applied sciences

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Remote Water Quality Monitoring System for Use in Fairway Applications

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Abstract: In the context of climate change, there is a growing need for accurate, real-time data on water quality in river waterways. This results in the development of advanced monitoring systems. This article presents a remote water quality monitoring system designed specifically for use in inland waterways, the basic elements of which are placed in a buoy with an IoT unit. The proposed system uses a network of sensors strategically placed along the waterway to continuously measure critical parameters: temperature, pH, dissolved oxygen, and conductivity. Various compatibility, efficiency, and ease-of-use tests have been conducted to verify each aspect of the monitoring system. It has been shown that the sensors operate within the intended accuracy ranges. The central unit equipped with a GSM (Global System for Mobile Communications) module can wirelessly transmit data to a main server, enabling remote access and analysis via a user-friendly interface of the developed application. The paper details the technical architecture of the system, the integration of GSM technology to ensure reliable data transmission, and the results of the monitoring studies of the proposed parameters. The remote monitoring system offers significant benefits in terms of early detection of pollution events, ensuring the safety of aquatic life, and supporting sustainable navigation practices. The research results highlight the potential of GSM-based remote monitoring systems to revolutionize water quality management in waterways in various regions.

Keywords: remote water quality monitoring; environmental sensors; data transmission; Internet of Things

Citation: Staude, M.; Brożek, P.; Kostecka, E.; Tarnapowicz, D.; Wysocki, J. Remote Water Quality Monitoring System for Use in Fairway Applications. *Appl. Sci.* **2024**, *14*, 11406. https://doi.org/10.3390/app142311406

Academic Editor: Vassilis Inglezakis

Received: 9 November 2024
Revised: 2 December 2024
Accepted: 6 December 2024
Published: 7 December 2024

1. Introduction

Water covers approximately 70% of the Earth's surface, yet less than 2% of this is utilized by humans for consumption and use [1,2].

Maintaining high water quality standards is crucial, particularly in the case of waterway applications, which include rivers, canals, and coastal areas. Water quality primarily impacts the health of aquatic ecosystems, but it also affects public safety [3–5]. Traditional water quality monitoring methods, which often rely on manual sampling and laboratory analyses, are labor-intensive, time-consuming, limited in spatial coverage, and, most importantly, do not provide real-time data.

The environmental disaster on the Oder River in Poland during the summer of 2022 [6], which led to the mass die-off of fish and other wildlife across several hundred kilometers of the river, is a significant example of insufficient information about water quality and the lack of effective preventive measures. In response to such challenges, the development and implementation of remote water quality monitoring systems, particularly in the context of the Internet of Things (IoT) [7–10], have become increasingly important. These systems utilize advanced sensor technologies and real-time data transmission capabilities, enabling continuous monitoring of key water quality parameters such as pH, dissolved oxygen, turbidity, temperature, and conductivity.

A particularly effective approach involves integrating Global System for Mobile Communications (GSM) technology, which provides a reliable and extensive communication network that facilitates data transmission from remote monitoring stations to central databases [11–14]. This enables near-real-time water quality monitoring and immediate alerts about any deviations from established standards. An example of such a solution is a remote water quality monitoring system based on an autonomous buoy, where water parameters are measured, and data are transmitted to a central server using GSM technology. This system employs innovative components, offering a robust and scalable solution that overcomes the limitations of traditional monitoring methods [15–17], providing fast and practical insights into water quality conditions.

The main component of the system, housed in the buoy, has been designed to allow operation and maintenance by personnel without specialized scientific qualifications while delivering high-quality data. The system ensures autonomy through hardware and software solutions for powering the central unit, including sensors. The modular design of the buoy's components makes them easy to maintain and operate. Furthermore, an algorithm for system operation has been developed, and sensors have been selected to allow easy replacement, enabling the monitoring of various water quality parameters. An application has also been created for monitoring, analyzing, and visualizing measurement data, further enhancing the system's functionality. These solutions make this system an efficient and modern approach to water quality monitoring, tailored to the needs of both scientists and practical users.

A remote water quality monitoring system surpasses traditional measurement methods, which typically rely on two approaches: sample collection for laboratory analysis or field tests using specialized, expensive probes. Traditional methods are limited to one-time sampling, making it difficult to monitor changes over time. In the case of laboratory analysis, samples are transported to research centers, which can result in changes in water parameters during storage and transport, affecting the accuracy of the results. This process is time-consuming, costly, and usually conducted at weekly intervals or in response to specific environmental incidents. Field tests, although conducted on-site, also require costly equipment and do not allow for continuous monitoring [18].

In contrast to traditional methods, the proposed system uses sensors installed on a buoy equipped with an IoT module and GSM data transmission technology, enabling continuous real-time monitoring of water parameters. Studies confirm that such systems can track key water quality parameters, such as pH, temperature, conductivity, and dissolved oxygen, allowing for the early detection of pollution events. Data are transmitted directly to the cloud, eliminating the need for manual sampling and enabling real-time data analysis. This solution not only increases the efficiency and accuracy of measurements but also significantly reduces operational costs compared to traditional methods, which require expensive laboratory equipment and personnel [19,20].

Research has also shown that these systems have the potential for integration with modern technologies, such as artificial intelligence algorithms, further enhancing their efficiency and reliability. The ability to transmit real-time data allows for faster responses to pollution incidents and more effective water resource management [18,19].

The autonomy of a buoy, meaning its ability to operate independently without external power supply, is crucial for its effective functioning on water. Alternative sources of electrical energy that can be applied are well documented in the literature. Photovoltaic panels can be mounted on the buoy to convert sunlight into electrical energy [14,21]. This solution is relatively easy to install, but its efficiency depends on sunlight availability, which can be problematic in regions with low solar exposure. Small wind turbines can generate electricity from wind [22,23]. However, both photovoltaic panels and wind turbines are susceptible to damage in extreme weather conditions and collisions with floating objects and require regular maintenance. Small water turbines [24,25], mounted underwater to generate electricity from water currents, are also prone to damage. In the article, the authors proposed a solution based on appropriately selected batteries and developed central unit software with energy optimization.

