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High-frequency, spatially distributed monitoring of water temperature: the MultiTEMP system

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ABSTRACT

High-frequency, spatially distributed monitoring of water temperature: the MultiTEMP system.

Water temperature is a key factor influencing physical, chemical, and biological processes in aquatic ecosystems. Accurate monitoring is crucial for understanding these dynamics, their variability, and their evolution, especially in the face of global change. In-situ measurements and satellite remote sensing methods have limitations ranging from high costs and logistical constraints to restricted spatial and temporal resolutions. This study introduces the MultiTEMP system, a cost-effective and customizable tool for high-frequency, spatially distributed water temperature monitoring. Leveraging open-source Arduino technology and digital sensors, MultiTEMP enables synchronized data collection across various locations (multiple submerged points), significantly advancing the study of thermal dynamics. The system has been tested in regulated rivers affected by hydropeaking events. Field deployments have demonstrated its capability to capture detailed spatiotemporal temperature variations, which are essential for understanding the ecological impacts of artificial changes in flow regime. Overall, MultiTEMP represents a simple but valuable monitoring system, offering an affordable, flexible, and scalable approach to water temperature monitoring. Its continued development and integration into broader monitoring networks could significantly improve the environmental management of flows and the conservation of fluvial ecosystems.

KEY WORDS: Arduino, water temperature, aquatic ecosystems, thermal dynamics, spatiotemporal variability, rivers.

RESUMEN

Monitoreo de alta frecuencia y distribuido espacialmente de la temperatura del agua: el sistema MultiTEMP.

La temperatura del agua es un factor clave que influye en los procesos físicos, químicos y biológicos de los ecosistemas acuáticos. Un monitoreo preciso es fundamental para comprender estas dinámicas su variabilidad y evolución, especialmente frente al cambio global. Las mediciones in situ y los métodos de teledetección satelital presentan limitaciones que van desde los altos costos y las restricciones logísticas hasta resoluciones espaciales y temporales limitadas. Este estudio presenta el sistema MultiTEMP, una herramienta eficiente y adaptable para el monitoreo de la temperatura del agua con alta frecuencia y distribución espacial. Basado en tecnología Arduino de código abierto y sensores digitales, MultiTEMP permite la obtención sincronizada de datos en múltiples ubicaciones (varios puntos sumergidos), lo que representa un avance significativo en el estudio de la dinámica térmica. El sistema fue probado en ríos regulados afectados por eventos de hydropeaking. Las *mediciones en campo han demostrado la capacidad de MultiTEMP para capturar variaciones espaciotemporales detalladas de la temperatura, esenciales para comprender los impactos ecológicos de los cambios artificiales en el régimen de caudales. En conjunto, MultiTEMP representa un sistema de monitoreo simple pero valioso, que ofrece un enfoque asequible, flexible y escalable para el control de la temperatura del agua. Su desarrollo continuo e integración en redes de monitoreo más amplias podrían mejorar significativamente la gestión ambiental de los caudales y la conservación de los ecosistemas fluviales.*

PALABRAS CLAVE: *Arduino, temperatura del agua, ecosistemas acuáticos, dinámica térmica, variabilidad espaciotemporal, ríos.*

INTRODUCTION

Water temperature is a fundamental parameter in the ecology and dynamics of aquatic ecosystems, one that is crucial for understanding the functionality of water bodies. In aquatic ecosystems, temperature varies across daily, seasonal, and interannual time scales and also exhibits spatial variation, not only longitudinally but also vertically and transversely (Webb et al., 2008). Temperature regulates the metabolism of stenothermic and poikilothermic organisms (e.g. Brown et al., 2004); it increases up to a tolerable limit, leading to heightened rates of primary production and increased respiration in both autotrophs and heterotrophs (e.g. Straile, 2005, Reynolds, 2006). Moreover, temperature modulates the physical and chemical properties of water: thermal gradients drive chemical gradients (e.g. oxygen stratification, nutrient distribution), which, in turn, affect organism distribution and community structure (e.g. Poole & Berman, 2001). In river ecosystems, hydrological and thermal fluctuations do not create strong stratification, unlike in lentic systems, but they do influence the biological cycles of aquatic communities. These changes can cause mismatches between resource availability (for example, primary production from phytoplankton or periphyton) and the trophic requirements of higher levels (such as macroinvertebrates and fish), thereby affecting ecological synchrony—defined as the temporal alignment between resource availability and consumer demand across trophic levels (Stenseth & Mysterud, 2002)—and the efficiency of energy transfer throughout the food web (Margalef, 1983, Joehnk et al., 2008).

Overall, water temperature is a key factor in the health and survival of aquatic organisms, influencing reproduction, growth, and distribution. Temperature also affects the physical and chemical properties of water, including dissolved oxygen concentration and gas solubility according to Henry’s law (Sander, 2015). Therefore, multi-temporal (time series) and multi-spatial (spatially distributed) water temperature datasets are essential for understanding dynamics of temperature regimes, helping identify patterns, alterations, and recovery processes.

