Development and testing of a monitoring platform for underwater archaeological sites

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***Abstract*—Aquatic ecosystems are inherently dynamic and challenging to monitor, facing escalating anthropogenic threats such as climate change and widespread pollution. Consequently, continuous and reliable environmental monitoring is critical to preserve biodiversity, maintain the health of delicate ecosystems, monitor and regulate pollutant concentrations, and ensure the sustainability of resource exploitation (e.g., fishing). Furthermore, specialized monitoring is required for submerged cultural heritage sites (e.g., archaeological findings). While these sites share general environmental concerns, they also necessitate dedicated surveillance against physical damage, degradation, and unauthorized access or theft. Despite this critical need, a significant portion of aquatic environmental monitoring remains labor-intensive, relying on infrequent and localized sampling by human operators. This approach is inherently time-consuming, spatially sparse, and susceptible to sampling error, rendering it insufficient for the continuous, high-resolution data collection required. The urgent need is therefore for a next-generation monitoring system capable of providing constant, autonomous surveillance of both water and air parameters with sufficient temporal frequency and spatial resolution to deliver comprehensive and actionable insights. In this work we present he effort to design, realize and test a floating platform for the dedicated surveillance of a specific underwater archaeological site. We also present the results obtained from the testing deployment.**

***Index Terms*—monitoring coastal environment, internet of things, LoRa, archaeological underwater sites.**

I. Introduction and related work

Aquatic environments are delicate, dynamic and varied ecosystems that are subject to multiple threats and dangers. Rivers, lakes, lagoons, seas and oceans are crucially important for a wide variety of species, both marine and land-based: they support life and many aspects of human well-being. Occupying over 70% of the Earth's surface, the global ocean is a critical regulator of the biosphere, driving the complex exchange of heat, moisture, and biogeochemical cycles—most notably carbon sequestration. Beyond its role in climate modulation and biodiversity conservation, marine ecosystems represent a vital socio-economic backbone, providing essential food security, mineral resources, and energy for global populations. Climate change, due to greenhouse emissions and anthropogenic factors are putting in danger such delicate ecosystems. [1]. Detecting changes and attributing them to specific drivers has been especially difficult in ocean and coastal ecosystems because drivers, responses and scales (temporal, spatial, organizational) often overlap and interact. Because of the threats they are subject to, aquatic environments need extensive and real-time monitoring. To implement such an effective monitoring the UN Ocean Decade Initiative [2] has devised a strategy to implement an initiative called the Global Ocean Observing System (GOOS) [3]. This initiative identifies achievable recommendations that can be implemented to cover the gaps in achieving effective global ocean and maritime monitoring. Some of the recommendations include upgrading and expanding ocean observing capacity in poorly-observed areas and establishing new and sustained financing mechanisms for global ocean observing. The coalition represented in GOOS leads and supports a community of international, regional and national ocean observing programmes, governments, UN agencies, research organizations and individual scientists.

Beyond general environmental threats, underwater archaeological sites face unique risks from unauthorized access and looting. As vital witnesses to human history and cultural heritage, these artifacts require preservation efforts that are as essential as they are logistically challenging. The Apulia region of Italy serves as a primary example; its history as a Mediterranean seafaring nexus has left a dense concentration of submerged sites, such as the Tripolitanian wreck [4]. Consequently, these sites necessitate automated, real-time monitoring systems capable of alerting authorities to anthropogenic threats or environmental degradation, enabling immediate intervention.

In [5] the authors present a review on water monitoring systems based on the Internet of Things (IoT) architecture. They define the IoT as a global network of uniquely addressable networked nodes that communicate through established protocols. They analyze the area of water quality management and how the IoT concepts can enhance the application of

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This work was partially supported by DIH InnovaMare - Cross-border Digital Innovation Hub for innovative marine technology" funded by the Interreg Programme Italy-Croatia 2021-2027.