The GSM network coverage in Central Europe provides superior data transmission quality compared to other methods for sensor data collection. This is primarily due to the extensive and reliable GSM infrastructure in the region, which ensures consistent and high-quality connectivity, which allows for seamless data transfer from sensors placed along the river, ensuring real-time monitoring and data accuracy. The use of GSM for data transmission is advantageous because it leverages existing cellular networks, reducing the need for additional infrastructure and maintenance costs.

In contrast, alternative methods such as satellite communication or proprietary radio networks often face challenges like higher latency, increased costs, and limited coverage in certain areas. Satellite communication, while offering broad coverage, can be prohibitively expensive and may suffer from signal delays [26,27]. Proprietary radio networks, on the other hand, require significant investment in infrastructure and may not provide the same level of reliability and coverage as GSM [28]. Therefore, GSM stands out as the most efficient and cost-effective solution for data transmission from sensors placed in both rural and urban areas of a river, ensuring continuous and reliable data flow essential for environmental monitoring and management.

This article presents the efficiency and practicality of using remote water quality monitoring systems based on IoT and GSM technology in the context of quickly detecting and responding to deviations in water quality parameters. The effectiveness and reliability of the GSM-based remote water quality monitoring system were demonstrated in providing real-time data for the early detection of contaminants and supporting sustainable management of inland waterways.

This article is divided into four sections and concludes with findings. Section 2 consists of two parts: one describing the architecture of the remote water quality monitoring system and the other describing the main server and peripheral devices. The results of the remote water quality monitoring system and their general discussion are presented in Section 3. Finally, Section 4 contains the final discussion and conclusions.

2. Materials and Methods

2.1. Remote Water Quality Monitoring System Architecture

Thanks to the use of modern technologies, such as hydrological sensors, it is possible to continuously and precisely collect data on the physical and chemical parameters of water for the management of water resources and environmental protection. Technologies consistent with the concept of the Internet of Things (IoT) were effectively used to monitor water quality in the river by implementing an intelligent system that automatically collects, analyzes, and transmits data using a series of sensors, control electronics, and GSM telecommunications technologies. Figure 1 shows a diagram of the remote water quality monitoring system.

The system consists of a central unit located in an autonomous buoy and a main server connected to a computer or mobile device with a monitoring and analytical application installed. This creates an integrated environment that allows for the collection, processing, and analysis of data in real time or at a specified interval.

- Central unit

The main components of the central unit are the integrated water quality sensor system (IWQSS), the signal processing unit (SPU), and the GSM module for data transmission. The autonomy of the central unit is ensured by battery power supply. The central unit has a modular character; i.e., each element of the system (IWQSS, SPU + GSM, battery) is connected by quick connectors and is located in hermetic enclosures.

- SPU + GSM module

The choice of an Arduino-based or compatible SPU was due to its properties:

- Programming simplicity;

- Modularity;
- Low price;
- Support and documentation (a large number of ready-made libraries, which simplify the implementation of various functions);
- Versatility and possibilities for rapid prototyping (can be easily adapted to various applications);
- Expandability with ready-made modules or shields.

As a result of research and analysis, consisting of tests of various models and microcontroller development kits, in order to determine the optimal one in terms of energy consumption while maintaining the correct data transmission, the DFR0355 board manufactured by DFRobot was selected (Table 1). This system is compatible with the Leonardo module of the Arduino platform, with an integrated GSM/GPRS/GPS SIM808 module enabling the creation of IoT projects. The DFR0355 board is based on the ATmega32u4 microcontroller (DFRobot, 63-640 Bralin, Poland.), which provides 20 digital inputs/outputs, 7 PWM channels, 12 analog inputs (4 of them are used to measure water quality), and popular communication interfaces.

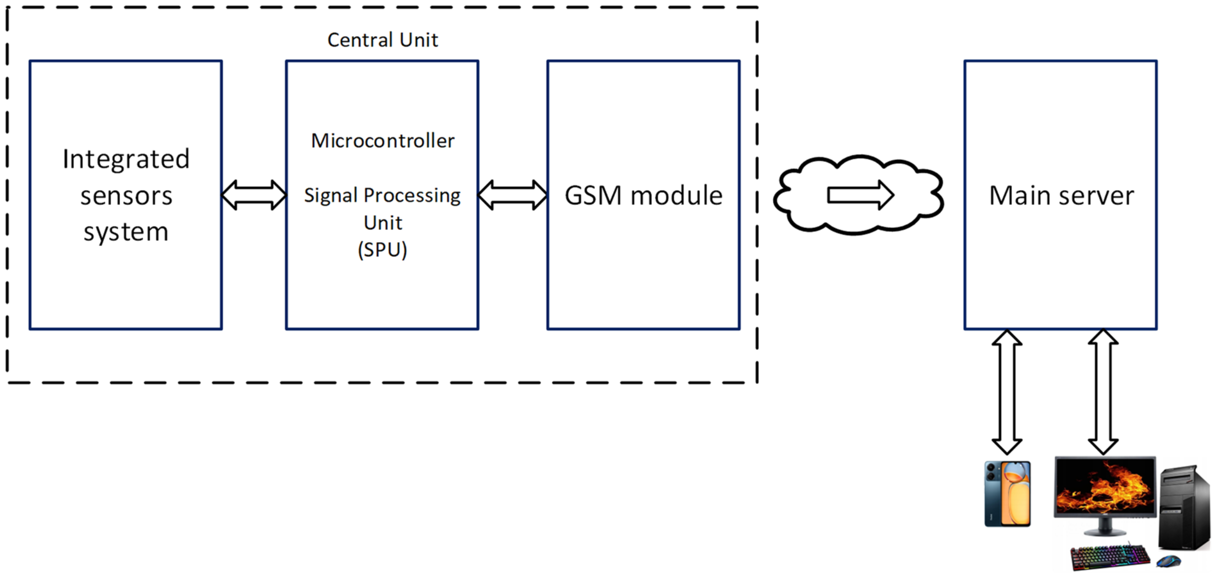


Figure 1. Schematic diagram of the remote water quality monitoring system.

Table 1. Analysis of different Arduino + GSM system topologies.

