;

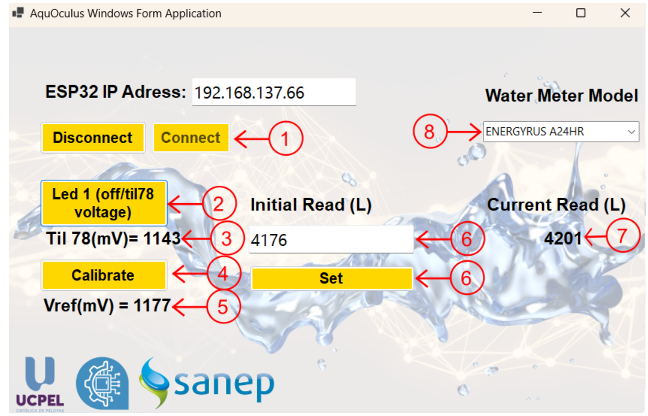

Fig. 9. Server application: After calibration, the comparison voltage was defined as 1177 mV; the current phototransistor voltage is 1143 mV; the initial water meter visual reading was registered as 4176 L; after operation, the consumption registered by AquOculus was 4201 L.

VII. Proof-of-Concept Experiments

To run preliminary functional tests, consistent with TRL 3, a hairdryer was used as a simple form to cause the dL indicator to rotate. Although we didn't use water, the experiment is valid because AquOculus reads consumption indirectly, exclusively based on the already calibrated existing hydraulic water meter.

In the first experiments, overcounting was identified as a result of electrical and mechanical noise. To solve that, the inverting Schmitt Trigger comparator was applied.

The tests conducted have shown that the Schmitt Trigger comparator was able to deal with noise and glitching on its own and that the low-pass filter capacitor C1 was attenuating the phototransistor signal, requiring its removal.

After solving the electronic problems, it was observed that using the hairdryer at full speed, the reading of AquOculus was bigger than indicated by the hydraulic water meter. In fact, the water meter used in this work (ENERGYRUS A24HR) has a nominal flow of 1.5 m^3/h and the maximum flow is 3 m^3/h. So imposing a flow bigger than the maximum can cause eventual reading errors by the hydraulic water meter or even damage. It seems that the internal gears of the water meter lose contact when the speed is too high, which is an inherent limitation of the water meter itself. This is an example of the benefits obtained using AMR devices for management purposes, because they can indicate if the customer's water meter is under-fit and needs to be substituted, reducing under-billing and apparent losses.

In terms of functionality, the AquOculus AMR has tracked the water meter reading perfectly when flow is around 1.5 m^3/h=0.41 L/s (dL indicator period equal to 2.4 s). Non-cumulative reading differences observed between AquOculus AMR and the hydraulic water meter are up to a maximum of 1 L, since the sensor mechanism monitors the dL indicator (one revolution per liter). However, such a difference is negligible for billing, usually based on m^3 readings.

In the following section, future work towards system completion is discussed.

VIII. Future Work and Estimated Materials Cost

The first AquOculus AMR prototype has shown to be functional. However, various other development steps must be executed to attain TRLs 4, 5, and 6 as presented in Subsection VIII-A, Subsection VIII-B, and Subsection VIII-C. Such improvements will increase the AMR cost, however, almost all have been considered to compute the estimated AMR device cost, which is our second topic, presented in Subsection VIII-D.

A. Immediate Future Work to achieve TRL 4

The immediate work to be addressed consists in developing a more consolidated, standardized, and reproducible prototype, based on the limitations observed up to now.

As explicitly stated in Table I, AquOculus AMR current TRL level is 3, so we haven't focused yet on optimizing all subsystems. For instance, the power supply used for the functional experiments was a 5 V smartphone battery charger, which surely has to be replaced by a carefully designed circuit, considering durability, surge and electric shock protection, robustness, etc.

The installation of the flow sensor will require the development of an automatic calibration routine for the microcontroller using the dL indicator as a reference, registering how many low-flow indicator pulses correspond to each dL indicator pulse, possibly as a function of flow.