As climate change and human activities progressively alter global water temperature patterns, a better grasp of the role of water temperature in water bodies is becoming increasingly urgent for predicting effects on aquatic life and ecosystem services. By examining the effects of water temperature at different temporal and spatial scales, we can better comprehend the broader implications of variations in temperature patterns due to global change. This understanding is vital for informing conservation strategies and effectively managing water bodies in the face of environmental change. Therefore, high-resolution measurement and monitoring of water temperature is of paramount importance. In addition, it is worth highlighting hydraulic infrastructures’ thermal impacts, which are well known but often poorly documented. For example, studies on equilibrium temperature dynamics (e.g. Buendía et al., 2015) and case analyses such as those conducted in the Cinca River provide valuable insights into how human interventions can reshape the thermal regimes of rivers, with significant ecological consequences (Carrero-Carralero et al., 2024).

Several low-cost and open-source approaches for monitoring water temperature have been developed in recent years, including Arduino- and Raspberry Pi-based systems designed for environmental sensing and distributed aquatic monitoring (e.g. Tonolla et al., 2010, Kelleher et al., 2012). These systems have demonstrated the potential low-cost technologies hold for acquiring high-frequency thermal data in freshwater environments, often providing flexible and customizable alternatives to commercial monitoring equipment. However, many existing approaches are limited in either the number of simultaneously connected sensors, spatial deployment flexibility, or the integration of synchronized geolocation data. Commercial multi-sensor platforms are available, but they are frequently associated with high implementation costs and reduced adaptability for experimental monitoring designs. In this context, the MultiTEMP system is designed to fill a methodological gap by combining (1) synchronized multi-point temperature measurements using a single logger, (2) flexible horizontal and vertical sensor-chain deployment, and (3) integrated global navigation satellite system (GNSS) geolocation for spatially explicit thermal monitoring within a cost-effective and adaptable framework.

The aim of this paper is to present the MultiTEMP system as a cost-effective and flexible tool for high-frequency, spatially distributed monitoring of water temperature, intended to improve our understanding of thermal dynamics in aquatic ecosystems and support effective environmental management.

METHODOLOGY

Water temperature in aquatic environments is routinely monitored using a range of in-situ and remote sensing technologies that provide data at different spatial and temporal resolutions depending on study objectives (Webb et al., 2008, Dugdale, 2016). In limnological and riverine research, measurements are commonly obtained using thermistors, resistance temperature detectors (RTDs), thermocouples, distributed temperature sensing (DTS), and thermal infrared imaging techniques.

Table 1 summarizes the different available methods and technologies in terms of their capabilities to obtain point measurements and multi-point or spatially distributed measurements, and different general options for monitoring water temperature.

Point measurements

Water temperature at a specific location is commonly measured using discrete in-situ sensors, which provide high temporal resolution and accurate local thermal characterization. Thermistors (e.g. the YSI 400 series by Yellow Springs Instruments) are among the most widely used sensors in aquatic sciences due to their sensitivity, rapid response time, and relatively low cost (Stevenson et al., 2004, Webb et al., 2008). Digital thermistors, such as the DS18B20 (Maxim Integrated®), facilitate multi-sensor integration through the 1-Wire protocol, which is a single-wire serial communication bus that enables multiple sensors to share the same data line. These sensors are particularly suitable for distributed monitoring applications because of their low power requirements and ease of deployment. RTDs, such as the CS655 by Campbell Scientific®, provide high precision and long-term stability, making them appropriate for long-duration monitoring programmes, although at higher cost (Nicholas & White, 1994, Frutiger et al., 2004). Finally, thermocouples (e.g. Type K by Omega Engineering®) are robust and inexpensive sensors suitable for harsh environments, although generally less precise than thermistors or RTDs.

Multi-point and spatially distributed measurements

Several technologies allow for spatially distributed measurements of water temperature beyond single-point observations. DTS uses fibre-optic cables to obtain continuous temperature measurements over long distances, entailing high equipment and deployment costs (Selker et al., 2006, Tyler et al., 2009). Satellite thermal imagery from platforms such as MODIS and Landsat enables large-scale surface water temperature mapping, although measurements are limited by atmospheric conditions, cloud cover, revisit frequency, and spatial resolution (Wloczyk et al., 2006, Dugdale, 2016, Malbéteau et al., 2018). Close-range thermal imaging, including thermal cameras (e.g. FLIR A320) fitted to drones or unmanned aerial vehicles (UAVs), provides high-resolution surface temperature mapping at

Table 1. Summary of methods for measuring and monitoring water temperature (*Cost: Low (€10-100); Medium (€100-1000); High (€1000-10000)). *Resumen de los métodos para la medición y el monitoreo de la temperatura del agua (Coste: Bajo (10-100€); Medio (100-1000€); Alto (1000-10000€).*

