Real-time monitoring and predictive maintenance for sustainable aquaculture management

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Abstract

The objective of this study is to investigate water quality monitoring in aquaculture systems using integrated sensors and predictive maintenance technologies, aiming to enhance production efficiency and reduce environmental impact. This research is focusing on remote sensing, on-site sensor monitoring, and machine learning for time-series forecasting, anomaly detection, and fault classification. Artificial Intelligence (AI), as a field of computer science that aims to simulate and reproduce intelligent human functions, plays a pivotal role in this approach. While AI [1] is increasingly adopted in public institutions in Romania to improve governance processes, its application in aquaculture brings significant improvements in system automation, decision support, and predictive capabilities. The frameworks developed by the Blue-GreenWay and iPREMAS projects provide a robust foundation for understanding aquaculture water quality management. The methodology integrates remote sensing data and in-situ water quality sensors to continuously monitor critical parameters such as temperature, dissolved oxygen, and chlorophyll-a concentration. A predictive maintenance platform employing machine learning algorithms was implemented, with data collected in a case study at the Ovidius Aqua Line sturgeon farm. The combined system effectively detected changes in water quality, providing timely alerts and enabling proactive maintenance scheduling. These results highlight improved operational efficiency, optimized feed management, and a reduced risk of disease outbreaks, in line with the established theoretical framework. Additionally, the integration of these technologies allowed for more precise water resource management, ensuring long-term sustainability Findings offer valuable insights for sustainable aquaculture management and environmental protection, emphasizing practical applications in facility management and future water quality forecasting. Our results demonstrate the potential of combining the technologies developed in the Blue-GreenWay and iPREMAS projects for effective water quality monitoring in aquaculture systems, contributing to the sustainable management of water resources in aquatic resources.

Keywords: water quality monitoring, predictive maintenance, sustainable management, environmental impact, aquaculture.

1. Introduction

Marine Aquaculture (fish, mussel, oyster and seaweed) is among the emerging sectors of the blue economy [2]. The interest in marine aquaculture production keeps increasing due to the wide potential on food security, derived compounds and their bioactivities [3].

Due to the growing interest to move large scale aquaculture operations further out into the open ocean the need for new solutions to tackle the challenges of the harsh and exposed environment increases [4]. A novel approach is replacing monoculture systems by integrated multitrophic aquaculture (IMTA) to solve environmental issues such as eutrophication [5]. Remote control, predictive maintenance as well as smart infrastructure are crucial for large scale commercialisation.

The iPREMAS and BLUE-GREENWAY projects were two research initiatives that aimed to improve the environmental and economic aspects of aquaculture and coastal ecosystems.

The iPREMAS project (Intelligent Predictive Maintenance for Aquaculture Systems) focused on improving aquaculture farms' performance by introducing a new platform and a new service for intelligent predictive maintenance. The platform is based on innovative monitoring systems and intelligent infrastructure using Machine Learning (ML) and Artificial Intelligence (AI) techniques [3]. The platform measures vital parameters in real-time, introducing multi-sensor innovative indicators that power a chain of ML models for Time Series Forecasting (TSF), Anomaly Detection, Fault Classification, and Remaining Useful Life (RUL). These measurements provided the current state of the farm site, while the predictions offered insights into its future status. The prevision analyses allowed us to identify whether preventive or corrective maintenance was needed [6]. A cloud-based integration of various platform components improved connectivity and security while optimizing operational processes, enabling farmers to benefit from personalized software.

The Software-as-a-Service (SaaS) approach benefits aquaculture farmers by providing a digital equivalent of the platform. Blockchain technology is being used to provide trust and traceability, such as securely managing sensor data information and the identity of stakeholders in the project outcomes. Security and confidentiality are ensured by implementing reliable and secure data transport. The new service offers farmers real-time access to the current state of the farm and facilitates planning activities and measures based on the predicted state.