Since the AquOculus AMR device is supposed to be powered by the customer's electrical service entrance, a junction box to protect the electronic elements will be necessary.

The system will also require a backup rechargeable battery and recharging circuit because, otherwise, in case of a lack of AC power, counting would cease. In such a mode, power consumption would have to be temporarily reduced as well as communication throughput, which has to be taken into account for the next software upgrade.

Experiments showed that sunlight affects the sensor to a high degree, so a sealed overall cover for the water meter could be a solution, also working as protection against vandalism or fraud. To allow human reading, a small window shall be opened exactly over the numbering. Additionally, using ESP32 PWM signal to switch the IR LED along with band-pass filtering could improve the signal-to-noise ratio, providing improved robustness and sunlight immunity; however, this would require operational amplifiers, such as TL082, for example.

A new CAD-designed 3D printed plastic part to hold the emitter and receiver should be designed with longer and thinner holes, so that IR radiation has a narrower straight path, avoiding sunlight from reaching the phototransistor and providing a higher signal-to-noise ratio. Parts with different heights shall be produced to be chosen during installation according to the effective distance from each particular water meter acrylic cover in relation to the white background. A piece suited for each water meter model and having alignment points would certainly ease the installation process, which will inevitably require trained staff.

WDS pressure estimation is possible for customers with particular tanks, as such a variable is related to flow by a monotonically increasing function. The mathematical relation depends on the pipe section characteristics, the elevation of the tank, and the float-valve orifice area [15] (see Equation 2). The ΔZ, K, and K_p constants can be obtained automatically by a calibration algorithm using the Least Squares Method if WDS pressure estimation samples are available from a reliable hydraulic model, along with the measured tank inflows.

$$h_{WDS} = \Delta Z + Q^2 \cdot (K_p + K) \tag{2}$$

where:
h_{WDS} is the WDS pressure head in the customer derivation point (m)
ΔZ is the elevation difference between the inlet of the customer tank and the derivation point in the WDS (m)
Q is the inflow to the customer tank (m^3/s)
K float-valve coefficient $(m^{-5} \cdot s^2)$
K_p is the pipe headloss coefficient between the WDS derivation point and the inlet of the tank $(m^{-5} \cdot s^2)$

As Fig. 5 illustrates, the sensor signature signal isn't symmetric, so its waveform contains information about flow direction, which is a very important feature to diagnose problems in the operation of the WDS or even a pipe burst occurring nearby. To attain that, an appropriate algorithm shall be written using ADC1 readings from GPIO34. For instance, the one revolution signature signal from the dL phototransistor could be registered into flash memory during the calibration process using the low-flow indicator pulses as triggering for the ADC1 acquisitions; then, during normal operation, for each low-flow indicator pulse (using an interruption request routine), the quadratic difference residual between the measured and expected dL phototransistor signals could be progressively calculated; after a complete period, if the value of such residual was superior to a certain limit, then the rotation direction would be considered as reversed.

Another important feature of the signature signal is that it swings around a certain bias voltage determined by installation and water meter properties, such as the acrylic transparency, white background reflectance, and indicator dimensions, so that violation detection is possible. Indeed, attempting to remove the sensor or cutting any of the wires would result in anomalous voltages on the phototransistor output, exceeding the range registered during calibration ($\approx 1\ V\ -\ 1.7\ V$ as observed in our first prototype). For instance, if we add a high resistance pull-up resistor to the ADC1 input (GPIO33), a periodic reading of ADC1 (every 1 s, for example) would be enough to detect the following events:

- 3V3 or GND wire cut - the IR Led would be turned off, causing the phototransistor to be in cut-off state, so ADC1 would measure 3.3 V;
- Phototransistor output wire cut - the pull-up resistor would cause ADC1 to measure 3.3 V;
- Frontal water meter cover removal - external additional light would reach the phototransistor, causing the ADC1 to measure a voltage inferior to the minimum observed during calibration (less than 1 V, for example);
- Sensor removal - under daylight, the symptom would be as in the previous case; at night, the phototransistor wouldn't receive the reflected IR radiation, then ADC1 would measure around 3.3 V.