SPU Module	GSM Module	Load Current (Standby Mode)	Battery Life (Estimated)	Load Current Maximal (Data Transfer)	Data Transfer Quality
Arduino Uno Rev3	Quectel MC60	120 mA	6.94 days	240 mA	Correct
Arduino Uno Rev3	GPS SIM7000E	110 mA	7.57 days	230 mA	Correct
Arduino Uno Rev4	Quectel MC60	70 mA	11.9 days	140 mA	Connection breaking
Arduino Uno Rev4	GPS SIM7000E	65 mA	12.8 days	121 mA	Connection breaking
Leonardo + GSM module		45 mA	18.5 days	112 mA	Correct

The battery life B_L was determined from a simple relationship:

$$B_L[\text{days}] = \frac{B_C[\text{mAh}]}{24 \cdot L_C[\text{mA}]}, \tag{1}$$

where

B_C—Battery Capacity;

L_C—Load Current.

In the chosen development kit, the GSM module communicates with the microcontroller module via the UART serial interface (RX, TX) by AT commands. This set allows for the implementation of advanced projects, such as location tracking, SMS communication, voice calls, and data transfer over the Internet.

- Integrated Sensors System

The selection of appropriate sensors for monitoring water quality in waterways is critical to obtaining reliable data that will aid in assessing the aquatic environment, managing resources, and early detection of pollution. Key arguments justifying the choice of the parameters studied are presented below:

- **Conductivity** measures water's ability to conduct electrical current, which can indicate the presence of chemical pollutants, dissolved salts, and heavy metals. Conductivity also reflects changes in the riverine ecosystem and potential threats to aquatic organisms, making it a crucial parameter for monitoring river water quality [29,30].
- The **pH** level of river water is vital due to its impact on aquatic organisms and the chemical processes occurring in river ecosystems. pH plays a key role in the ability of organisms to adapt to environmental changes, influencing the solubility of chemicals, metabolic processes, and the overall structure of the aquatic ecosystem. It is also an indicator of the presence of toxic substances and the effects of anthropogenic factors on river water quality [29–31].
- **Temperature** monitoring is essential for understanding the biological, chemical, and physical processes within the river ecosystem. Temperature influences the solubility of gases, metabolic processes, the growth of aquatic organisms, seasonal changes, and the effects of anthropogenic impacts and climate change. It serves as a critical indicator for assessing the health of the river ecosystem and water quality [32–35].
- The **dissolved oxygen** level in river water is crucial for sustaining aquatic life and assessing the health of the river ecosystem. Dissolved oxygen is essential for the respiration of aquatic organisms and serves as an indicator of water quality and the dynamics of biological, physical, and chemical processes. It is also a vital parameter for evaluating the effects of anthropogenic threats and climate change on river waters [36–38].

In the process of selecting sensors based on identified parameters, appropriate types of sensors were chosen. Various technologies were considered: both multi-parameter sensors, which measure multiple parameters simultaneously (e.g., conductivity and temperature) and single-parameter sensors. The selection of sensors took the following into account:

- **Accuracy and sensitivity:** the ability to detect changes at low concentrations and provide precise measurements;
- **Environmental resistance:** durability in the face of temperature changes, humidity, sediment accumulation, and algae;
- **Versatility:** compatibility with wireless data transmission;
- **Cost-effectiveness:** the cost of purchasing, installing, maintaining, and servicing the sensors.

Tests were conducted on various available sensors, focusing on the Gravity system sensors due to their versatility and full compatibility with Arduino. The following sensors were analyzed:

Dissolved Oxygen Sensors: DFRobot Gravity—Analog Dissolved Oxygen Sensor X (SEN0237-A) (DFRobot, 63-640 Bralin, Poland).

Salinity Sensors: Gravity—Analog Salinity Sensor for Water and Soil (DFR0300-H), Gravity—Analog Electrical Conductivity Sensor for Solutions and Temperature PRO (SEN0451), and DFRobot Gravity—Analog Water Salinity Sensor (DFR0300).

pH Sensors: DFRobot Gravity—Analog pH Sensor Pro V2, DFRobot Gravity—Analog pH Meter, and Gravity—Analog pH Meter V2 (SEN0161-V2).

In this study, reference analyzers were utilized to enable both laboratory and field examination of the measured parameters, allowing for comparison with the values indicated by the sensors being tested. The analyzers employed were as follows:

- **AZ86031 Water Parameter Analyzer:** This professional, portable meter is designed for the analysis of water parameters. It can measure pH, salinity, ion density in water (TDS), oxygenation, and conductivity. A key advantage of this analyzer is its ability to simultaneously use three probes. The measurement ranges include pH from 2.00 to 12.00, temperature from −5 °C to 60 °C, salinity from 0 to 10.00 ppt, oxygenation from 0.0 to 199.9% (0.0 to 30.0 mg/L), and conductivity from 0 to 1999 μS/cm;
- **Elmetron—CX-705 Multifunction Instrument:** This is a highly accurate laboratory instrument that can also be used in the field. In addition to measuring pH, redox potential, conductivity, salinity, resistance, ions, dissolved oxygen (both in water and air), atmospheric pressure, and temperature, it has a semi-automatic titration function. The device offers measurement ranges for various water parameters and includes temperature and atmospheric pressure compensation features;
- **SensoDirect 150 Multi-parameter Meter:** This portable multi-parameter meter from LOVIBOND TINTOMETER enables rapid and accurate measurements of pH/redox, dissolved oxygen, and conductivity/TDS. It provides measurement ranges for pH, ORP, dissolved oxygen, conductivity/TDS, and temperature.

The research was conducted in a laboratory environment, where a Water Environment Simulation Setup was constructed. The central component of the setup is a 240 L aquarium, providing sufficient space for simulating an aquatic environment. The aquarium's dimensions are standardized, ensuring precise execution of experiments and observations of aquatic organisms' behavior. Additionally, the aquarium lighting system was designed to simulate the natural day–night cycle, allowing the study of light variations' effects on aquatic life and accelerating potential fouling of the sensors being tested.

Furthermore, an external flow-through heater with adjustable power was implemented to maintain a stable water temperature in the aquarium. Maintaining the correct water temperature is critical for the health of aquatic organisms and for simulating realistic environmental conditions.