The BLUE-GREENWAY project was the first project to apply new ecosystem restoration methodologies and identify shortcomings in wastewater management from urban & rural sources. The project aimed to increase knowledge-sharing between Academia/PAs to improve the environmental status of ecosystems, manage freshwater and wastewater, strengthen farmers to enter this processing market, and build capacity for comprehensive sustainable water management [7]. The project addressed the intertwined challenges of the land-sea chain by focusing on green procurement of products and services in wastewater management, treated water pollution problems resulting from land-based sources, and introduced innovative methodologies to restore ecosystems. A report was developed describing step by step the Living Lab approach, to help PPs realise Living Labs. The labs were used to integrate research and innovation processes, created a user-centred open innovation ecosystem based on systematic co-creation approach, promoted and strengthened transnational cooperation and networking amongst existing clusters/networks. Living Labs were organised in 3 countries, to transfer the knowledge of pilots to territorial stakeholders (SMEs, clusters, PAs, policy makers etc). The projects' added value lies in innovative, cost-efficient initiatives addressing the above challenges transnationally. It supported European entities in pooling efforts to implement new solutions to these challenges. This contributed to a change in procurement policies and wastewater management, led to positive socio-economic impacts.

Both projects aimed to contribute to the European goals of enhancing environmental protection and fostering eco-innovation.

The target of the iPREMAS project was to reduce Maintenance and Operation (M&O) costs for farmers and provided additional tools for mitigating adverse environmental effects in the event of calamities. Using machine learning and artificial intelligence techniques optimized the operations and maintenance of aquaculture farms, reduced their environmental impact and increased their efficiency. The BLUE-GREENWAY project intended to apply new ecosystem restoration methodologies and identified green products and services for wastewater management, improved the water quality and biodiversity of coastal ecosystems. Their aim was to train the participants in using the eGPP (Global Prime Partners) platform and raised awareness of topics of eutrophication and anoxia management. Together, both projects planned to involve knowledge-sharing and capacity-building among different stakeholders.

2.Theoretical framework

2.1. iPREMAS

The pilot station in Romania was implemented at the Ovidius Aqua Line fish farm located on the banks of the Danube in Borcea, Calarasi county. It operates in an enclosure (yard) of 7 1500 sqm. This enclosure is a 600 sqm hall, thermally insulated, divided into rearing space, storage space, space for processing eggs and meat (DSV authorized), and offices. In this farm are reared for sale: sturgeon and trout species, both adults capable of reproduction and roe. The following steps were followed to define the technical solution:

1. Analysis of the recirculating aquaculture system (RAS) on the farm;
2. Identification of fish species;
3. Identification of stress factors;
4. Identification of assessment methodologies and processes;
5. Identification of methods for monitoring water quality parameters in the system;
6. Definition of sensor requirements for the pilot station.

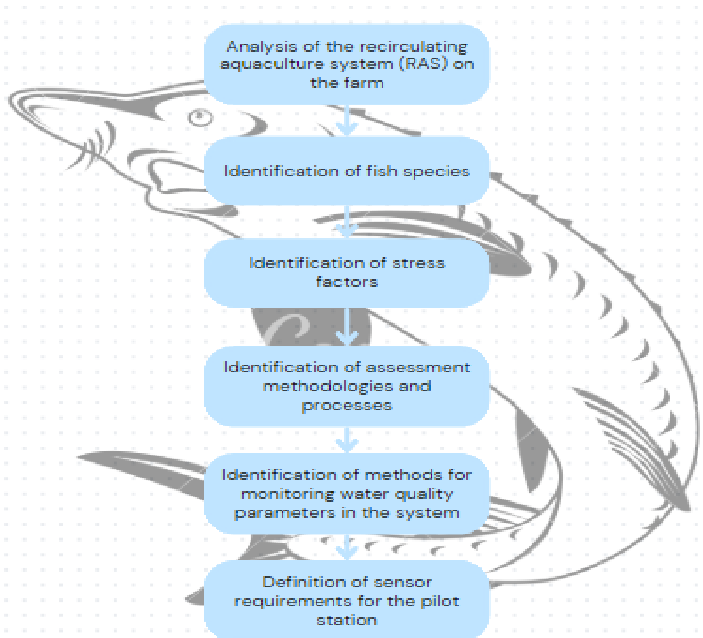

Fig. 1. Steps regarding the process/Steps defining the technical process

The "iPREMAS" project ensured fish welfare by monitoring in real-time the parameters such as temperature, pH, electroconductivity, dissolved oxygen, nitrates, nitrites, and pond water level. For the configuration of the monitoring system within the pilot station, the chosen solution was the Libelium Smart Water Extreme Station [8], together with the sensors for measuring the parameters already mentioned.