Once all of these improvements are executed, and an easily reproducible and more complete prototype is achieved, it must be submitted to the evaluation of a specialized laboratory to certify the metrological behavior under different water flow ranges, and for different water meter models. Volume, flow, and estimated WDS pressure measurements must be characterized in comparison to standard professional equipment. The evaluation should also include other main features: electric shock and surge protection, autonomy without AC power supply, sunlight immunity, negative flow detection, and violation detection. As a result, the project maturity will become consistent with TRL 4.

B. Medium-Term Future Work to achieve TRL 5

After the laboratory certification, the next step consists of the production and installation of a significant amount of the AquOculus AMR devices for validation in a relevant environment defined along with the water distribution company to test the AMR devices' ability to establish an AMI. Their behavior under communication failure, system expansion, energy breakdown, violation attempt, and negative flows must be assessed for the integrated system, identifying communication parameters as throughput, latency, and packet loss, characterizing the achievement of TRL 5.

As a prerequisite to that, communication software must be upgraded based on the adoption of an appropriate Wireless Mesh Network protocol [16] [17] [18] [19]. Such a network must efficiently integrate the AMR devices and available Wi-Fi internet networks from the water company buildings or even the customers', by agreement. Taking advantage of proximity in urban environments, data would flow through the very AMR devices in various parallel dynamic paths towards the available internet gateways, providing resilience, as illustrated in Fig 10. Also in that context, the ESP32 software shall be improved using the Espressif IDE libraries, providing more reliable and efficient data transmission.

C. Later Future Work to achieve TRL 6

The final steps towards system completion involve demonstrating the integration of the AMR devices with the main server software to be developed for system management and LDL. It's important to note that in the context of LDL, a customer's consumption flow is usually designated as customer demand.

The main server software must access database information about all registered customers, including their ID, geographical coordinates, elevation, water meter model, AMR battery health, consumption statistics, current water consumption volume (m^3), dated warnings log (violation, reverse flow, suspected fraud, water meter undetfitting, AC power outage, low battery and customer property leakages), particular tank identified, the three WDS pressure function parameters, and demand measurements. The database shall also store WDS elements' information as inflows from reservoirs, tanks' levels, pumps' operation logs, valves' operation logs, and pressures in the output of these elements, as measured by specific instrumentation. A database software module must control data storage based on the maximum storage time period set by the system administrator.

Such database information is important for various management purposes, such as: billing, conscious use of water, reduction of customer internal property leakages, reduction of fraud, system maintenance (water meter substitution, AMR repair or battery substitution), reduction of real losses through WDS pressure control, reduction of apparent losses through intermittent supply [15], system operation improvement, and LDL

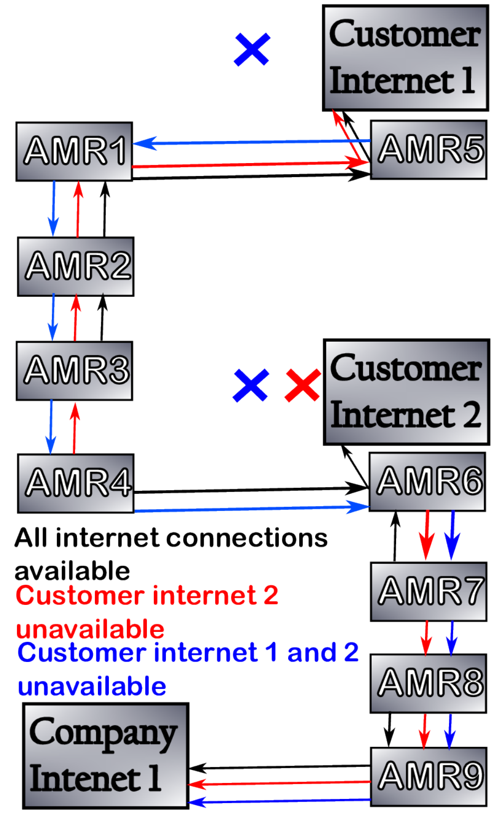

Fig. 10. Illustration of various data paths according to available internet connections.