Category	Method/Technology	Description	Limitations	Cost*
Point Measurements	Thermistors (Stevenson et al., 2004, Webb et al., 2008)	High sensitivity, rapid response, commonly used in ecological research	Requires calibration and can be affected by biofouling	Medium
	Digital Thermistors (Maxim Integrated ®, DS18B20)	Digital output and easy integration with monitoring systems	Limited temperature range compared to RTDs	Low-Medium
	RTDs (Nicholas & White, 1994, Frutiger et al., 2004)	Highly accurate and stable for long-term studies	More expensive and requires proper calibration	High
	Thermocouples (Omega Engineering (R), Type K)	Wide temperature range and durable in harsh environments	Lower accuracy than RTDs and thermistors	Low
Multi-Point Measurements	Distributed Temperature Sensing (DTS) (Selker et al., 2006, Tyler et al., 2009)	Fibre-optic cables provide continuous temperature profiles over long distances	Expensive installation and complex data processing	High
Remote Sensing	Satellite Imagery (Wloczyk et al., 2006, Dugdale 2013, Malbéteau et al., 2018)	Large-scale surface temperature monitoring	Measures only measures surface temperature, affected by cloud cover	Low-Medium
	Thermal Imaging (Torgersen et al., 2001, Dugdale et al., 2013, Collas et al., 2019)	High-resolution aerial temperature mapping	Expensive, weather-dependent	High
Long-Term Monitoring	Fixed Stations (Piccini et al., 2015, González-Piana et al., 2017, Mangope et al., 2018)	Continuous, high-precision monitoring at a single location	Limited spatial coverage, requires maintenance	Medium-High
	Moored Sensor Arrays (Martin et al., 2012)	Measures temperature at multiple depths in lakes or oceans	Requires careful data management and extrapolation	Medium-High
	Wireless Sensor Networks (WSNs) (Dugdale, 2016, Collas et al., 2019, Redana et al., 2024)	Real-time data transmission with flexible deployment	High power and data-processing demands	High
Short-Term/Mobile Monitoring	Unmanned Surface Vehicles (USVs) (Marteau et al., 2022, Redana et al., 2024)	Collects real-time spatial temperature data over large areas	Limited by accessibility and high operational costs	High

local scales and is increasingly used for thermal assessments in rivers (Torgersen et al., 2001, Dugdale et al., 2013, Collas et al., 2019, Marteau et al., 2022). Analysis of rivers' thermal regimes requires time series data on water temperature, whether spatially distributed or at a single location. This section describes systems used for long-term monitoring. The study of thermal variables at a spatiotemporal scale is conditioned by the measurement system used. The platform where the sensor is deployed or installed is key, as it determines the capacity to record continuous (temporal) datasets at resolutions specified by the user. Furthermore, energy demands and the flexibility to select the frequency with which data are measured, integrated, and saved are also crucial. Finally, while remote sensing approaches can help cover large areas, they have limitations in terms of how often the platform revisits a given area and the spatial resolution of the sensor it uses.

Spatially distributed maps of water temperature at low temporal resolutions

Satellite-sensed imagery makes it possible to map surface water temperature at a temporal resolution dictated by the revisit time of the satellite platform. In this context, spatial resolution is determined by the characteristics of the sensor. Remote-based approaches are typically considered a low-cost option compared to other monitoring methods, as they can cover large areas without the need for on-the-ground infrastructure. However, the fusion of data with ground measurements is often required for calibration and validation purposes (e.g. Dugdale, 2016, Malbéteau et al., 2018, Collas et al., 2019, Marteau et al., 2022, Redana et al., 2024). Thermal imagery acquired using unmanned surface vehicles (USVs) or drones may improve both spatial and temporal resolution, but such approaches are generally deemed expensive due to the cost of the specialized equipment required, as well as the operational costs of deploying and maintaining the technology.

Monitoring water temperature at high temporal resolutions

Fixed stations are widely used for long-term water temperature monitoring at specific locations in rivers, while buoys are more common in reservoirs and lakes. Equipped with sensors and data loggers, these platforms provide continuous, high-precision measurements, making them essential for detecting long-term trends. Furthermore, advances in telemetry allow for real-time data transmission to remote databases, improving monitoring efficiency (Piccini et al., 2015, Piccolroaz et al., 2016, González-Piana et al., 2017, Mangope et al., 2018). The cost of these systems varies but is generally medium to high, depending on sensor precision and data transmission capabilities.

Platforms such as moored arrays consist of multiple temperature sensors deployed at different depths in lakes, reservoirs, or oceans. They are particularly useful for studying thermal stratification and seasonal variations. These systems provide valuable vertical temperature profiles, but data extrapolation between sensors must be done carefully to avoid inaccuracies (Martin et al., 2012). Challenges include sensor synchronization, power supply management, and potential biofouling. Given the complexity of deployment and the need for specialized data loggers, moored sensor arrays are considered low medium-cost solutions.