Data was acquired from the sensors every 15 minutes, transmitted live to the cloud platform, and could be visualized using Grafana [8]. An alarm system was developed to detect water quality parameters from exceeding the optimal range. When a parameter goes out of range, a message with a brief description of the problem was sent to the Telegram app. The Libelium solution implemented in the iPREMAS project uses 4G technology for data transmission. It consists of the acquisition module (Waspmote) and the Meshlium device, which acted as an IoT- Gateway [9]. Once the data reached Meshlium, it was stored in the InfluxDB - iPREMAS database. Subsequently, this acquired data was transmitted to the Grafana visualization platform using the MQTT Broker to display relevant information to users in tables or graphs [10]. MQTT is an extremely simple and easy-to-use publish/subscribe protocol designed for limited devices and for low-bandwidth, high-latency or insecure networks. The design principles intended to minimize network bandwidth and device resource requirements while ensuring reliable and secure data transmission.

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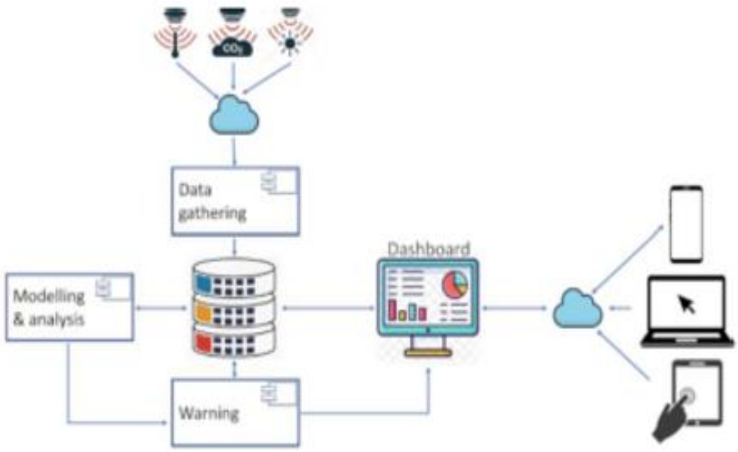

Fig. 2. Possible Architecture of the Farmer Support Service Platform

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MQTT is an extremely simple and easy-to-use publish/subscribe protocol designed for limited devices and for low-bandwidth, high-latency or insecure networks. The design principles intended to minimize network bandwidth and device resource requirements while ensuring reliable and secure data transmission. The data gathered from grafana by utilising the MQTT Broker are exported in CSV format to the MiraX platform. The MiraX platform was tested and validated within the project. This is an advanced, cloud-based, digital platform specifically designed by HAEDES BV for water systems management within the iPREMAS project. This platform uses state-of-the-art technology to create virtual detail representations of physical water systems, allowing the user a comprehensive and real-time visualization of their operations.

Main components of the platform:
1. Real-time monitoring and simulation
2. Comprehensive visualization tools
3. Improved decision-making (scenario analysis and risk assessment)
4. Collaboration platform
5. Scalability and flexibility