water monitoring systems. One of the key parameters that were considered is the ability of the system to send real-time data. One of the highlights of the research is that current transmission technologies such as Bluetooth, WiFi or Zigbee have a short communication range and a high power consumption. Instead, in [6] the authors focus on real-time aquaculture monitoring. They consider Long Range (LoRa) as a transmission technology given its wide coverage and low energy consumption. Focusing on oyster aquaculture, this work describes a monitoring network that delivers real-time air and water quality data to users. By enabling informed decision-making through data visualization, the study demonstrates the system's overall effectiveness. Concerning aquatic anthropic environments, such as port areas, the authors in [7] propose a robotic aided monitoring platform that allows to provide four main services that are instrumental in port activities: anti-grounding, ship hull inspection, quay wall inspection and bathymetry data collection. The system is based on robot-mounted sensors that collect the data and transmit them to the shore station via underwater communications and long range WiFi. The final user can analyze these data via a web interface and then feed the decisional process. The design is then validated via a live test in the port of Hamburg. An approach that is both efficient and affordable is presented in [8] where the authors focus specifically on the monitoring of underwater archaeological sites. The system consists of a subsea node placed near the monitoring site, connected to a surface buoy through an umbilical cable. This node is then connected to a buoy, which contains an LTE router for data transmission to a remote web platform for data storage and visualization. The system includes an underwater camera, capturing images in the near-infrared, provided with a biofouling detector. Along with the camera, the other sensors are temperature, pH, dissolved oxygen, and oxidation-reduction potential (ORP). They tested the device in Calabria, Italy, although it is not clear for how long.

This paper presents the design, development and testing of an unexpensive floating monitoring platform, tailored for underwater archaeological sites. The paper is structured as follow: Section II illustrates the desing and the development of the device, Section III presents and shows the way we organized the testing campaign and illustartes the collected measurements. Section IV finally concludes the paper, presenting also future developments.

II. System design and development

Wireless and More and the University of Padova, thanks to ARTI Puglia and upon requirements provided by the Archaeological Department of the University of Salento and the Marine Protected Area of Porto Cesareo, designed, realized and tested a floating platform for the dedicated surveillance of a specific underwater archaeological site.

Two core monitoring requirements were defined:

1) **Optical Surveillance**: Real-time video capture of the underwater site;

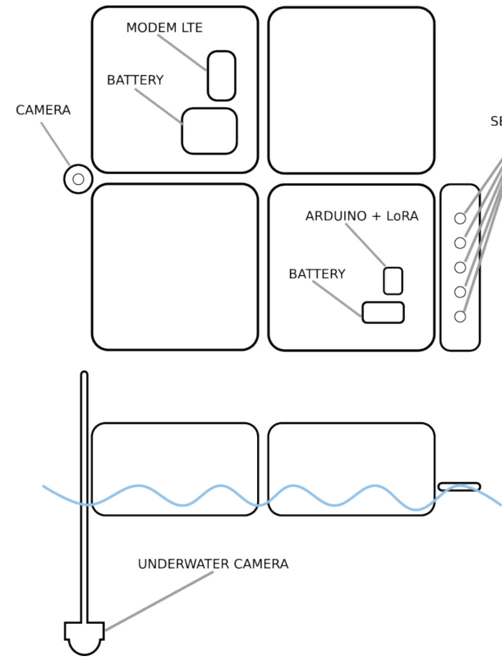


Fig. 1: Structure of the device, from above and from the side

2) **Environmental Assessment**: Parametric monitoring of the surrounding water characteristics.

To satisfy these requirements, the design phase incorporated two distinct subsystems:

1) **Subsea Camera System**: Design, implementation, and rigorous testing of an underwater camera capable of streaming the video signal remotely to an onshore station.
2) **Multi-Parameter Sensor Node**: Integration of the SENSWICH device [9], a pre-existing monitoring platform previously validated in Chioggia, Italy, and developed through a collaboration between the University of Padova and SubSeaPulse srl [10].

The primary technical objectives of this project were two: to successfully meet all defined monitoring requirements, and to realize a device characterized by high energy efficiency and cost-effectiveness.

The floating structure is composed by four floating cubes: two of them completely filled with expanded foam to provide buoyancy and stability while the other two cubes host the two aforementioned subsystems.