Wireless sensor networks (WSNs) enhance flexibility in water temperature monitoring by allowing interconnected sensors to transmit real-time data over large areas. They can improve spatial coverage and reduce the need for manual data retrieval, depending on the number of sensors deployed and their distribution and configuration, all of which are critical factors for effectiveness in dynamic aquatic environments. However, they require significant power, advanced data processing, and robust communication infrastructure (Dugdale, 2016, Malbéteau et al., 2018, Collas et al., 2019, Redana et al., 2024). Although WSNs offer high scalability, their cost is generally high due to the expenses associated with multiple sensors, network maintenance, and data storage.

The MultiTEMP system

Although various methods exist for measuring water temperature, many of their commonly cited limitations—such as cost, depth profiling, and calibration requirements—are shared across technologies, including newer platforms like MultiTEMP. Therefore, it is essential to evaluate what specific advantages MultiTEMP offers in terms of cost-efficiency, ease of deployment, adaptability, and long-term reliability, rather than focusing solely on the shortcomings of traditional systems. In this technical note, we present MultiTEMP, a low-cost, Arduino-based system designed for high-frequency temperature monitoring at multiple submerged points. Its flexible configuration allows for both transverse and vertical profiling, with applications across diverse aquatic environments. The system has been successfully tested in a hydropeaked river reach, i.e. a fluvial segment subjected to marked and rapid fluctuations in flow for hydropower energy generation (e.g. Batalla et al., 2021), where it proved capable of capturing rapid spatial and temporal temperature variations. It thus offers a practical and scalable solution for thermal mapping in lakes and rivers.

Assembling sensors based on Arduino technology

The prototype design is built around an array of water temperature sensors connected to an Arduino® MKR baseboard paired with programmable accessory development boards (Bluetooth and GNSS). Additionally, it includes a controller (pushbutton) and two visual elements, specifically a counter and an LED signal. Depending on the programming, the system is capable of recording data automatically at a given temporal frequency, or manually via use of the pushbutton. The baseboard is connected to the GNSS and Bluetooth development boards using cables, along with the pushbutton as a recorder, the counter display, and an LED indicator. The circuit includes a 4.7 kΩ pull-up resistor, which is the standard configuration for DS18B20 sensors operating on a 5 V 1-Wire bus. The system uses a 2 V battery as its power source. The temperature sensors are connected to the controller at one end of the 1-Wire bus to complete the circuit. Data recordings are stored on an SD card via an MKR SD Proto Shield adapted to an Arduino® MKR baseboard (Fig. 1).

The temperature sensors are linked linearly using a metal chain (Fig. 2A). The size of the chain has to be adapted to the sediment size if the system is to be deployed horizontally or cross-sectionally, allowing the sensors to be placed near the bed and register temperatures at the same level above it. If the sensors are to be used vertically (in lakes or dams, for instance), the size of the chain will determine its weight and the ease of correct deployment. The length of the chain is determined by the objective of the study and the spacing between sensors. In our prototype, a total of 11 sensors are connected linearly, starting from the connection on the Arduino baseboard. All features are compatible with the chosen Arduino board, requiring no further adjustments. The only adaptation necessary involves interconnecting sensors every two metres using a triple splice, where two sensors are soldered at each one-metre interval. This results in a total of 12 metres of cable with 11 temperature sensors. Figure 2A shows a diagram of an array of sensors and figure 2B the prototype developed in this study (12 m in length, 10 kg in weight, a metal chain with a 98 mm diameter, and 11 sensors at one-metre intervals). The 1-Wire protocol theoretically allows many DS18B20 sensors to operate on a single bus (commonly up to ~100 devices under suitable conditions), although practical limits depend on cable length, power stability, electrical noise, and bus capacitance. Because sensors are queried sequentially, there is a small temporal lag between consecutive readings; however, under the sam-

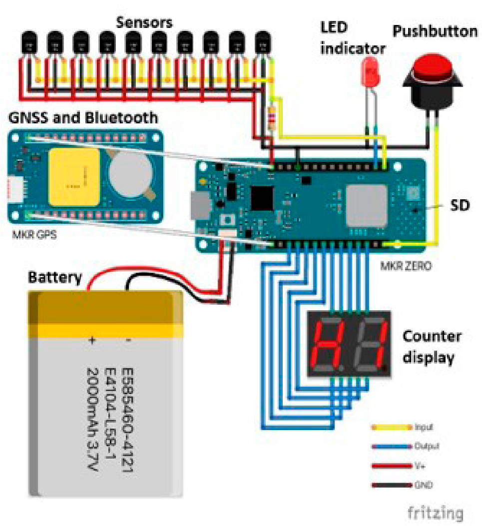

Figure 1. Schematic diagram showing the circuit layout, the temperature sensors, and the associated wiring (hardware). The schematic was created using Fritzing® software (version 0.9.3b). *Diagrama esquemático que muestra la disposición del circuito, los sensores de temperatura y el cableado asociado (hardware). El esquema fue elaborado utilizando el software Fritzing® versión 0.9.3b.*