The WDS model is usually developed using a simulation software such as EPANET[9] for LDL. Database information is used as input to characterize the model. WDS model nodes are associated with real system elements (and respective properties/measurements): customers (geographical coordinates, elevation, demand), reservoirs (hydraulic head), and tanks (elevation, dimensions, level). Similarly, WDS model links are associated with pumps (operational curve, on/off status), and valves (specific control parameter depending on type, on/off status).

Once such data is input to the WDS model, the numerical computation algorithm behind EPANET enables the simulation of the system's expected behavior, which is the foundation for model-based LDL. The comparison between the WDS model simulated pressure values and the real system measured pressures, for example, is one of the most explored strategies in the literature for LDL. It's also important to note that, as online demand data using AMR has not usually been considered in the literature on WDS LDL, demand data is frequently estimated based on total system inflow, through a demand calibration process, which must be periodically executed, to take system expansion into account. Considering that, AquOculus represents an important contribution, dismissing

[9]https://www.epa.gov/water-research/epanet

demand estimation, allowing real-time system loss calculation (in place of annual water balance), and also providing WDS pressure measurements.

Software-based LDL in WDS is a vast research field, also including data-driven and mixed model-based/data-driven approaches. For a comprehensive understanding, it's important to read the most complete and recent systematic literature reviews on the topic [6] [20].

The main server management software is then expected to display the WDS model graphical representation along with operational warnings, also including eventual leak localization points. Based on that, a priority ordered task list would be generated, guiding efficient actions and ultimately providing sustainable WDS management.

To achieve TRL 6, the management software must be developed, demonstrating its functionalities when integrated to the AMR devices and other WDS elements.

D. Estimated AMR Cost

Considering the materials used in the prototype as well as the ones for the improvements of Subsection VIII-A, the estimated AMR cost was calculated in Table II. However, other minor cost materials would be necessary, such as the printed circuit board, cables, and connectors, probably not exceeding a total US$ 16.74 price. Note that the AMR device comprises only the local elements for individual customer monitoring, as the sensor element, the power supply, and the electronic circuitry for processing and data communication. The costs of additional AMI elements, such as LoRa gateways or cloud storage (offered by some commercial solutions), for example, are not included, as they aren't required by the AquOculus system.

Once the customer's AC power supply is used, an additional important strategy to reduce costs is to use AquOculus AMR devices to register electrical energy consumption using phototransistors to capture pulses. That is perfectly viable, once modern electrical energy meters provide optical pulse outputs, with a typical 1 pulse per Wh ratio. Doing that, electrical energy distribution companies can benefit and divide costs as well. Other works in the literature also consider such an integrated strategy [21]. In our specific case, however, low cost is extremely emphasized by leveraging existing water and electrical energy traditional meters, making large-scale implementation viable, especially for developing countries.

Once the battery and recharging circuit represent not only economic, but also environmental important costs, alternative solutions based on self-powered AMR devices shall still be further considered [22] [23].

In this section, we made it clear that AquOculus is currently in TRL 3, requiring several improvements and developments for consolidation. It's necessary to improve the original prototype, also for reproducibility, so that it can be submitted to the certification of a specialized laboratory, under adequate hydraulic conditions, assessing reliability and metrological characteristics, to achieve TRL 4. Then, various AquOculus AMR devices must be produced and validated in a relevant urban environment to evaluate the AMI capabilities, so that TRL 5 can be achieved. Finally, as a requirement to reach an integrated system demonstration (TRL6), we discussed the need to develop a management-oriented software application that gathers data from the AMI into a database, displaying system model graphical representation, and generating maintenance priority ordered task lists. The management software must include a LDL module indicating the geographical location of detected leaks, which is also a challenging development to be addressed.