The study was conducted in a simulation setup using water collected from the river, with a day–night cycle simulated and microorganisms introduced to test the potential for sensor overgrowth. The selected sensors were tested under conditions resembling real-world scenarios to confirm their effectiveness and accuracy. Physical clogging of the buoy was not considered due to ongoing work on optimizing the buoy design to prevent floating debris from blocking the sensors. Discussions with sampling teams and our research showed that within the interval between cleaning and calibration (1 month), no sensor overgrowth was observed. Field studies are planned for the next stages after improving the buoy design. The testing and calibration process involved laboratory calibration by verifying measurement accuracy in controlled conditions. Both laboratory and field tests demonstrated that the use of three different sensors measuring four parameters would be the optimal technological and economic solution for the buoy-based water quality assessment:

- Gravity—Analog pH Meter V2 (SEN0161-V2) [39]: This analog pH sensor offers accurate measurements of the acidity and alkalinity of aqueous solutions. Powered by 3.3 V to 5.5 V, it generates an output signal ranging from 0 V to 3 V. It includes a laboratory-grade probe and operates within a pH range of 0 to 14 with an accuracy of ± 0.1 pH at 25 °C. An integrated LED, BNC connector, and PH2.0 interface make it easy to integrate with Arduino systems (Leonardo).
- DFRobot Gravity—Analog Dissolved Oxygen Sensor X (SEN0237-A) [40]: This analog sensor, compatible with Arduino, provides high-precision measurements of dissolved oxygen levels in water. Powered by 3.3 V to 5 V, the output signal ranges from 0 V to

3 V. It features a galvanic probe that connects easily via a BNC connector. The detection range of 0 to 20 mg/L allows for effective water quality monitoring. The sensor also has durable electrodes and can be maintained based on the type of water used.
- Gravity—Analog Electrical Conductivity Sensor PRO (SEN0451) [41]: The Gravity sensor allows precise measurement of the electrical conductivity of water solutions. Powered by 3 V to 5 V, it generates a stable output signal between 0 V and 3 V. Equipped with an industrial-grade probe and a platinum resistance thermometer (PT1000) for temperature measurement, it enables precise monitoring of water quality across a wide range of 1 to 2200 µS/cm. With its resistance to pressure and high IP68 waterproof rating, it is ideal for use in harsh environments.

The selected sensors demonstrated full compatibility with the previously chosen Leonardo + GSM module unit (Table 1).

- Power supply for the central unit

Full autonomy of the buoy (measurement and data transmission system) requires an internal power source. In the implemented system, a battery was used without a hybrid system with a second energy source, a photovoltaic system, or a wind generator, as is the case in other solutions [1,2,4]. This is due to the fact that the autonomous buoy is exposed to damage in the waterway (usually a river), e.g., to contact with floating tree branches, twigs or vessels, which would cause damage to the external energy source.

Installing additional sources of electrical energy on buoys involves numerous risks, both above and below the water. Below are the main aspects of the issue:

- Risks above water:
  - Collisions with floating objects: Buoys located in busy waterways are susceptible to collisions with floating vessels such as boats, ships, and other watercraft. They are also at risk of contact with floating debris like tree branches. Such incidents may damage both the buoy and the devices installed on it.
  - Exposure to weather conditions: Devices (e.g., photovoltaic panels and wind turbines) installed on buoys are exposed to rain, wind, snow, hail, and UV radiation. Severe storms, fluctuating temperatures, and intense sunlight can cause mechanical damage, corrosion, and material degradation.
  - Vandalism or theft: Devices installed above water can be easily accessed by unauthorized individuals, increasing the risk of intentional damage or theft.
- Risks below water:
  - Collisions with underwater objects: Buoys may come into contact with drifting debris, branches, ice, or other underwater obstacles, which can damage the devices.
  - Corrosion and biofouling: Constant exposure to water promotes the corrosion of metal components of energy-generating devices (e.g., water turbines). Additionally, the growth of marine organisms like algae, mussels, or barnacles can burden the structure, limit functionality, or render it completely inoperative.
  - Hydrodynamic forces: Water currents, waves, and tides can affect the buoy's stability, creating stresses that may lead to damage to installed devices. Vibrations and oscillations can further accelerate component wear.

On Figure 2, examples of damaged buoys are shown.

In conclusion, installing external energy sources on buoys is highly problematic due to the numerous risks associated with the aquatic environment.

The battery selected in the solution must meet high requirements related primarily to its service.

The operation of a new generation $LiFePO_4$ 20Ah 12.8 V battery for powering the central unit was proposed, tested, and compared to a classic lead–acid battery. The advantages of the $LiFePO_4$ battery in its application to the intelligent buoy are as follows [42]:

– Lower weight: The $LiFePO_4$ 20Ah battery weighs about 2 kg compared to its lead–acid equivalent of 5 kg, which is crucial for installation in a buoy and in its subsequent operation (replacement);
– Longer service life: It offers over 10 years of operation, and thanks to the low self-discharge, even after a year of non-use, the battery should be fully ready for operation. It has a lifespan of up to 3000 cycles at full discharge (DoD 100%), or up to 5500 cycles at lower discharge (DoD 60%);
– The efficient nanophosphate cells allow for the use of high charging and discharging currents, and the operating temperature ranges from −10 °C to 55 °C, allowing it to be used in buoys on the waterway;
– Safety: $LiFePO_4$, unlike its lead–acid counterpart, does not emit dangerous gases, and carries no risk of exposure to corrosive electrolytes;
– Its standard charging current of 10 A and discharge current of 20 A, as well as peak discharge current of 30 A, guarantee fast charging and efficient power supply of devices with high energy consumption. In the context of application in the intelligent buoy, the charging speed plays an important role (the battery can be charged immediately on the serving unit).

As shown in Table 1, continuous power supply to the central unit will require frequent battery recharging. The battery replacement period is also related to the frequency of sending data from the central unit to the main server (current consumption max—Table 1). This operation additionally significantly discharges the battery.

(**a**)

(**b**)

Figure 2. A damaged buoy taken from the waterway: (**a**) made of metal; (**b**) made of composites.

The power demand can be limited by hardware or software. The hardware method (e.g., using the Leonardo Module integrated with the GSM/GPRS/GPS SIM808 module selected for the system implementation in relation to Arduino with various GSM modules) allows for a maximum reduction in power demand by about 60% (Table 1). This is not sufficient. The possibility of software "sleep" of the Leonardo module was tested, while no measurements were taken and no data were sent (this was performed every 30 min). Internal Arduino libraries were used, allowing the controller to "sleep" in various ways. The tests performed showed that limiting current by putting the controller into "sleep" is effective, reducing consumption to about L_C = 2 mA.