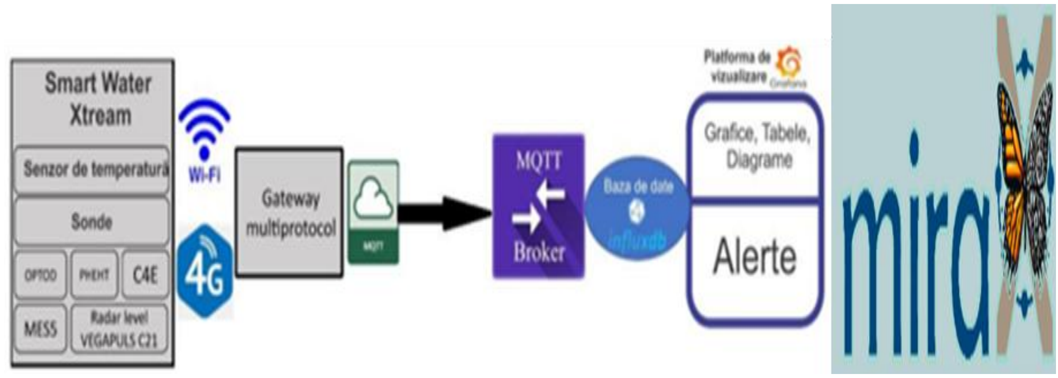

Fig. 3: General Architecture

Fig. 4. Testing and implementation of the monitoring system

2.2 Blue-greenway

To address the everyday challenges of the land-sea chain, the "BLUE-GREENWAY" project followed a dual approach.

First, with short-term restoration measures in the sea part of the chain. The areas faced pollution, freshwater & wastewater management problems. Human activities resulted in high loads of nutrients and organic matter in water bodies with poor circulation. In marine systems with limited water exchange and excessive anthropogenic input of nutrients/organic matter, water became eutrophic and permanently hypoxic/anoxic. The final result was the hydrogen sulfide production in the water column and massive fish mortality events [9]. The project focused on designing mesoscale pilots, cost-efficient restoration methods, and transferable monitoring systems. Knowledge-sharing on using geoengineering materials ensured the success of the remediation of ecosystems and the achievement of "BLUE" waters.

Fig. 5. BLUE-GREEN WAY project's pilot in Romania

Second, land measures focused on identifying & knowledge-sharing on the use of green products & services in wastewater management. This was achieved via developing an integrated transnational, adaptable database with critical data on user profile types/needs; developed an eGPP tool for users to implement green criteria in tenders; establishing Experts' Board for setting the green criteria within the online tool; developed users' toolkit of educational material for knowledge-sharing via the online tool; supported stakeholders/users network to ensure their deep engagement and sustainability of project outcomes; and developed guidelines to reduce nutrients loads from point and diffused pollution sources. This has achieved the "GREENWAY," its transferability after implementation, and its extension into take-up policies across European regions. Training material was distributed to the participants and expert partners were invited to train them.

The outcomes of the Labs were recorded in reports by the host partners, including evaluation of the Labs by the participants.

The organisation of Living Labs by partners has enhanced cooperation and improved mutual knowledge and understanding between the donor and beneficiary states.

The tool developed in the **BLUE-GREENWAY** project was an innovative solution designed to monitor and improve the environmental status of eutrophic and anoxic coastal ecosystems. It integrated an advanced water quality monitoring system, an early warning mechanism, and a digital e-procurement platform to promote green products and services.

The water quality monitoring system, which consisted of a floating platform equipped with sensors that measured essential physicochemical parameters both in the air and in the water column. The collected data was transmitted in real-time to a receiving station, where it was analyzed to detect anoxic and eutrophic events at an early stage. The tool incorporated a unified e-procurement platform, which facilitated the integration of green criteria in public procurement. This platform included a transnational database with specifications for environmentally friendly products and services available on the market, providing public authorities and economic actors with a reliable decision-support system. Additionally, the platform featured smart functionalities for product analysis and assessment, as well as an eco-innovative Life Cycle Costing (LCC) tool, which helped public procurers select the most cost-efficient and sustainable solutions. To validate the tool's effectiveness, a series of pilot experiments were conducted to reduce eutrophication and recycle nutrients. In the Aitoliko lagoon, an open-style submerged mesocosm was implemented, utilizing geoengineering materials to evaluate their ability to retain pollutants and improve water quality. In addition, in the Liopetri River (Cyprus), pilot systems were developed to reduce and recycle nutrients from agricultural drainage water using low-cost sorbents and microalgae, providing a sustainable alternative for wastewater management. The tool was tested under real-life conditions through pilot actions in Greece, Romania, and Cyprus, and the results were incorporated into a methodological guide for further implementation at the European level. In the long run, through its monitoring capabilities, early warning system, and support for green public procurement, the tool developed in BLUE-GREENWAY contributed to changing procurement policies, improving wastewater management, and promoting innovative solutions for the sustainable restoration of aquatic ecosystems.