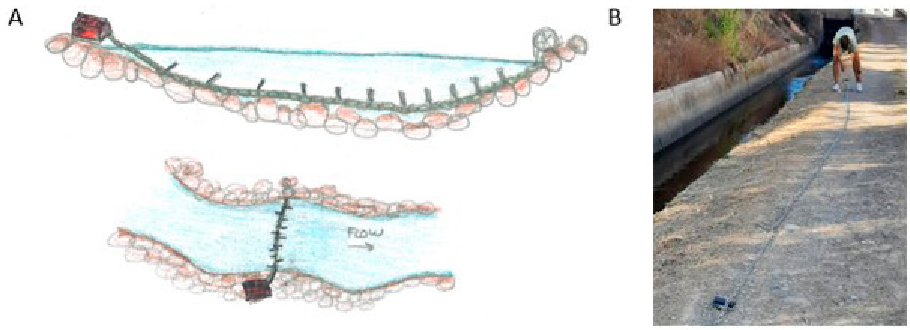

Figure 2. A) Diagram of an array of sensors installed in the river; B) Prototype developed in this study. *A) Diagrama de una matriz de sensores instalada en el río; B) Prototipo desarrollado en este estudio*.

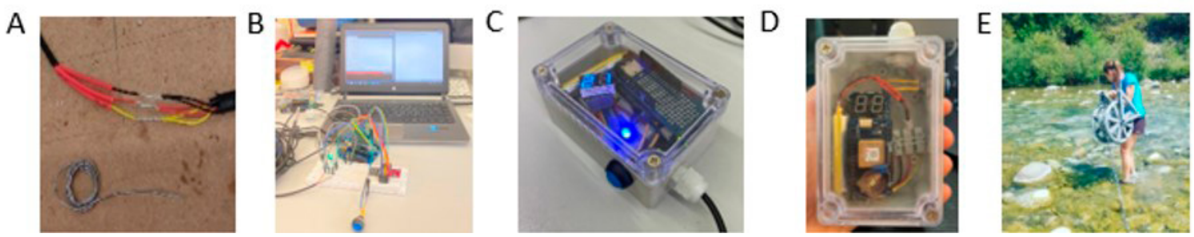

Figure 3. Photos showing the components of the system: A) Triple splice between sensors; B) Board connected to the computer and the Arduino software to test the experimental setup's connectivity; C) Assembled control unit; D) Final component of the device with the control unit; E) Sensor chain spooled on a plastic hose reel. *Fotografías que muestran los componentes del Sistema; A) Empalme triple entre sensores; B) Placa conectada al ordenador y al software del Arduino para comprobar la conexión del montaje del dispositivo experimental; C) Unidad de control ensamblada; D) Componente final del dispositivo con la unidad de control; E) Cadena de sensores enrollada en un carrete de manguera de plástico.*

pling intervals used in this study, the delay was considered negligible relative to river thermal dynamics.

The system uses DS18B20 temperature sensors encapsulated in waterproof housing suitable for submersion. These sensors were chosen for their accuracy and compatibility with a control system capable of storing data locally. They provide an accuracy of ±0.5 °C within the –10 °C to +85 °C range, decreasing by approximately ±0.2 °C outside this range. The DS18B20 sensors have the following specifications: operating voltage: 3.0–5.5 VDC; temperature range: –55 °C to +125 °C; accuracy: ±0.5 °C from –10 °C to +85 °C; resolution: programmable from 9 to 12 bits; interface: 1-Wire protocol; response time: under 750 ms; cable length: 3 m. In terms of long-term performance, drift is minimal over short deployments; however, recalibration is recommended after approximately six months of continuous use. The cost of each sensor is €6, resulting in a total of €10 per metre with the price of the metal chain factored in. The sensors are connected by triple-tin soldering (Fig. 3A). After waterproofing the joints with heat-shrink tubing and water-resistant insulating silicone, the cable is attached to the rings of a longer aluminium chain to provide weight and prevent buoyancy. Although the sensor housings (TO-92 encapsulated in stainless steel probes) are rated to IP68, long-term waterproofing reliability—particularly under turbulent flow conditions—depends on the integrity of silicone-sealed joints, which therefore require periodic inspection.

To evaluate the internal consistency and reliability of the MultiTEMP system, a laboratory intercomparison was conducted prior to field deployment. All 11 DS18B20 sensors were simultaneously immersed in a thermally homogeneous water bath at five target temperatures (5, 10, 15, 20, and 25 ºC). Water temperature in the calibration bath was independently monitored using a certified Pt100 RTD reference thermometer (accuracy ±0.1 ºC).

Based on the outcomes of this laboratory calibration, individual sensor offsets were calculated and applied during post-processing.

In addition, field validation was performed by comparing temperature data recorded by MultiTEMP sensor S10 with measurements obtained from a nearby independently deployed Levelogger® 5 Junior during a hydropeaking event. See the Results section for full details of the calibration and validation outcomes.

All sensors corresponded to the same commercially manufactured DS18B20 model and therefore shared identical factory calibration specifications and operating characteristics.