The possibility of using a free analog channel in Arduino to measure the supply voltage and send this information to a remote server was investigated. The voltage value will determine the battery charge status. The battery discharges slowly in the first period of operation (a small voltage decrease—around 0.1–0.3 V), so that when it is close to discharge, the voltage drops significantly by 1–2 V (Figure 3).

The use of a new, technologically advanced battery, combined with the development of energy-optimized software for the measurement unit, has extended its lifespan, reducing the need for recharging to at least once a month. Maintenance work currently carried out by river service staff every 3–4 weeks (to oversee standard buoys) will be fully sufficient for replacing the battery as needed.

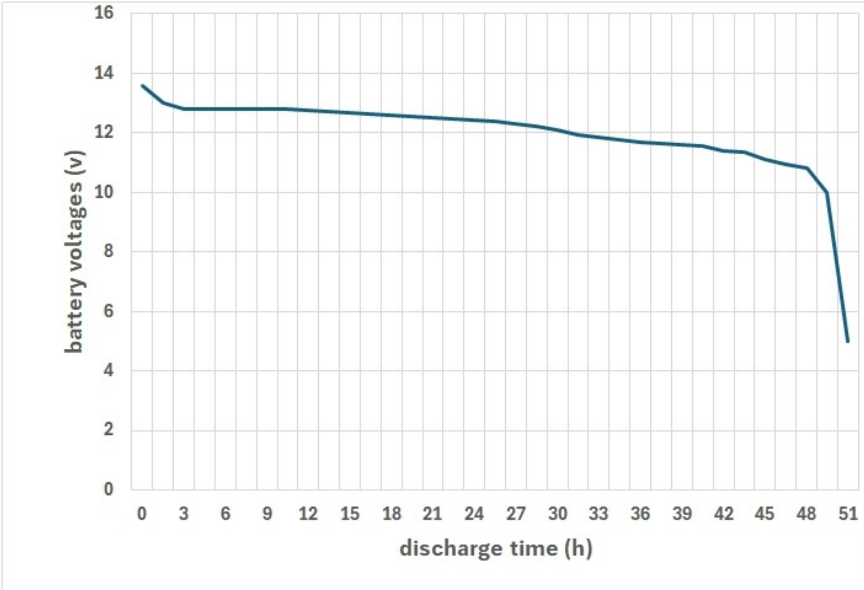


Figure 3. Time course of the discharge voltage of a $LiFePO_4$ 20Ah battery with a discharge current of 400 mA.

- Central unit topology

The entire system of the central unit is shown in Figure 4. Data collection from sensors located in the buoy is carried out automatically using an integrated system of sensor networks connected to the central unit using signal converters. The sensors are powered directly from the Leonardo board.

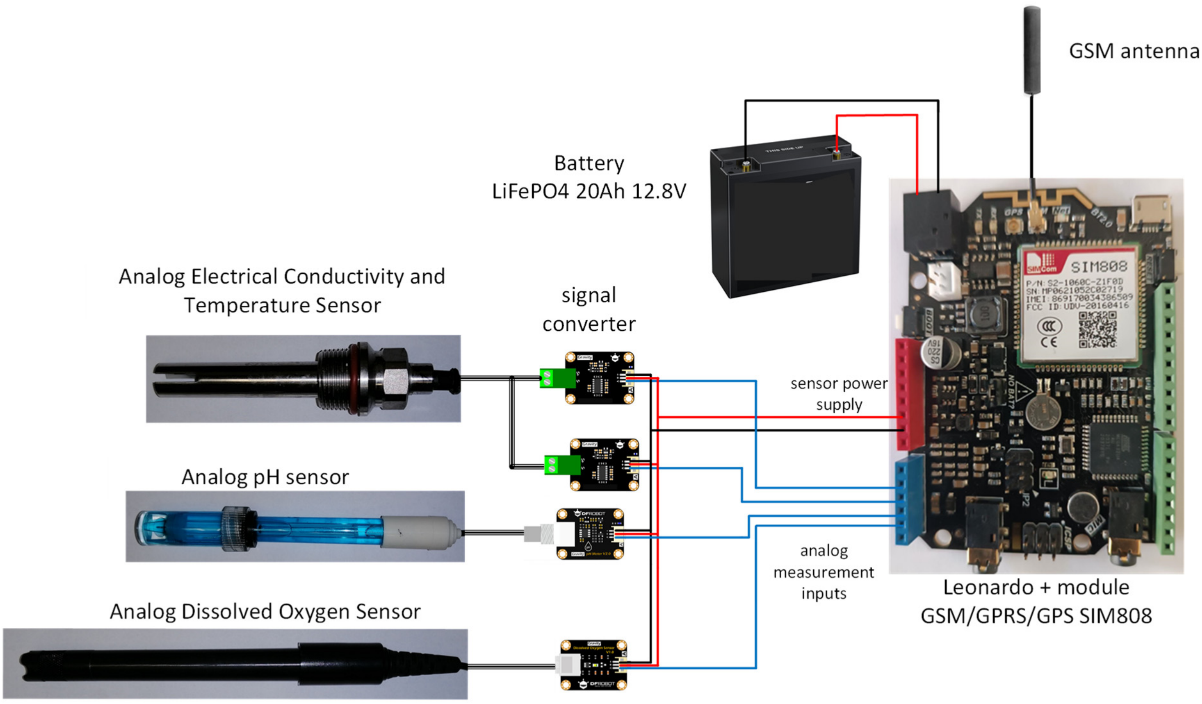
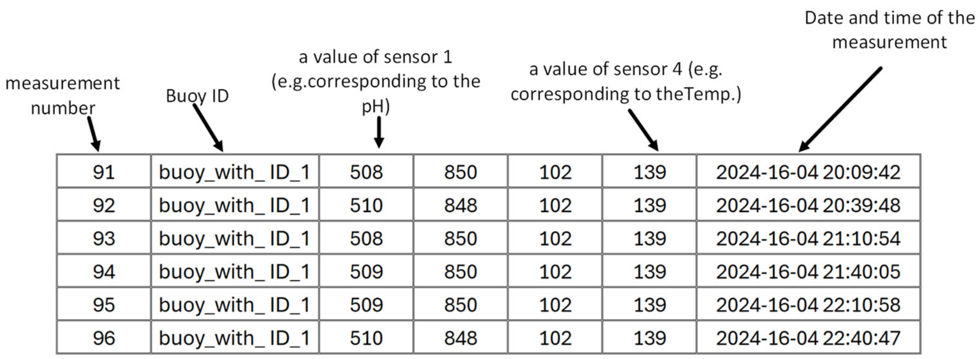


Figure 4. Central unit topology.

