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Research paper

Laboratory appraisal of measurement electrodes for a wet circuit in closed channels

Tomasz Sionkowski[1], Wiktor Halecki[2], Krzysztof Chmielowski[3]

Abstract: The research aimed to develop, construct, and evaluate a device for measuring voltage dynamics in wet circuits. This involved assessing fluctuating voltage levels at varying depths within specialized columns, revealing the intricate interplay between probing equipment and aquatic environments. Regression analysis highlighted a nuanced correlationcm between water levels and electrode voltage, particularly within the initial 10 cm of immersion. Key outcomes included the examination of materials suitable for sensor construction, such as crusted gold and cuprum, and the refinement of methodologies for electrode measurement and data transmission to central systems, with a focus on open channels. Utilizing these insights, a wet circuit was engineered to enhance the operational efficiency of sewage systems, allowing real-time monitoring of water quality and leak detection. The water level measurement device holds significant potential for widespread adoption in municipal facilities, offering streamlined monitoring capabilities and aiding in the optimization of sewage system integrity and functionality, especially in confined channels serving sewage and stormwater systems.

Keywords: engineering materials, experimental procedure, sewage infrastructure, measurement water precision

[1]PhD., Eng., Grundfos Pompy Ltd., Klonowa Street 23, 62-081 Przezmierowo, Poland, e-mail: sionkowski@poczta.onet.pl, ORCID: 0009-0009-8101-8766
[2]PhD., Eng., Institute of Technology and Life Sciences - National Research Institute, Falenty, Al. Hrabska 3, 05-090 Raszyn, Poland, e-mail: w.halecki@itp.edu.pl, ORCID: 0000-0001-7802-2849
[3]Prof., DSc., PhD., Eng., AGH University of Science and Technology, Department of Natural Gas Engineering, Faculty of Drilling, Oil and Gas, Al. A. Mickiewicza 30, 30-059 Cracow, Poland, e-mail: chmielowski@agh.edu.pl, ORCID: 0000-0001-9758-0854

1. Introduction

The monitoring of failures and detection of issues related to wastewater constituted a pivotal element in ensuring the effective management of sewage infrastructure and environmental protection [1]. Contemporary technologies offered an array of tools and systems enabling swift detection of failures and monitoring the condition of sewage networks [2]. The approach to new technologies was comprehensive and reflected a strategic vision for economic and societal modernization, harnessing technological advancements for growth and innovation [3]. Water utility companies strived to delineate protective zones around pipelines, although specific guidelines were lacking. Analyses demonstrated the impact of parameters such as pressure and groundwater levels on the timing and location of water leakage [4]. Following research, the effectiveness of methods and devices in detecting damages within the water distribution system and progress in implementing new technologies could be objectively evaluated. Water main failures resulted in water and economic losses and posed a safety threat [5]. Additionally, the development of new technologies also allowed for a better understanding of processes occurring within water distribution systems, enabling more precise forecasting and response to potential hazards [6–9]. Utilizing advanced monitoring systems enabled faster detection of potential problems, leading to more effective management and minimization of adverse impacts of failures on local communities and the environment [10]. It was also worth noting that investments in modern technologies could contribute not only to improving operational efficiency but also to enhancing the resilience of water systems to changing environmental conditions and challenges associated with climate change [11, 12]. Improving monitoring and management of water infrastructure using advanced technologies could significantly reduce the risk of failures and water losses, contributing to sustainable water resource management [13]. The application of pressure, flow, and water quality monitoring sensors allowed for real-time analysis of parameters in sewage systems [14]. These systems were capable of automatically detecting irregularities, such as leaks, excessive flow, or undesirable changes in the chemical composition of wastewater [15–19]. Additionally, advanced telemetry systems enabled remote monitoring and management of sewage networks, allowing for prompt response to failures or potential threats [20–25]. These systems were often equipped with alarm notification systems, informing relevant services of any abnormalities in real-time [26–28]. The implementation of modern failure monitoring and wastewater issue detection technologies not only minimized the risk of serious incidents but also allowed for prompt intervention and repair, contributing to maintaining a high standard of environmental safety and ensuring the efficient operation of sewage systems. The study aimed to achieve the following objectives: 1) to assess the suitability of materials for measuring water immersion in wet circuits, and 2) to evaluate electrode performance in relation to water level. This study on measurement electrodes in wet circuits within closed channels might be a significant development in Poland, possibly the first application of such a device in the country.