Key limitations of the DS18B20 include its response time (<750 ms), sensitivity to power supply stability, and potential measurement inaccuracies due to cable capacitance effects when cable lengths exceed 10 m.

The sensors are connected to an Arduino-based open-source hardware platform featuring a microcontroller and a development environment (Arduino software) designed to facilitate the use of electronics in multidisciplinary projects. This baseboard controls the recording of temperature data from a chain of temperature sensors linked linearly. By programming and controlling the temperature sensors, the system obtains records from each, providing multi-temporal and -spatial data sets.

The Arduino® open-source hardware platform is based on Atmel AVR microcontrollers, the most commonly used of which is the Atmega328 in both DIP and SMD formats. This platform consists of a board with a microcontroller, input and output ports, and an easy-to-use development environment with C as its native language. It has several versions for different needs and levels of complexity, starting with the Arduino® Uno, the entry-level board recommended for beginners looking to learn all about the platform.

The Arduino® MKR used in the design of the system described here is an electronic board based on the Atmega328 microprocessor with a clock speed of 16 MHz and an auto-reset circuit. The Arduino® MKR is one of the best-known boards, serving as an excellent entry point into electronics and a standard reference for many modules. It provides numerous digital and analogue input/output pins, allowing for connection to various sensors compatible with the board's technical requirements (Fig. 3B).

As mentioned above, and explained in greater detail in section Applying MultiTEMP in a hydropeaked river reach, MultiTEMP can be operated automatically and manually. In automatic operation, each sensor's water temperature data are saved at a set temporal frequency (bearing in mind the limitations explained previously). In manual operation, temperature data are saved when the pushbutton is activated (Fig. 3C). The LED indicator (Fig. 3C) shows when the signal is sufficiently strong to press the button and record the data. The set of development boards and modules used to deploy MultiTEMP in the different modes of operation comprises the following:

- Telemetry and recording. Remote data transmission and data logging. The Arduino® MKR ZERO is used for local data logging in the system, as it includes a built-in microSD card slot (via MKR SD Proto Shield) and is powered by the Arm® Cortex®-M0+ 32-bit (SAMD21) processor, providing reliable timing and compact integration for environmental monitoring applications. The cost of this board is €40-50.
- GNSS. Arduino® MKR GPS Shield: The MKR GPS Shield provides geolocation data for the system, making it possible to position the sensor chain and estimate individual sensor locations based on known spacing. The cost of this board is €40.
- Additional component. Arduino® MKR Proto Shield: The MKR Proto Shield is used to facilitate prototyping and electrical connections between MKR boards and custom circuits. The cost of this board is €20.

Given the prototype's exposure to outdoor conditions in an aquatic environment during recording, it is necessary to encapsulate the set of boards and modules in a waterproof box to provide full protection and sealing (e.g. IP66). Openings in the box, sealed appropriately to prevent water ingress (Fig. 3D), allow for external connections and outputs. To facilitate the transportation and installation of the 12-metre sensor chain, it is spooled on a hose reel (Fig. 3E).

Coding and programming

This section offers a detailed description of the software's structure, architecture, and key components using the Arduino® Integrated Development Environment (IDE). Arduino's versatile hardware and software, along with its modular design, make it ideal for sensor applications. The system controller plays a crucial role in operating sensors and managing data recording. Programming is done in C/C++ language adapted for Arduino, using its own software development kit (SDK) or programming interface.

The program code written for the Arduino board is called a sketch. The Arduino® IDE contains the following parts (Fig. 4): a text editor, where the program code is written in C/C++; a message area, which displays errors and provides feedback on saving and exporting the code; a text console, which shows text output from the Arduino environment, including complete error messages and other information; and a toolbar, including buttons such as Verify (Compile), Upload, New, Open, Save, and Serial Monitor.

There are two types of control loops in the system: a) automatic data recording and b) manual data recording. Programming variations within the loop allow for different functionalities. The prototype designed supports both options, requiring only a change in the code to switch between modes.