2.2. Main Server and Peripherals

The ATmega32u4 microcontroller, which is the heart of the central unit, has a built-in multi-channel 10-bit analog-to-digital converter. This means that measurement data obtained from analog inputs, based on standardized 0–5 V signals, are mapped in digital form using an integer value from 0 to 1023. Such values, from 4 measurement channels, which correspond to appropriate chemical or physical quantities, are sent to the main server. Figure 5 shows a matrix of sample data as stored on the main server.



91	buoy_with_ ID_1	508	850	102	139	2024-16-04 20:09:42
92	buoy_with_ ID_1	510	848	102	139	2024-16-04 20:39:48
93	buoy_with_ ID_1	508	850	102	139	2024-16-04 21:10:54
94	buoy_with_ ID_1	509	850	102	139	2024-16-04 21:40:05
95	buoy_with_ ID_1	509	850	102	139	2024-16-04 22:10:58
96	buoy_with_ ID_1	510	848	102	139	2024-16-04 22:40:47

Figure 5. Examples of data on the main server.

Data from the central unit, thanks to IoT modules, are sent to the main server at specific intervals, thanks to the use of GSM communication networks. Information is stored on the SQL server (Structured Query Language). Further data extraction from the main server can be achieved with a personal computer or mobile device (e.g., smartphone, tablet, etc.) with an Internet connection.

An application has been developed in which data received from the main server, still in values ranging from 0 to 1023 as sent by the central unit, are converted into specific chemical or physical quantities that can be subjected to further analysis. The application is used to analyze and visualize measurement data from four different sensors simultaneously. Its main purpose is to enable complex monitoring of measurement data from the buoy at regular intervals. Data recording takes place every 30 min and includes values of four measured parameters, the date of reading, and the buoy identifier. The application can be installed and operated on a personal computer, as well as on a portable device equipped with the Android system. The application's capabilities are as follows:

- **Automatic data collection:** enables recording of data from various sensors at regular intervals;
- **Data analysis:** possibility to analyze data according to patterns of individual parameters and sets of parameters;
- **Trend visualization:** display of trends, and minimum and maximum parameter values with the option to customize time ranges;
- **Flexible reporting:** color-coding of parameters, ability to zoom in, zoom out, and select different time ranges;
- **Editing conversion factors:** possibility to adjust conversion factors to calculate actual measurement values;
- **Charting:** generate and save your own charts directly on your device;
- **Automatic notifications:** the system sends a notification when the minimum and maximum values set for individual sensors are exceeded;
- **Server Switching:** the ability to switch between different servers to access different sets of measurements, allowing for the flexibility to manage and analyze data from different sources if needed.

Figure 6 shows an example visualization of data received from the central unit.

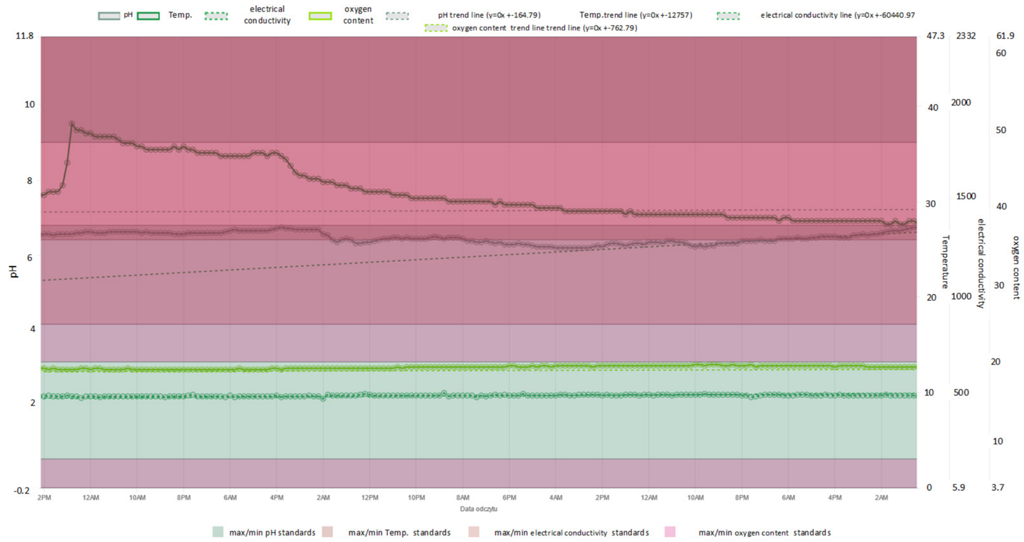


Figure 6. Sample visualization of water parameters measured.

3. Results

Water quality tests were conducted using the previously described Laboratory Stand for Simulation of Water Environment Conditions, which replicates real environmental conditions (water flow, natural day–night cycle and heater control, and river water). The measurements of the physicochemical water parameters were carried out over a period of more than three weeks (from 11 April 2024 to 5 May 2024). Sensor calibrations were performed on 15 April and 25 April.

The graph presented in Figure 7 illustrates the changes in dissolved oxygen levels in the water.

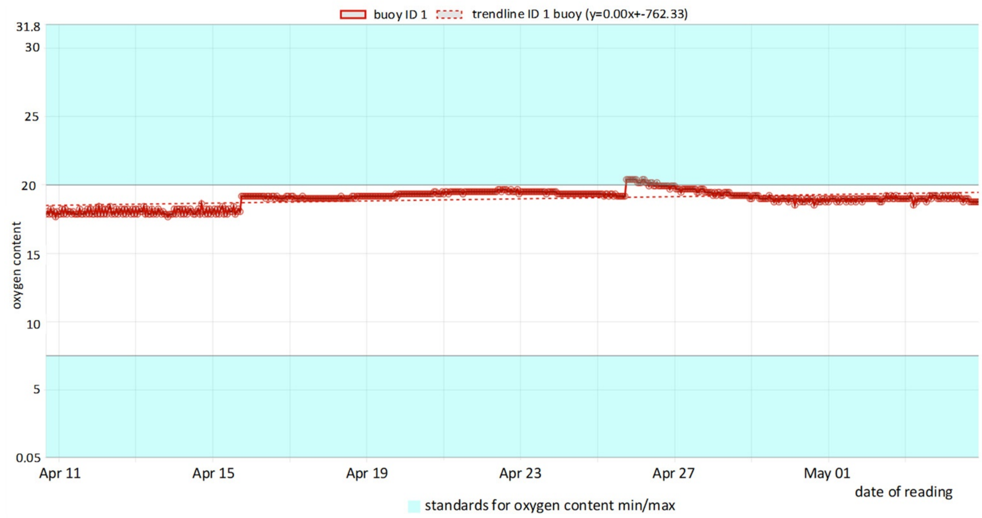


Figure 7. Dissolved oxygen levels in water as a function of time.