A. Subsea Camera System

One of the cubes, as can be seen in Figure 1, hosts the camera and LTE system. The camera system consists of an IP camera module, embedded in a custom made 3D-printed watertight encasing and connected with a Power-over-Ethernet cable to the Ethernet port of the LTE modem and to a 12V Dc-Dc converter for the supply. The electric power is supplied by a load/charge regulator connected to a 50 W_p polycrystalline photovoltaic panel and a sealed AGM lead battery (12 V - 18 Ah). Given an overall power consumption of 200 mA

Fig. 2: Screenshot of the video stream displaying the archaeological relics

capable alone of powering the system for up to 3 days in absence of solar contribution.

The IP camera module hosts an Real Time Streaming Protocol (RTSP) server, providing a standardized streaming endpoint. This allows remote clients or headless systems to consume the real-time video feed via a direct network request. Video is H.264 encoded in two levels of qualities, accessible in two different ports: high quality with 1080p resolution and low quality with lower resolution. LTE modem is connected to a remote server via a secure VPN connection, exploiting OVPN protocol. As standard LTE SIM cards typically lack static IP addresses and operate behind Carrier-Grade NAT (CG-NAT), establishing a persistent secure tunnel is essential. This connection is fundamental for enabling remote RTSP stream access and facilitating centralized system administration. In the remote server, where the VPN connection is terminated, an instance of FFmpeg [11], an open-source video transcoder, acts as RTSP client.

The remote server is entirely private, with access restricted exclusively to the administrator. For demonstration purposes, the video feed has been redirected to a dedicated YouTube channel, allowing public live streaming of the seabed. While this approach is ideal for tourism-oriented applications, the remote server retains the versatility to manage the feed differently. For instance, in a monitoring-system scenario, the video could be shared privately with a select group of authorized users.

The LTE traffic comprising the VPN overhead and the video feed was estimated to be in the order few Mbit/s. Some ISP detect continuous uplink traffic from a specific node and decide to limit the bandwidth of the LTE connection. For this reason, the administrator can decide to switch from high quality video streaming to low quality based on network statistics. Furthermore, to reduce the load on the network, the video stream was scheduled to start around 5 a.m. and end around 8 p.m. given that, outside this time frame, the absence of daylight does not allow to capture the image anyway. A sample frame of the video stream can be seen in Fig. 2.

B. Multi-Parameter Sensor Node

The other cube is hosting the SENSWICH and its battery as can be seen in Figure 1. The SENSWICH is an affordable, real-time device for monitoring aquatic environments. It can track pH, temperature, Dissolved Oxygen (DO), turbidity, Electrical Conductivity (EC) and liquid level and send the acquired values to any remote server through LoRa connectivity and LoRaWAN protocol.

The base computing board is an Arduino MKRWAN 1310, which features an integrated SX1276 LoRa transceiver, and interfaces with the different sensors. Following a successful LoRaWAN join procedure to authenticate the device in the network, SENSWICH is configured to sample sensor values regularly at specific intervals, tuned to 10 minutes. Between two consecutive samplings, the sensors are completely turned off to reduce the overall power consumption. A key advantage of LoRaWAN is that the device can remain in sleep mode for the majority of the time, awakening only for the transmissions scheduled at the aforementioned intervals. This results in a battery-powered system with a significantly maximized operational lifespan.

A LoRaWAN network consists of three main segments: the end-nodes (e.g. SENSWICH), the gateways that provide wide-area connectivity, and the cloud infrastructure. The latter comprises a Network Server for protocol management and an Application Server, which facilitates user access and data visualization. A LoRaWAN gateway was deployed to provide connectivity in the SENSWICH installation site. The LoRa gateway was installed on top of a nearby historical tower called *Torre Chianca*: this building also provided a wired connection to the Internet, thus allowing the gateway to be connected to a remote server. This deployment provides network coverage across a multi-kilometer range, encompassing the specific bay where the buoy is installed.