2.3 Combined methods

Both iPREMAS and BLUE-GREENWAY were research projects that aim to improve the environmental and economic aspects of aquaculture and coastal ecosystems. Combining the technologies developed in these two projects, we proposed a comprehensive approach to water quality monitoring in aquaculture using different systems for measuring key parameters in real time, such as water quality, oxygen level and nutrients concentration.

Furthermore, we employed artificial intelligence techniques for analyzing the data collected by the monitoring systems and providing forecasts, warnings, and decision support [11]. Moreover, geoengineering materials for restoring the environmental status of eutrophic and anoxic coastal ecosystems were used in order to increase oxygen levels and reduce pollutants.

3.Results and discussion

In the iPREMAS project, users created an isolated organization in Grafana, with dashboards with multiple panels in the form of a graph or table [12]. Grafana also supports integration with official modules (such as maps) and applications that can be monitored.

Each dashboard is versatile and can be customized for a specific project.

Fig. 6. Dissolved oxygen parameter visualized in Grafana
Source: https://grafana.beia-telemetrie.ro

Fig. 7. Different parameters visualized in Grafana
Source: https://grafana.beia-telemetrie.ro

Sturgeons are cold-water fish and, like many other fish species, they require an adequate level of dissolved oxygen in their environment to thrive. The recommended quantity of dissolved oxygen for sturgeons is generally higher than for some other fish species. This type of fish typically prefers dissolved oxygen levels between 7-9 mg/L to maintain their health and well-being. Otherwise, the fish become stressed, stops consuming food, and are more susceptible to illnesses. A decrease in dissolved oxygen below 3 mg/L or prolonged exposure to concentrations below 5 mg/L could lead to fish suffocation. Also, the water PH needed to be 7,0 and the temperature between 18 – 22°C. Anoxic coastal basins, fjords, and lakes constitute a transnational problem across Europe.

In BLUE-GREENWAY, the methodologies of the Meso-scale pilots on eutrophication treatment and drainage water quality were sustainable & transferable to other regions that face similar obstacles in eutrophic and anoxic coastal ecosystems [7]. Solutions were proposed using innovative geoengineering materials that could adsorb the pollutants and improve water quality. The real-time monitoring system, the early warning system, and the model acting together could safeguard public safety by warning the region of toxic H2S in the air. The transferability of the project's achievements was based on continuous interaction between the project and its target groups through its platform and pilots. The pilots showed the exact methodology to reduce pollutants and improve water quality. The project developed networking with actors outside the partnership for disseminating project achievements. The exchange of good practices and results with areas outside the territory benefited more regions beyond the initial study area. An integrated database was designed to collect critical data for a set of user profile types and needs that were applicable and replicable to the whole project area, to aid PAs in procuring products, developing general directives, and supporting policy take-up. Stakeholders across Europe were invited to register to the platform and update its data on their region so that the results could apply and be replicable to the broader Europe area.The common results of the projects were the development of smart sensors and IoT devices for collecting and transmitting data on water quality, fish health, environmental parameters and the usage of artificial intelligence and machine learning algorithms for analyzing the data and providing decision support, risk assessment and early warning.

4.Conclusions

Incorporating advancements from both projects, we presented an all-encompassing method for monitoring water quality in aquaculture systems. By synergizing the technologies developed, we offered a comprehensive approach that ensured efficient and accurate assessments. This integrated system revolutionized the aquaculture industry, enabling real-time monitoring, early detection of issues, and prompt responses to maintain optimal conditions for aquatic life [13]. Through continuous data collection and analysis, our solution empowered aquaculturists with invaluable insights, promoting sustainable practices and minimizing environmental impacts. With enhanced precision and ease of implementation, this innovative approach heralded a new era of improved productivity and ecological stewardship within aquaculture operations. It was important to note that these two projects provide advantages in different areas, such as climate, environment, food, energy, health and job creation [2].

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Appendices

Internal documents: iPREMAS Project Proposal, BLUE-GREENWAY Project Description, iPREMAS Scientific and Technical Report.

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