The graph may indicate optimal dissolved oxygen (DO) levels (e.g., 7–20 mg/L). Exceeding or dropping below this range can have negative impacts on aquatic life and overall water quality. The graph of dissolved oxygen levels helps assess the water's capacity to support life and its overall quality. Regular monitoring of DO is crucial for protecting aquatic ecosystems, especially in bodies of water exposed to pollution or excessive nutrient production.

Figure 8 illustrates conductivity measurements, focusing on analyzing changes in conductivity over time and their impact on water quality. Water conductivity measures its ability to conduct electricity, which is directly related to the amount of dissolved salts and minerals in the water. Higher conductivity indicates a greater number of ions, which may suggest the presence of pollutants or minerals. The conductivity graph enables the monitoring of dissolved substances in the water and rapid detection of quality changes. High conductivity typically indicates pollution or elevated mineral levels, while low conductivity suggests cleaner water with minimal salt content.

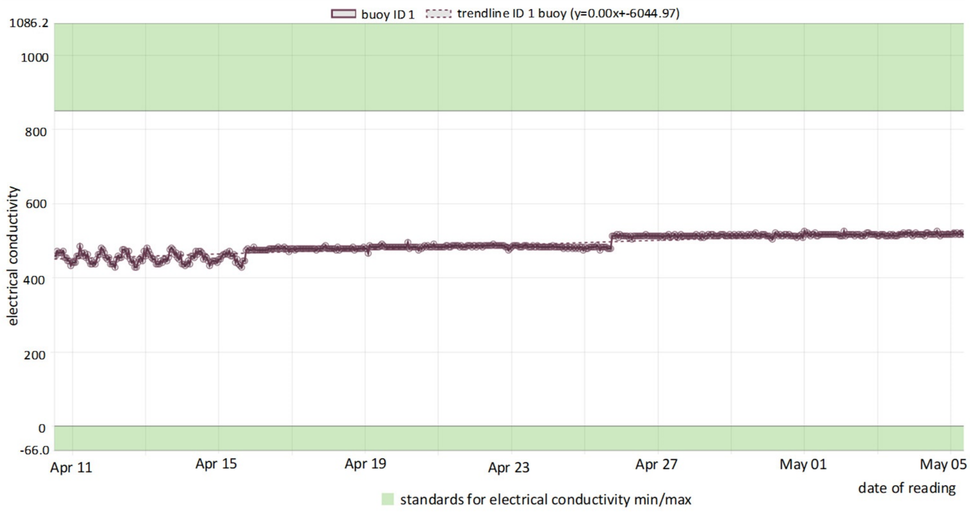


Figure 8. Conductivity of water as a function of time (unit: mS/m).

The graph in Figure 9 shows pH values over time, allowing for the assessment of water's chemical stability and the detection of potential pollutants. Optimal pH boundaries (e.g., from 6.5 to 8.5) are marked on the graph to easily evaluate whether the water quality is within the acceptable range. If the pH line exceeds these boundaries, it may indicate potential risks to water quality. It is also important that the pH remains relatively stable within this range to avoid harming aquatic organisms.

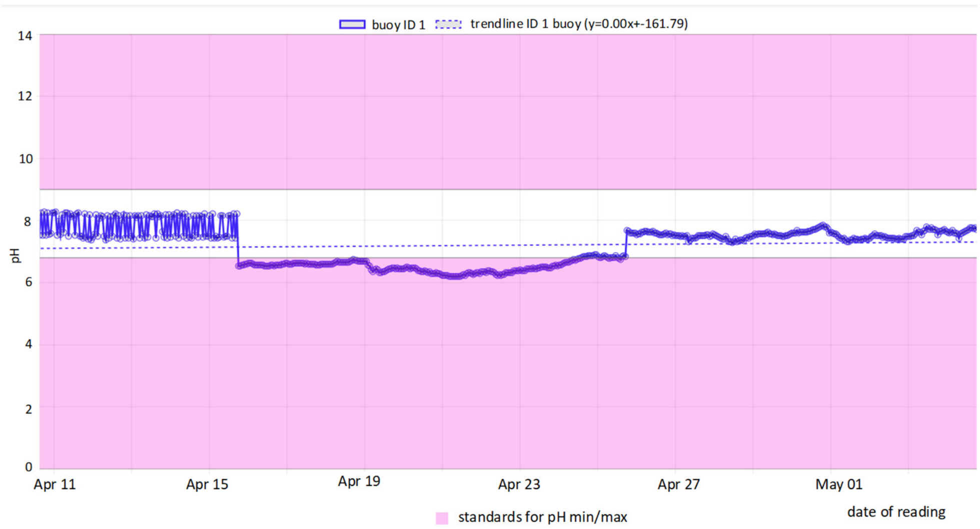


Figure 9. pH levels of water as a function of time.

The pH measurement graph for water quality allows for monitoring its chemical stability and quickly detecting abnormalities that may impact the health of humans, animals, and plants. Regular tracking of pH changes is crucial for maintaining adequate water quality.

The graph in Figure 10 presents temperature changes over time. If the temperature line is flat or exhibits minimal variations (as shown in Figure 10, it may indicate stable environmental conditions conducive to maintaining suitable water quality parameters. Boundary conditions for temperature were set in the program with a minimum temperature (T_{min}) of 0 °C and a maximum (T_{max}) of 26 °C. Monitoring temperature trends allows for the detection of potential threats to water quality, as temperature significantly influences aquatic environments.