The cloud infrastructure was hosted in Amazon Web Services (AWS), that offers a variety of services for IoT and LPWAN, including LoRaWAN. Fig. 3 depicts the AWS infrastructure designed for the system, detailing the specific cloud services leveraged for data ingestion, management, and storage. At the architectural level, the LoRaWAN gateway deployed in Puglia establishes a secure WebSocket connection to AWS IoT Core. As a fully managed serverless platform, AWS IoT Core facilitates seamless device-to-cloud integration while eliminating the operational overhead of infrastructure management. It acts as LoRaWAN Network Server, where the administrator provisions and authenticates both end-nodes and gateways to grant network access. An AWS IoT Rule is configured to trigger immediately upon the arrival of a LoRaWAN packet. This rule acts as a router, forwarding the received uplink packet to an AWS Lambda function, a serverless compute service containing the core logic for data processing. The function parses the encoded sensors measures, validates the data integrity, and performs the necessary unit conversions. Once processed, the samples are saved persistently in Amazon Timestream, a time-series database

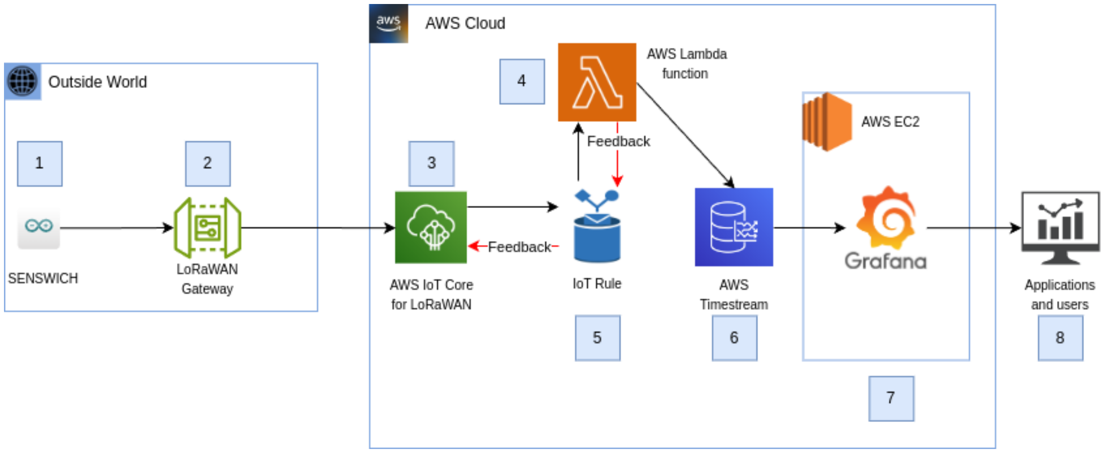
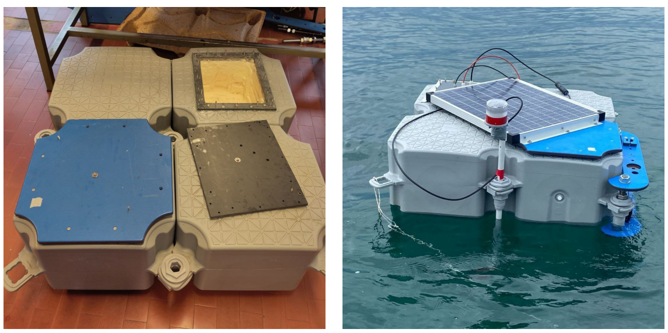


Fig. 3: AWS infrastructure overview



(a) (b)

Fig. 4: (a) The device under construction and (b) the device deployed in Porto Cesareo, Italy.

optimized for the high-velocity arrival and long-term storage of sensor data, such us SENSWICH. The data access layer is hosted on an Amazon EC2 instance running Grafana, an industry-standard platform for real-time monitoring and observability. This instance is configured with the necessary IAM permissions for direct integration with Amazon Timestream, enabling high-performance querying of the stored sensor data. Through a centralized Grafana dashboard, users can filter data by specific SENSWICH nodes, with dedicated panels providing time-series visualizations for each individual sensor metric. For further analysis and processing, the user can also download sensor data in CSV format directly from Grafana dashboard.