2. Materials and methods

2.1. Assumptions for constructing the research setup

The research setup at the Department of Sanitary Engineering and Water Management, meticulously crafted within the laboratory-prototype facility, stands as a testament to technological sophistication at the Faculty of Environmental Engineering and Land Surveying, University of Agriculture in Krakow. It encompasses a diverse array of meticulously designed components aimed at facilitating comprehensive experimentation and analysis in water management and engineering. The research station comprises a robust supporting structure for stability, an engineered chamber designed for water level elevation equipped with state-of-the-art instrumentation for simultaneous observation and data collection, and an efficient pumping system tailored to ensure precise and reliable handling of the test liquid. Furthermore, an innovative electronic system utilizing Raspberry Pi technology for measuring analog signals with unparalleled accuracy and efficiency has been integrated. Carefully selected and calibrated, a comprehensive set of measurement electrodes ensures optimal performance across various conditions. Moreover, an integrated power supply system guarantees uninterrupted operation, seamlessly powering all components.

2.2. Submersion step analysis and electrode measurement error reduction

The study delved into measuring the conductivity of direct current within a system of copper electrodes immersed in water, as illustrated in Figure 1. This investigation was meticulously carried out utilizing an experimental setup featuring both copper and aluminum electrodes. The water under scrutiny exhibited a Total Dissolved Solids (TDS) value of 194 ppm, with a measurement accuracy of ±10% F.S. at 25°C. Probes were strategically positioned within a transparent cylinder, facilitating observation in a closed system configuration.

To execute this experiment with precision, our laboratory leveraged probe-connected breadboard technology alongside Raspberry Pi microcomputers, as depicted in Figure 2. Measurements were meticulously recorded at varying levels of probe submersion, precisely spaced at 10 cm intervals. Dat a collection involved capturing an average of 3–4 readings per second over several minutes for each submersion level, ensuring comprehensive analysis of conductivity trends. For material selection, etching of Cu PCB probes was undertaken in an iron chloride aqueous solution (Fig. 3). Notably, the maximum submersion depth reached 80 cm for a 1-meter-long probe (Fig. 4). Electrodes with the icrsyted with golds material - AU number were measured, and statistical modeling was performed on a total of 150 selected samples for laboratory analysis. Additionally, comprehensive Pearson correlation analyses of all electrode areas were conducted using Statistica software version 13.1 to gain an understanding of conductivity measurements and electrode performance. This commitment to thorough scientific inquiry and data analysis propels our efforts to advance knowledge in water management and engineering.