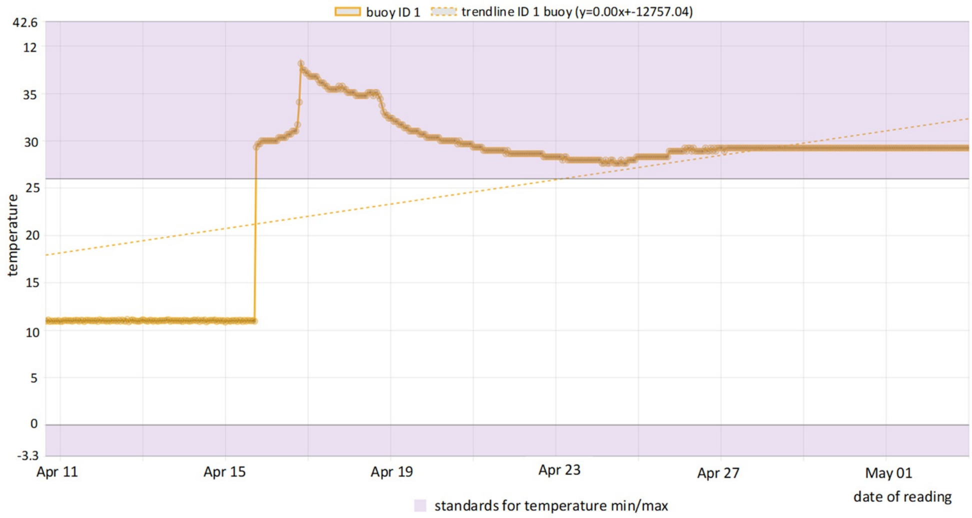


Figure 10. Temperature variation over time.

The graphical data present key water quality parameters and their impact on aquatic ecosystems:

- Dissolved Oxygen: The optimal range is 7–20 mg/L. Levels outside this range can negatively affect aquatic life and water quality. Regular monitoring allows for assessing the water's capacity to support life and detecting pollution or nutrient excess.
- Electrical Conductivity: High conductivity indicates pollution or high mineral concentrations. Low conductivity suggests cleaner water with minimal salt content. This enables the rapid detection of water quality changes.
- pH Values: The optimal range is 6.5–8.5. Stability within this range is crucial for maintaining the chemical balance of the water and protecting aquatic life. Deviations may indicate pollutants and potential risks to the ecosystem.
- Temperature Range: 0–26 °C. Stable temperatures support the maintenance of appropriate water quality parameters.

Monitoring detects potential threats arising from changes that could impact aquatic environments.

In summary, the analyzed parameters enable a comprehensive assessment of water quality and the early detection of threats to aquatic ecosystems.

These parameters are interconnected and provide a holistic view of water quality: Changes in temperature affect dissolved oxygen levels and influence pH stability. Abnormal conductivity often correlates with changes in other parameters, indicating pollution or contamination. Together, they help identify the source and nature of potential issues, from chemical imbalances to biological threats.

By focusing on these four parameters, water quality can be assessed effectively, ensuring the protection of aquatic ecosystems and identifying potential risks in a timely manner.

4. Conclusions

The presented water quality measurement system with IoT-based data transmission yields several important conclusions:

- Effectiveness of IoT Technology in Water Quality Monitoring: Wireless IoT-based systems are effective tools for the continuous monitoring of water quality parameters.

The system detailed in this article demonstrates that IoT technology enables rapid response to changes in water quality and identification of potential threats.

– Advantages of Wireless Data Transmission: Wireless data transmission allows for immediate access to information regarding water conditions without the need for physical intervention. This enhances the efficiency of water resource management and minimizes operational costs.
– Faster Response to Threats: Immediate notifications of irregularities or exceedances of established norms facilitate quick responses and reduce risks to public health.
– Long-Term Trend Analysis: The system enables data collection over extended periods, allowing for trend analysis and identification of long-term changes in water quality.
– Challenges and Future Development Opportunities: Despite numerous benefits, challenges related to data security and the integration of various IoT systems persist. Future development will focus on refining data analysis algorithms and enhancing system resilience against failures.

Prospects for Future Applications: IoT technologies will play an increasingly significant role in monitoring and protecting water resources worldwide. Innovative solutions may include leveraging artificial intelligence for predicting changes in water quality and automating purification processes.

The implementation of wireless water quality monitoring systems in IoT is a crucial step toward sustainable water resource management. Continued research is essential for improving measurement accuracy and expanding the applicability of IoT technologies in the water sector. The authors will focus future work on the following:

- Development of an autonomous buoy:
    - Finalizing the design of an autonomous buoy made from innovative materials, ensuring durability, resistance to harsh environmental conditions, and potential collisions.
    - Expanding the power supply system with alternative energy sources to support the long-term operation of the device without frequent maintenance, especially for water bodies with low exposure to risks.
- Advanced data analytics:
    - Implementing machine learning and artificial intelligence algorithms for predictive analysis of water quality trends.
    - Developing anomaly detection systems to automatically identify unusual patterns or sudden changes in water quality.
- Scalability and Integration:
    - Ensuring compatibility with other IoT networks and environmental monitoring systems to create a comprehensive ecosystem approach.
    - Expanding the system's ability to monitor multiple water bodies simultaneously.
- Field testing: Conducting extensive field tests in real-world conditions to verify the system's performance under varying circumstances.

The proposed future work demonstrates the system's potential for broad application while addressing current limitations.

Author Contributions: Conceptualization, M.S., P.B., E.K., D.T. and J.W.; methodology, M.S., P.B. and D.T.; software, M.S.; validation, P.B. and D.T.; formal analysis, E.K. and J.W.; investigation, M.S. and P.B.; resources, M.S., P.B., E.K., D.T. and J.W.; data curation, M.S.; writing—original draft preparation, M.S., P.B. and D.T.; writing—review and editing, M.S., P.B., E.K., D.T. and J.W.; visualization, M.S.; supervision, D.T.; project administration, E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to ongoing research projects.

Acknowledgments: The manuscript was created as part of the project: Intelligent waterway routing system for inland navigation enhancing navigation safety, supplemented with the ability to dynamically acquire hydrological and physicochemical data (HYDROSTARTEG1/001P/2022).

Conflicts of Interest: The authors declare no conflicts of interest.

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