The device was firstly assembled in the laboratory to dry test the functionalities, then partly disassembled and reassembled at the deployment site. Figure 4 shows two phases of the deployment: the assembling phase and the deployed device.

III. Testing Campaign and Collected Data

Apulia region presents a lot of archaeological sites submerged into the water, in some cases not too far from the coast. In light of this, the region was chosen for the first deployment of a pilot test for the InnovaMare project [12] concerning the development of an automatic, IoT-based, remote monitoring platform. The device was deployed in the Torre Chianca bay, in Porto Cesareo (Lecce, Italy), above an archaeological underwater site, known as *relitto del Sarcofago*. The underwater archaeological site lies approximately 4 meters under the surface and presents tombstones from the roman era, part of a Roman necropolis dating back to the 3rd-4th century CE [13]. The device was anchored to the seabed via three dead weights and ropes that kept the device not only in place, but also at a fixed angle: this allowed to set the position both for the solar panel and the camera. The long-term trial assessment lasted for approximately seven months, from May to November 2025, and allowed to understand the effectiveness of the architecture, including reliability and affordability. The device was moved, for a short period, to a different archaeological site, further away form the coast, known as *relitto delle tripolitane*, to test the coverage of both the LoRa gateway and the LTE network.

Considering that the device was under maintenance for some of the periods and also underwent some technical updates to improve the lifetime of the sensor array, a total of 52 days of water parameters data were collected, for a total of 7900 data samples. The total amount of video data collected reached 285 recordings, each of approximately 9 hours, totaling more than 2500 hours of recording.

Figure 5 presents the data collected over seven consecutive months, from May 6th to November 28th. To ensure clarity, null values—stemming from battery depletion or maintenance intervals when the buoy was removed from the water—have been excluded. While the dataset provides oceanographic insights, its primary utility is as a diagnostic record of the system's operational health. Given that the device underwent rigorous evaluation during this phase, logistical constraints occasionally delayed battery replacement and sensor recalibration. By filtering out periods of inactivity, the segmented visualization in Figure 5 facilitates a more effective analysis of the device's performance throughout the deployment.

It must be highlighted that the complete sensor array was substituted at the beginning of November 2025: the new sensors were calibrated and the battery was swapped with a new, charged one. This can be clearly seen in the final part of the plots where data restart having consistent and meaningful behavior

The DO sensor demonstrated a high degree of operational fidelity during the initial deployment phase, evidenced by the clear acquisition of diel biological signals. The transition into the failure phase was marked by a significant attenuation in signal amplitude. As the battery voltage began to decline and maintenance became irregular, these cycles dampened significantly. The subsequent drop to near-zero values during the peak failure served as a diagnostic signature of an electronic bias failure. The November validation phase, which saw DO levels return to the $\sim$6 mg/L range, confirmed that the sensor's polarographic membrane was damaged and that replacing the sensor was necessary to start getting correct values again

The EC sensor readings remained largely consistent with seawater values ($\sim$54 mS/cm) until the data showed a failing behavior: the initial drops to approximately 8 mS/cm functioned as a binary diagnostic, indicating hardware failure: later plateauing to $\sim$0.19 mS/cm confirmed a broken sensor, as can be seen in Figure 5. The sensor was replaced a the end of June. Being based on an induction coil, these sensors have a binary state: either they produce a meaningful results or, in case of insufficient voltage, they fail give meaningful results.

The pH sensor's behavior was characterized by a reference junction drift, providing a map of the device's maintenance needs. Following a stable baseline period at approximately 8.45, the sensor began a linear descent, which can be identified as the exhaustion of the reference potential. During the peak failure phase, the sensor produced erratic or negative values, indicating that the high-impedance circuitry had been compromised by the lack of steady voltage. The successful rebound to baseline values in November after substitution and battery replacement shows again the meaningful values.