TABLE II
AQUOCULUS UNIT AMR HARDWARE MATERIALS ESTIMATED COST (SHIPPING CONSIDERED FOR THE PRODUCTION OF 1000 DEVICES, 2025/10/23)

Item	AliExpress Cost	DigiKey Cost
ESP-WROOM-32: microcontroller module with Wi-Fi	US$ 2.80	US$ 1.90
LM393: Dual Comparator for Schmitt Trigger circuits	US$ 0.15	US$ 0.03
BC548 (4 units): NPN transistor for PWM switching and tone decoding	US$ 0.08	US$ 0.28
TL082 (2 units): Dual AmpOp IC for bandpass filters, to improve robustness in relation to sunlight	US$ 0.48	US$ 0.30
Resistors (13 units): General use	US$ 0.65	US$ 0.13
TIL32 (2 units): 3mm 940 nm IR LED	US$ 0.14	US$ 0.56
TIL78 (2 units): 3mm 940 nm IR phototransistor	US$ 0.14	US$ 0.18
Capacitors (8 units): General use	US$ 0.2	US$ 0.72
IP67 sealed junction box: Circuits protection	US$ 3.00	US$ 3.33
LIR2032: 3.6 V rechargeable lithium ion battery	US$ 0.60	US$ 4.75
LIR2032 recharging circuit	US$ 1.92	US$ 1.92 (not found)
TOTAL	**US$ 10.16**	**US$ 14.10**

In the next section, we conclude and provide the online repository link for Aquoculus software.

IX. CONCLUSIONS AND DATA AVAILABILITY

This article presented the AquOculus AMI system, an under-development cost-effective solution focused on providing data for sustainable WDS management, with special focus on LDL.

In terms of factual achievements, TRL 3 was reached. The proof-of-concept experiment using 1.5 $\mathrm{m^3/h}$ flow rate (dL indicator period equal to 2.4 s) indicated the AMR prototype's ability to correctly track the volume registered by an ordinary water meter. Such data was visualized in the server application, to which the prototype communicated through Wi-Fi, using the HTTP protocol. The optical sensor, inverting Schmitt Trigger comparator, and automatic reference voltage calibration process worked as expected. However, the prototype presented sunlight susceptibility and installation difficulties. It was observed that the phototransistor signature signal characteristics enable reverse flow detection and violation detection, even though the software for that wasn't implemented in this work.

The software application developed corresponds to the installer technician interface and only communicates with a single AMR prototype, featuring very basic functions.

Future work demands prototype improvements, also for reproducibility; submission to the certification of a specialized laboratory; AMI capabilities validation in a relevant environment; and the development of a management-oriented main server application, including a leak detection and localization module. The AMR device cost, added with flow sensor, rechargeable battery, sunlight immunity improvement circuit, and circuit protection junction box, was estimated as inferior to US$ 16.74.

The key features of AquOculus are related to the leveraging of existing water meters, customers' electrical service entrances, and the AMR devices that would also function as AMI. The sensor applicability is broad, not requiring that the monitored indicator have specific color, metallic, or magnetic parts. Unlike other solutions, AquOculus is intended to provide volume, flow, and WDS pressure measurements, detecting reverse flow and violations.

Robust power source for high data throughput, flow and WDS pressure measurements, and reverse flow detection are essential AquOculus features to attain LDL, which is the most complex management task in a WDS.

Despite the current project's maturity level, in this article, we conceptually explained the characteristics intended for the complete system to overcome the limitations in existing academic and commercial solutions. The reduced system cost and advantageous features focused on LDL can boost AMI to become a reality, especially for developing countries, where the expenses on additional infrastructure are prohibitive. The real implementation of such a system would have a great impact on sustainable water management, reducing water loss worldwide.

Further studies shall contribute to the development of the complete solution, so that it can, in fact, be massively implemented, considering the continuously lower costs of electronic devices and sensors. As an initial point for researchers interested in testing or upgrading this work, the ESP32 firmware and server application are available at Github: https://github.com/matheuspilotto/AquOculus, where additional instructions are given.

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