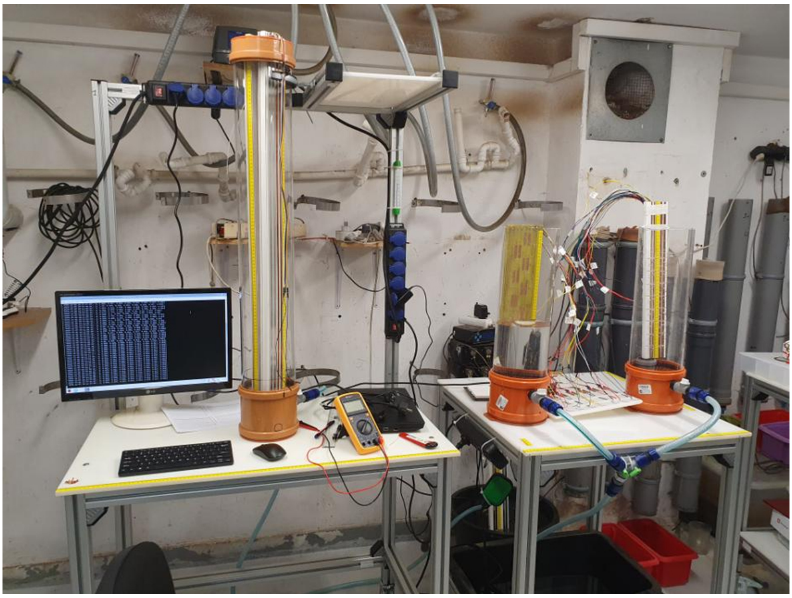

Fig. 1. Laboratory testing station

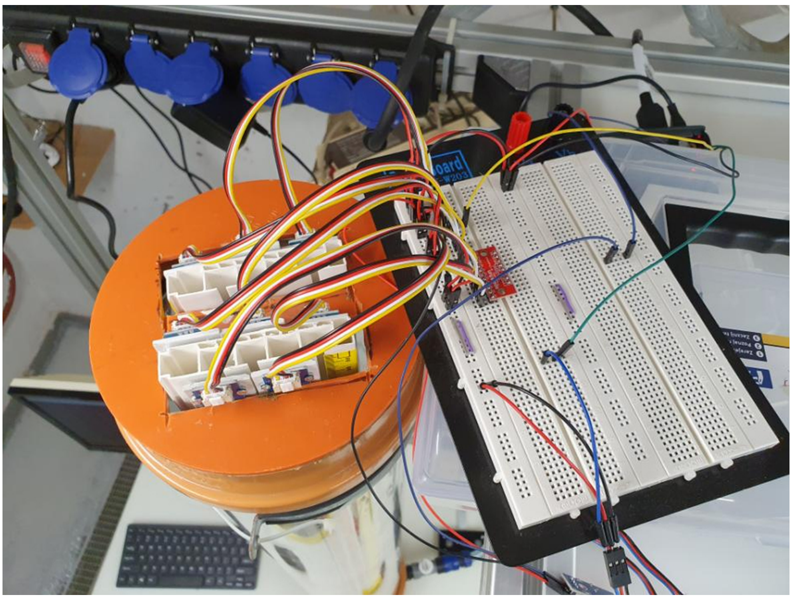

Fig. 2. Probe-connected breadboard

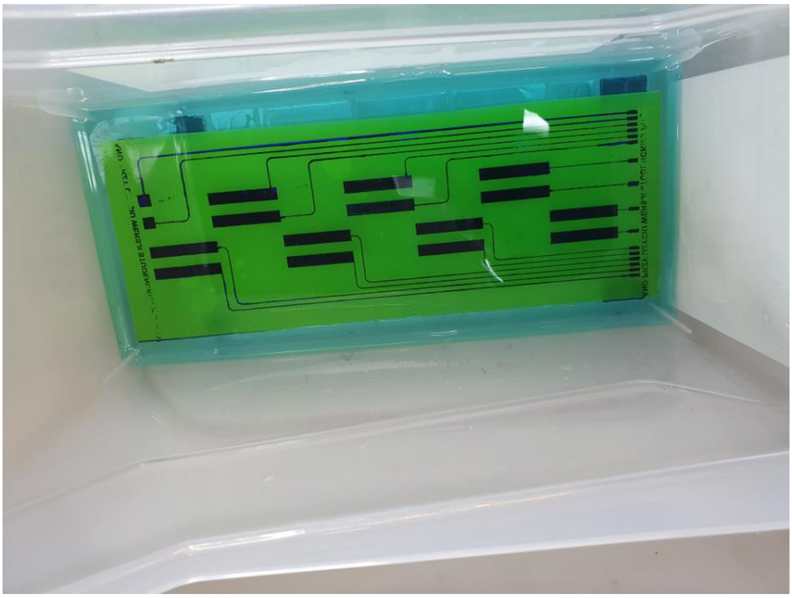

Fig. 3. Material selection example: etching of Cu PCB probe in iron chloride aqueous solution – fully etched copper surfaces visible (phase after 40 minutes)