The Temperature sensor demonstrated the highest operational resilience of the integrated array, maintaining a consistent and accurate thermal profile throughout the entire deployment. Unlike the chemical sensors, which were prone to potentiometric drift or signal collapse, the temperature probe remained unaffected by environmental interference or biofouling, accurately tracking the thermal inertia of the water column from May through November. The few observed anomalies—characterized by instantaneous spikes to 85°C—were easily isolated from the dataset and did not compromise the overall continuity of the record. These spikes are a known digital artifact of the 1-Wire communication protocol, appearing only when the supply voltage momentarily dipped below the operational threshold required for a complete data conversion. Because these events were infrequent and distinct from the ambient baseline, the sensor provided a stable and reliable reference for the duration of the study, confirming its role as the most robust component of the hardware suite.

By partitioning the dataset into four distinct operational windows, as shown in Figure 5, we can decouple the natural environmental fluctuations of the coastal site from the technical signatures of the instrumentation. This structured chronological division, moving from an initial baseline through periods of escalating power instability and culminating in a total hardware-swap validation, allows for a precise characterization of the system's operational history. Consequently, the data serve as a comprehensive record of both the local oceanographic conditions and the localized behavioral response of each sensor to the stresses of an autonomous, battery-dependent deployment.

- **Dissolved Oxygen (DO)**: columns 1 and 4 yield the most reliable data. Conversely, columns 2 and 3 show the onset of instability, where the sensor failed to maintain its polarographic bias due to insufficient battery voltage;
- **Electrical Conductivity (EC)**: while the sensor was initially stable, it began malfunctioning midway through column 1. By column 2, readings dropped to near zero, confirming a total hardware failure; the unit was subsequently identified as broken and replaced in early July. Consistent performance only resumed in columns 3 and 4 following the substitution;
- **pH**: the data reflects the sensor's high sensitivity to calibration. Meaningful trends are visible in columns 1, 2, and 4, though a characteristic downward drift appears toward the end of these periods as the battery approached discharge. Column 3 exhibits erratic behavior, likely stemming from an improper calibration during deployment;
- **Temperature**: this probe was the most resilient to environmental drift and hardware issues. It maintained a consistent behavioral pattern throughout the deployment, with errors appearing only when the supply voltage fell below the operational threshold during total battery depletion.

IV. Conclusion and Future Works

In this study, we successfully developed and deployed an inexpensive yet highly efficient autonomous multiparametric buoy. The system demonstrated its capability to simultaneously monitor critical water quality parameters—specifically Dissolved Oxygen, Electrical Conductivity, pH, and Temperature—while providing a continuous real-time video stream of the seabed. This dual-modality approach (combining chemical sensors with visual data) offers a comprehensive perspective on ecosystem health that single-method sensors cannot achieve.

The long-term trial, spanning from May to November 2025, was instrumental in assessing the platform's robustness. The deployment successfully captured, alongside baseline meaningful behavior, also the phases where it was necessary to replace the battery or recalibrate, or clean, the sensors. This allowed to establish a framework for scheduling maintenance operations on the device, for future deployments.

Beyond the collection of physicochemical data, the buoy's primary distinguishing feature was its ability to maintain a continuous real-time video stream of the seabed. This visual layer provided invaluable context to the sensor readings and control authorities, allowing for the direct observation of