<u>Automatic mode</u>

MultiTEMP can be programmed to automatical-

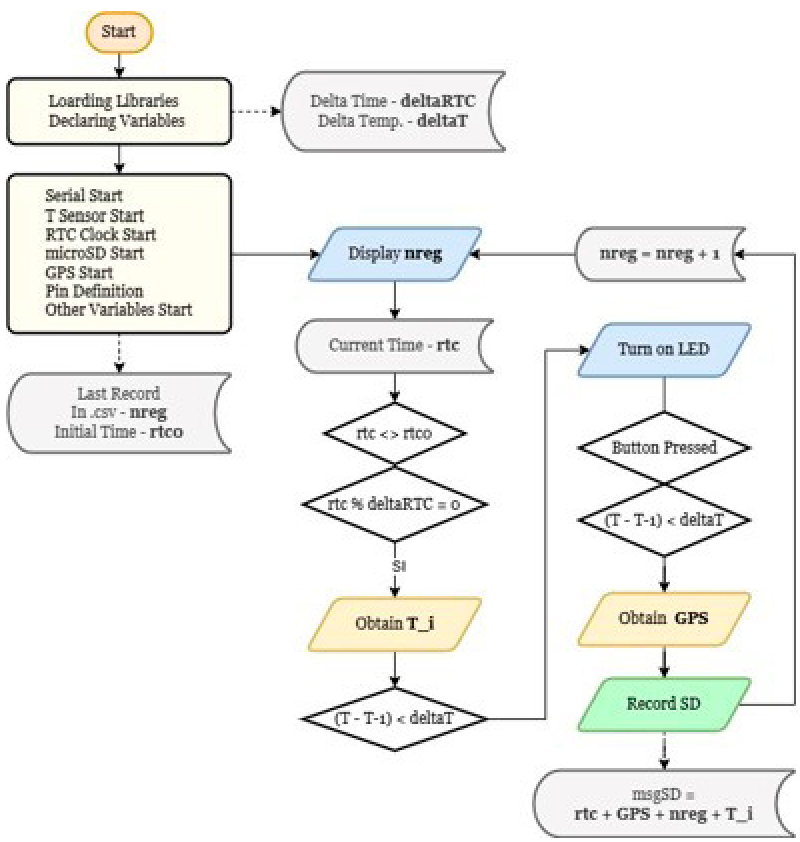

Figure 4. Screenshot of the Arduino® IDE, highlighting the main components used in programming the MultiTEMP system. *Captura de pantalla del entorno de desarrollo Arduino® IDE que muestra los principales componentes utilizados en la programación del Sistema MultiTEMP.*

ly record data at predefined temporal frequencies or intervals (e.g. every second). This allows for the generation of a temperature data table providing a spatiotemporal profile for a specified water section or column. Automatic mode is useful for monitoring changes in water temperature at multiple points (e.g. during hydropeaking). An example of code for the automatic mode is presented in the supplementary materials (see Automatic Mode Arduino Code in Supplementary Material 1, available at https://www.limnetica.com/en/limnetica).

Manual mode

The system is programmed to record data manually using a pushbutton. The procedure involves placing the sensors at the desired point, pressing the pushbutton to display the corresponding sampling number on the counter screen, and waiting for the sensors to stabilize and the GNSS to acquire a location. After a few seconds, the LED indicator confirms successful recording. Manual mode is useful for obtaining multi-spatial (vertical and/or horizontal) water temperature measurements in a short period of time (constant conditions) to create 2D or 3D water temperature maps based on the interpolation of horizontal and/or vertical measurements. An example of code for the manual mode is presented in the supplementary materials (see Manual Mode Arduino Code in Supplementary Material 1).

RESULTS. MULTITEMP GENERAL APPLICATIONS

Potential applications

Vertical temperature profiles

The metal chain keeps the sensors submerged vertically to extract water temperature data, while the other end is secured at the water surface (using a boat in a reservoir, for instance). In manual mode, the system can be used in a stop-push-and-go fashion, meaning that in short periods of time multiple points can be re-occupied, obtaining a temperature profile for each point, which makes it possible to investigate spatial changes in vertical temperature profiles. In automatic mode, the system can register temperature variation at high temporal frequencies, providing data on temporal trends at a single point.

Studies on vertical temperature variability in reservoirs and lakes focus on thermal stratification and its influence on water's physicochemical properties. Seasonal and vertical temperature variability is investigated to understand how it affects water quality and the availability of aquatic habitats. Another area of study is the effect of artificial aeration on temperature variability, and how the latter impacts reservoir management, water quality, and the distribution and growth of fish species (e.g. Xing et al., 2014, Liu et al., 2019, Duka et al., 2021, Chang et al., 2022).

Longitudinal and transversal water temperature profiles

The chain keeps the sensors submerged so that all temperature measurements can be made at the same point, located close to the bed. The chain is adapted to the materials/sediments, ensuring that the sensors are always located at the same height above the bed. In automatic mode, multitemporal data on cross-sectional variability in water temperature can be obtained. In manual mode, the system can be placed in a targeted section and the user can register temperatures whenever they wish, without having to enter the river or place a platform in it each time data are needed, given that recording data merely involves pushing a button. Thus, transversal temperature variability can be assessed by measuring temperature profiles across a body of water, such as a river. Such profiles provide graphical representations of how temperature changes throughout the cross-section. Studies analyse the spatial and temporal variability of water temperature and its relationship with geographical and climatic factors. The data obtained reveal patterns of warming and cooling in different areas of the river, knowledge of which is essential for understanding the thermal conditions of the ecosystem. Research focuses on how different local characteristics and hydrodynamic conditions influence the distribution and variability of water temperature (e.g. Brown & Hannah, 2008, Kaushal et al., 2010, Blaen et al., 2013, Manta & Alcántara, 2018).

Applying MultiTEMP in a hydropeaked river reach

This section presents a case study describing the application of the MultiTEMP system in the monitoring of the spatiotemporal variability of water temperature during hydropeaking events in a mountain river reach.