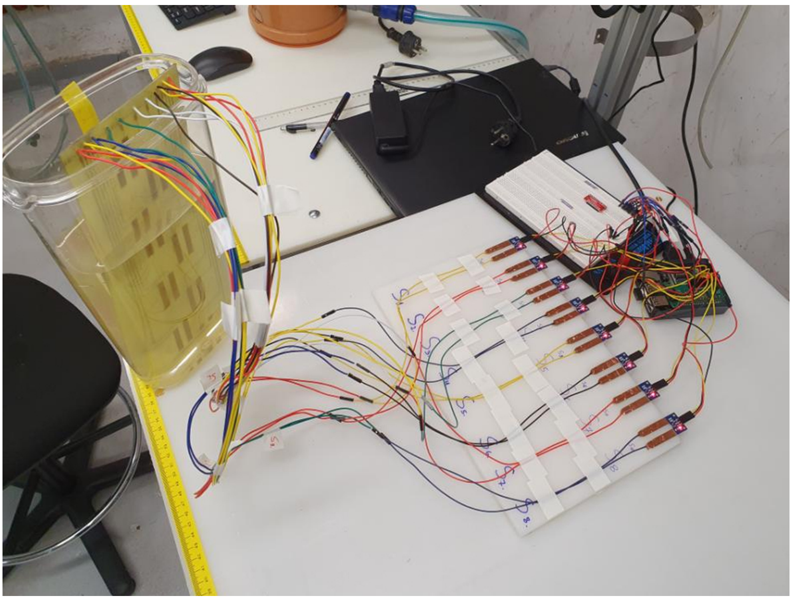

Fig. 4. Water level measurement using PCB-based probes

3. Results

Voltage measurements were conducted utilizing a finely crafted Cu 2×10 mm probe, characterized by a precise 5 mm gap, and meticulously submerged in water maintained at a consistent temperature of 18°C. The intricate readings unveiled a fascinating narrative of voltage dynamics, wherein the voltage reached its zenith at a depth of 2 cm beneath the water's surface. Beyond this depth, a gradual increment in voltage was observed, culminating in a steady state at 1.5 V beyond 5 cm. However, the voltage fluctuations did not cease there; rather, it unfolded with nuanced intricacy. Between the depths of 10 and 80 cm, the voltage exhibited a captivating variability, oscillating within the range of 1.55 to 1.7 V (Fig. 5). Delving deeper into the depths, the narrative of voltage changes continued to unfold, revealing intriguing nuances. Between the critical depths of 5 and 10 cm below the probing surface, voltage fluctuations ranged from a mere 0.02 V to a perceptible 0.16 V, offering a glimpse into the subtle yet consequential variations occurring within the aquatic environment. Notably, at the depth of 15 cm, the measured voltage changes remained constrained, not surpassing the diminutive threshold of 0.02 V, as illustrated in Figure 6. These captured voltage dynamics not only provide insight into the intricate interplay between the probing apparatus and the aqueous environment but also serve as a means to monitor water quality, showcasing the precision and sensitivity of the measurement techniques employed. Such detailed insights pave the way for a deeper comprehension of the underlying mechanisms governing voltage fluctuations in aquatic settings, thus enriching our scientific understanding of this complex phenomenon.

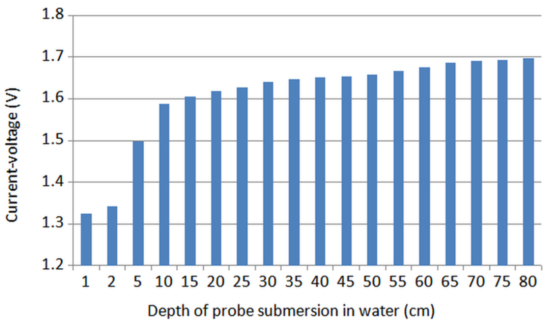

Fig. 5. Current-voltage for probe immarsed in water

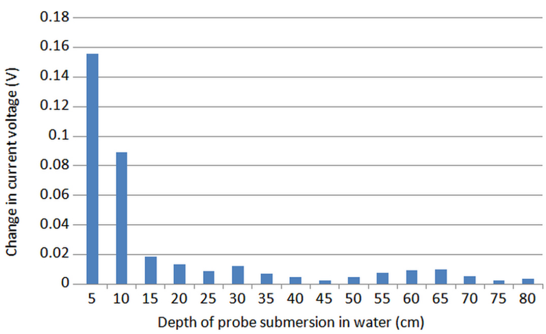

Fig. 6. Change in current-voltage for probe immarsed in water

Correlations between probes AU8 and AU7 were notably reduced at the highest level, with an R-value of 0.98 (Fig. 7), and for AU6, it stood at 0.89 (Fig. 8). This suggests that as voltage values decreased for AU8, they concurrently increased for the other probes. Likewise, the declining trend in AU8 values corresponded with those of AU5 (Fig. 9), AU4 (Fig. 10), and AU2 (Fig. 12). While AU3 (Fig. 11) and AU1 (Fig. 13) displayed increased values, the rise in AU8 and its magnitude of change were relatively minor, implying an overall correlation of voltage values. Additionally, it's noteworthy that for AU8, the determination coefficient R^2 experienced a substantial increase to 0.95 as the depth of the probe increased. This observation underscores AU8's potential as a dependable indicator for analyzing correlations with other probes employed throughout the study, further emphasizing its significance in understanding the convoluted interrelationships within the experimental setup.