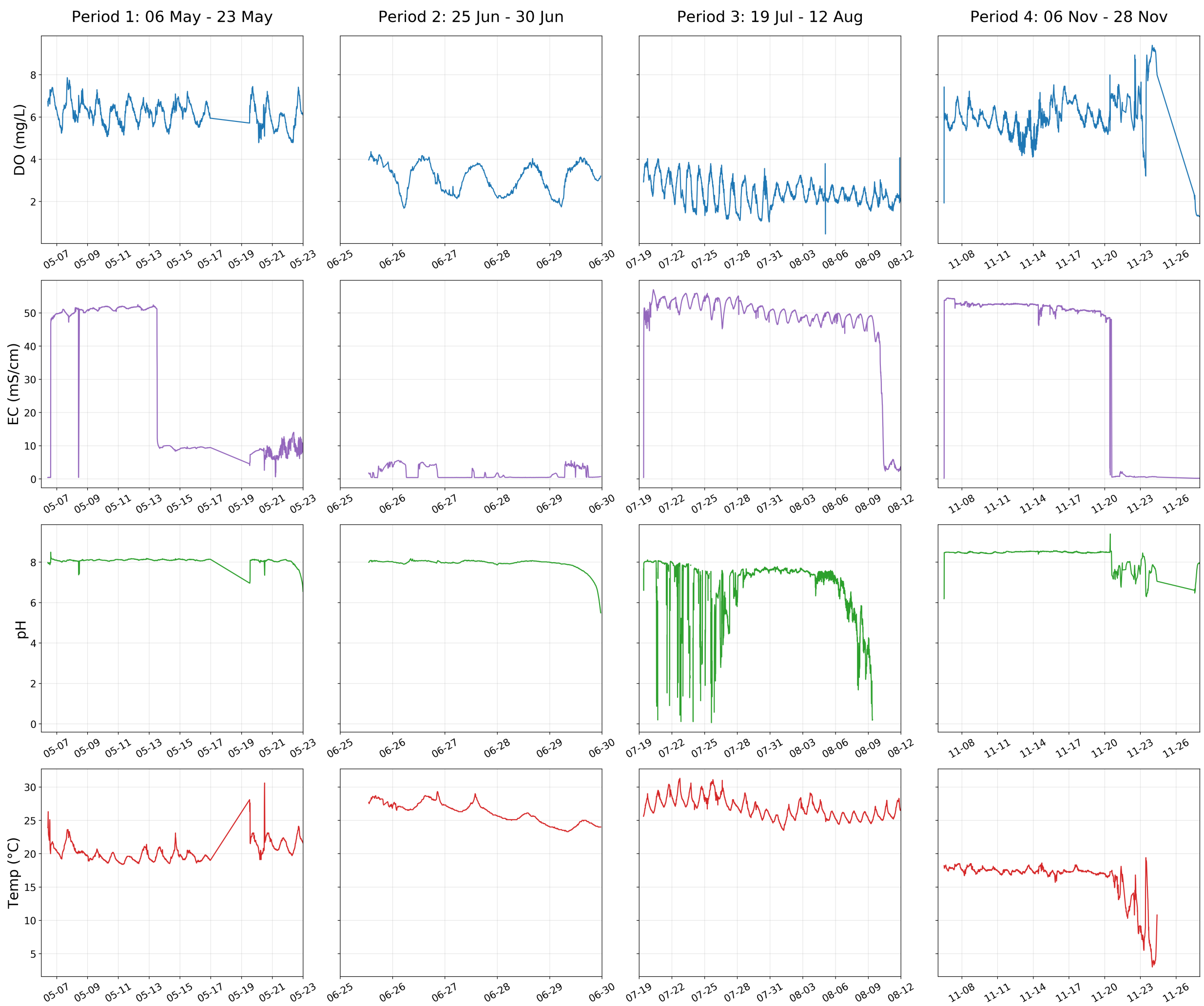


Fig. 5: Water quality matrix, divided per period

ancient archaeological relics lying on the benthos. By synchronizing the video feed with the environmental parameters, we were able to monitor the physical condition of these submerged artifacts in situ. This dual-approach confirmed that the platform could serve not only as an ecological monitor but also as a low-cost sentinel for underwater cultural heritage, documenting how seasonal shifts and environment-induced phenomena visually impact the site and its surrounding marine life.

However, the pilot test also highlighted critical areas for future improvement. The observed sensor drift in the pH probe during the latter half of the deployment emphasizes the challenges of biofouling and the need for either integrated self-cleaning mechanisms or more frequent calibration intervals in warm, high-salinity environments.

Future developments will include the strengthening of the overall structure to make it more resilient to high waves and tidal currents. Counter actions must also be taken to limit the dirt that is depositing on the solar panel and the biofouling depositing on the sensors. Additionally, the solar panel was powering only the camera and the LTE modem: the sensor and their control board was powered by their own battery. A future development will include the inclusion of solar panels to power also the sensor system, to avoid the need to replace the battery.

Ultimately, this prototype proves that high-fidelity environmental monitoring is possible with low-cost hardware, paving the way for scalable, distributed networks of autonomous buoys that can provide early warnings for ecological shifts in sensitive coastal zones.

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