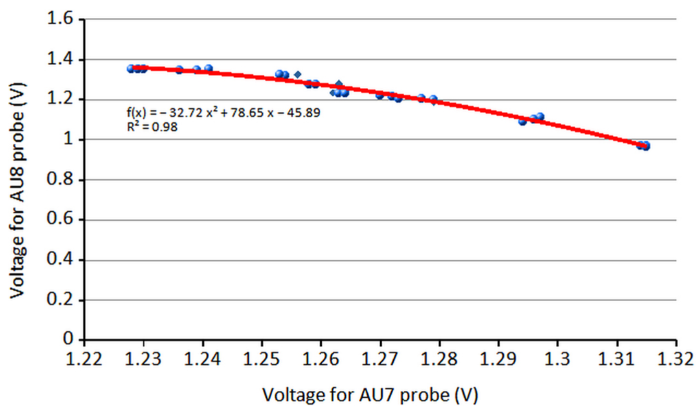

Fig. 7. Quadratic regression model and linear correlation between the control probe AU8 and AU7

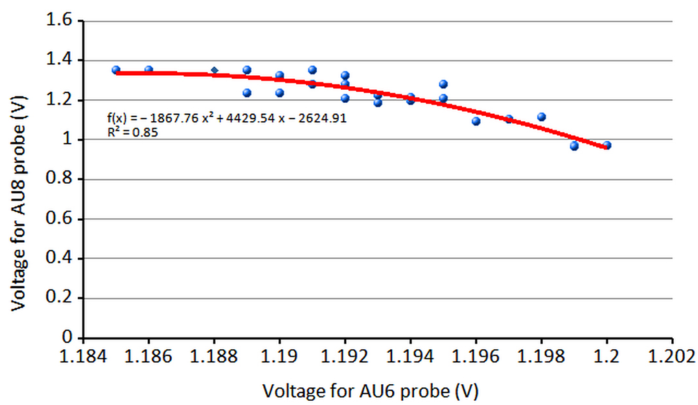

Fig. 8. Quadratic regression model and linear correlation between the control probe AU8 and AU6

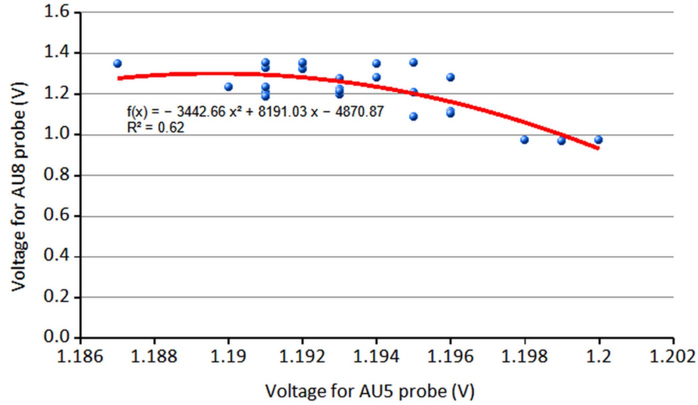

Fig. 9. Quadratic regression model and linear correlation between the control probe AU8 and AU5

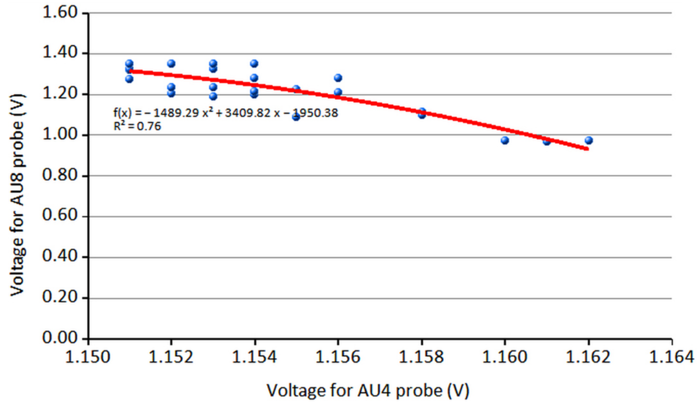

Fig. 10. Quadratic regression model and linear correlation between the control probe AU8 and AU4

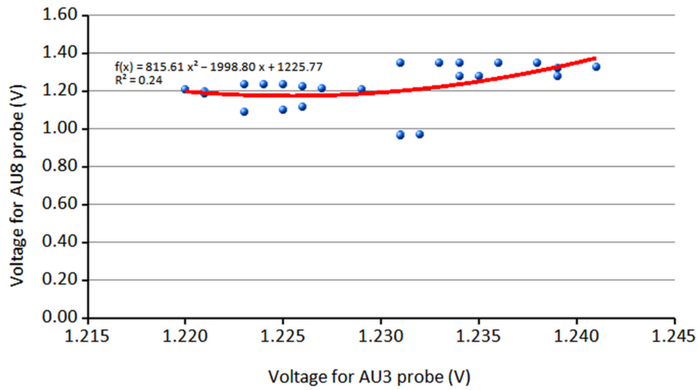

Fig. 11. Quadratic regression model and linear correlation between the control probe AU8 and AU3

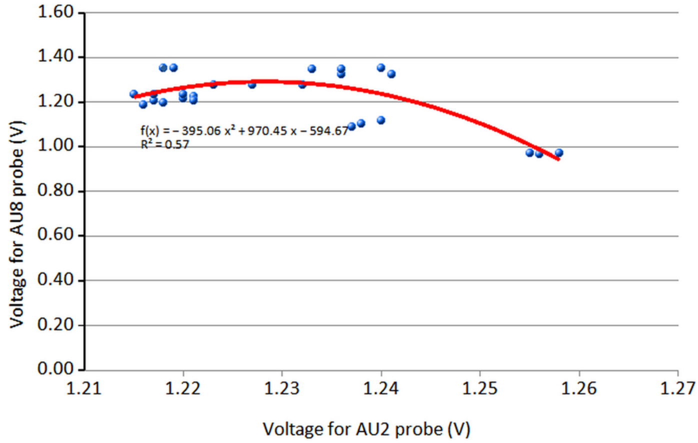

Fig. 12. Quadratic regression model and linear correlation between the control probe AU8 and AU2

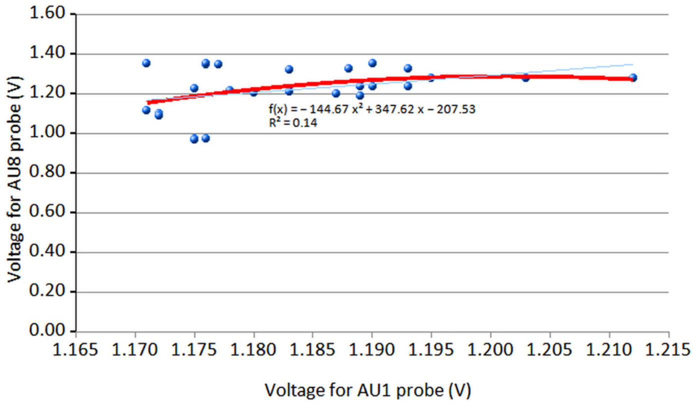

Fig. 13. Quadratic regression model and linear correlation between the control probe AU8 and AU1

4. Discussion

Additional analyses have unveiled the development of an innovative system tailored for detecting leaks within water distribution networks and conducting precise flow control experiments [29]. This system operates by leveraging pressure measurements within the network, automatically pinpointing leaks through a meticulously calibrated hydraulic model [30]. The project's solutions encompass a spectrum of features, including automated data collection and analysis, remote valve control capabilities, and advanced numerical simulations. Water losses within distribution networks often escalate to concerning levels, necessitating thorough analysis and modernization to attain cost-effective improvements [31]. For example, an assessment of losses at four water treatment plants in the Silesian Voivodeship revealed a range from 9% to approximately 27% of the water supplied to the network. With the adoption of sophisticated flow and pressure monitoring systems, one of the scrutinized installations succeeded in reducing losses by a commendable 10% over a span of five years [32].

Effective water management crucially hinges on precise measurement and continual monitoring of water volumes within distribution networks. Traditional methods frequently fall short in providing real-time data and accurate measurements, leading to operational inefficiencies and substantial losses [33]. However, recent technological strides, notably in electrode-based volume detection systems, offer promising avenues to elevate water management practices. Electrode-based volume detection systems operate on the fundamental principle of electrical conductivity [34]. As water courses through a pipe, it acts as a conduit, allowing electrical signals to traverse. By strategically deploying electrodes at key points along the pipeline, these systems can meticulously gauge changes in electrical conductivity, effectively correlating them with water volume fluctuations. Pearson correlations between probes AU8 and AU7 were notably reduced at the highest level, with an R-value of 0.98 (Fig. 7), indicative of a robust inverse relationship between the voltage values recorded by these probes. This suggests a sophisticated interplay between AU8 and AU7, where as voltage values decreased for AU8, they concurrently increased for AU7, and vice versa. Moreover, the correlation coefficient of 0.98 underscores a high degree of statistical significance, affirming the reliability of this observed relationship. Moreover, the correlation between AU8 and AU6, as depicted in Figure 8, remained substantial at 0.89, albeit slightly lower compared to AU8 and AU7. This implies a moderate yet discernible association between the voltage readings of these probes. The declining trend in AU8 values, as evidenced by the figures, corresponded with those of AU5 (Fig. 9), AU4 (Fig. 10), and AU2 (Fig. 12), highlighting a coherent pattern across multiple probes. These findings underscore the intricate dynamics within the system under study, wherein fluctuations in voltage values across different probes exhibit synchronized trends. Such nuanced correlations offer valuable insights into the underlying processes and interactions governing the behavior of these probes, thereby enriching our understanding of the phenomenon at hand. Another study focused on detecting illegal waste discharges into sewage systems, particularly from clandestine sources. Various electrodes exhibited promise in identifying different waste types in both static and dynamic sewage conditions, indicating potential for detecting illegal discharges [35]. Unlike conventional methods reliant on manual readings, electrode-based systems provide continuous, real-time monitoring [36]. Operators can swiftly detect leaks, unauthorized usage, or anomalies, enabling proactive intervention [37].

Direct measurement of electrical conductivity ensures high accuracy and precision in volume detection [38]. Even minor flow fluctuations can be detected, facilitating early leak identification and remediation using a machine learning approach [39]. While initial installation costs may exceed traditional methods, electrode-based systems yield long-term savings. Reduced water losses, minimized operational downtime, and optimized resource allocation contribute to cost-effectiveness over time. Highly scalable, these systems adapt to diverse pipeline configurations and sizes [40]. Whether integrated into existing infrastructure or deployed independently, they suit urban and rural water networks alike. Moreover, the susceptibility of electrodes to fouling or corrosion over time can lead to inaccurate readings, undermining the reliability of the system. Additionally, reliance on consistent electrical infrastructure for operation makes electrode-based systems vulnerable to disruptions in power supply, further complicating their effectiveness in detecting and mitigating water waste. Despite these challenges, overcoming limitations and enhancing the efficacy of electrode-based systems requires a concerted effort to improve calibration processes, mitigate fouling and corrosion risks, and bolster electrical infrastructure resilience. By addressing these challenges and integrating complementary technologies and practices, water utilities can optimize the performance of electrode-based volume detection systems and advance their capabilities in managing water waste effectively.

5. Limitations of the study and future recommendations

Water consumption plays a critical role in the effective planning and operation of water supply systems [41]. Comprehensive management of stormwater drainage within urban planning is essential for mitigating flooding risks and improving overall water management, thereby supporting sustainable development and resilience against future challenges [42, 43]. Furthermore, employing methods to identify cause-and-effect relationships is crucial for advancing sustainable development and achieving the goals of a circular economy. The deployment of electrode-based volume detection systems heralds a remarkable breakthrough in the battle against water wastage. Yet, as with any innovation, it confronts inherent limitations that demand attention. While excelling in pinpointing leaks within water distribution networks, these systems encounter challenges in identifying other forms of waste, such as inefficient usage or unauthorized consumption. Their reliance on conductivity changes, while effective, may not encapsulate all instances of water wastage. Additionally, the inability to discern between different types of waste impedes targeted mitigation efforts. Moreover, the effectiveness and dependability of electrode-based systems hinge heavily on the quality and maintenance of existing network infrastructure. Thus, the quadratic regression model and the linear correlation between the control probe AU8 and water depth yielded an R^2 value of 0.95 (Fig. 14). Outdated or poorly maintained networks may compromise detection capabilities, limiting their overall impact on reducing water waste. Despite these hurdles, a comprehensive approach to water monitoring necessitates the integration of complementary technologies, robust water policies, and efficient practices. Calibration demands, susceptibility to fouling or corrosion, and periodic maintenance requirements require vigilant attention, especially in closed channels. Furthermore, ensuring data security remains paramount, particularly with the integration of smart metering technologies. Electrode-based volume detection represents a transformative advancement in water management, offering real-time monitoring, precision, and cost-effectiveness for closed channels. By leveraging cutting-edge technology, utilities can optimize efficiency, minimize losses, and foster sustainable water management practices. Continued research, innovation, and collaboration are imperative to overcome challenges and fully unleash the potential of these systems in advancing water sustainability engineering goals.

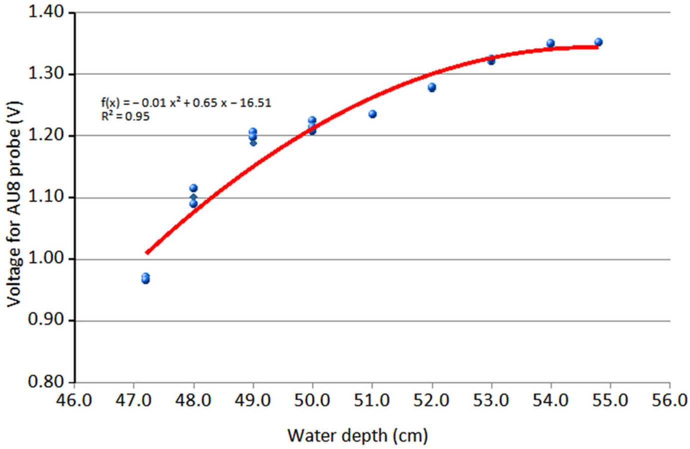

Fig. 14. Quadratic regression model and linear correlation between the control probe AU8 and water depth

6. Conclusions

The laboratory research has led to the development of a specific device, namely a sensor band, designed for measuring wetting circuits in closed channels. Through conducted studies, specific parameters for the electrodes, including material and shape of the measurement probes, have been established. It is recommended to incorporate protection for the measurement probes in the form of gold plating, ensuring long-term and accurate operation of the wet circuit. Additionally, utilizing electrodes with a width of 5 mm and a distance of 5 mm between them is proposed. Moreover, it is suggested to equip the band with several measurement electrodes for one circuit, preferably 8 electrodes, with the length determined by the measurement circuit itself. The obtained results will enable the optimal adjustment of the future shape of the wet circuit. It is believed that this device will significantly support the work of municipal utilities in identifying channels allowing rainwater infiltration during rainfall. This newly validated laboratory data for wet circuits offers measurements no. directly within the channel, eliminating the need to enter, collect, and analyze data separately.

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Ocena laboratoryjna odpowiedniego doboru elektrod pomiarowych do oceny obwodu zwilżonego w kanałach zamkniętych

Słowa kluczowe: infrastruktura kanalizacyjna, inżynieria materiałowa, precyzyjny pomiar wody, procedura eksperymentalna

Streszczenie:

Badanie miało na celu stworzenie urządzenia do dokładnego pomiaru napięcia w systemach obsługujących zamknięte kanały ściekowe i deszczowe. Oceniano poziomy napięcia na różnych głębokościach i pokazano, jak sprzęt pomiarowy współdziała z wodą. Analiza wykazała, że poziom wody wpływa na napięcie elektrod, zwłaszcza w pierwszych 10 cm po zanurzeniu opaski pomiarowej. Kluczowe wyniki obejmowały wybór materiałów na czujniki, takich jak złoto i miedź. Na podstawie tych wyników stworzono obwód, który poprawia efektywność systemów kanalizacyjnych, umożliwiając monitorowanie jakości wody i wykrywanie wycieków w czasie rzeczywistym. Urządzenie to ma duży potencjał do zastosowania w miejskich systemach kanalizacyjnych, pomagając w ich optymalizacji i utrzymaniu.

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