Temperature monitoring was conducted on a cross-sectional area of the Noguera Pallaresa River (located in the southern Pyrenees, in the northeast of the Iberian Peninsula), a mountain tributary of the Segre River (the main tributary, in turn, of the Ebro River). The studied reach is regulated by the Borén Reservoir, which stores water and diverts it to the Esterri-Unarre hydropower complex (43 MW) through a series of underground pipes. The hydroelectric power plant operates on demand, generating daily hydropeaks, and its maximum discharge through turbines is around 23 m3/s. This reach has been hydraulically and thermally monitored by the Fluvial Dynamics Research Group (RIUS) of the University of Lleida, in collaboration with the company that operates the hydropower complex, since May 2022 (Fig. 5).

The objective of the field campaign was to monitor water temperature along a cross-section 5 km downstream of the hydroelectric plant. Multi-spatial measurements of water temperature were obtained before, during, and after hy-

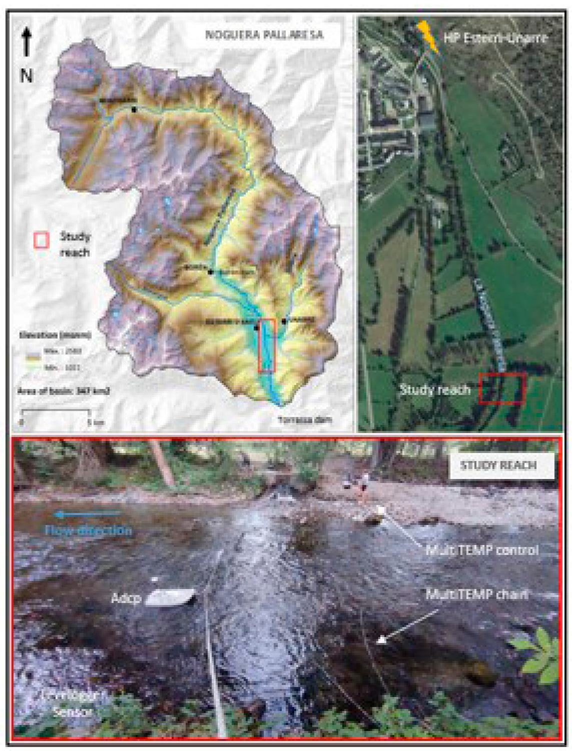

Figure 5. Location of the studied reach of the Noguera Pallaresa River in the upper Noguera Pallaresa basin. In the reach, it is possible to observe i) the MultiTEMP control unit (right bank) and the sensor chain crossing the section of the river, ii) the location of the Levelogger water depth and temperature sensor (left bank), and iii) the SonTek® M9 aDcp registering water depth and flow velocity. The position of the control unit corresponds to the GNSS-referenced deployment location (42.619243°N, 1.128180°E). *Ubicación del tramo del río Noguera Pallaresa en el área de estudio de la cuenca alta de la Noguera Pallaresa. En el tramo estudiado pueden observarse: i) la unidad de control MultiTEMP (margen derecha) y la cadena de sensores cruzando la sección del río; ii) la ubicación del sensor Levelogger de profundidad y temperatura del agua (margen izquierda); y iii) el equipo Sontex® M9 aDcp registrando la profundidad y la velocidad de flujo. La posición de la unidad de control corresponde a la ubicación de despliegue georreferenciada mediante GNSS (42.619243°N, 1.128180°E).*

dropeaking (turbine operation), to observe spatiotemporal changes in water temperature. On 28 July 2022, hydroelectricity production was scheduled for the early morning, from 5:30 to 8:30 a.m. (solar time). For measurement purposes, the MultiTEMP prototype was used in automatic mode (see Automatic Mode Arduino Code in Supplementary Material 1). The sensor chain was installed in the selected section at 5:30 a.m. and automatic data recording began, measuring the temperature from the base flow and throughout the rise and fall of the water level during the hydropeaking event. Additionally, a Levelogger sensor (Levelogger® 5 Junior by Solinst), which provides data on water temperature and depth in a single location, was positioned just a few metres downstream from where MultiTEMP was deployed, at the true left bank of the river, and took measurements at one-minute intervals. The closet MultiTEMP sensor to the Levelogger was S10. The discharge during the monitored hydropeak, measured with an acoustic Doppler current profiler (aDcp, a SonTek® RiverSurveyor M9; Fig. 5), ranged from 2 to 7 m^3/s, with field-measured velocity values of between 0 and 2 m/s (see Supplementary Material 2, available at https://www.limnetica.com/en/limnetica).

System performance and validation

A sensor-to-sensor comparison conducted in a controlled temperature bath showed a mean inter-sensor offset of ±0.12 °C, with a standard deviation of 0.08 °C across the 11 DS18B20 sensors.

Field validation was performed by comparing temperature data from MultiTEMP sensor S10 with measurements obtained from a co-located Levelogger® 5 Junior sensor during the hydropeaking event. The comparison showed strong agreement between both instruments, with a root mean square error (RMSE) of 0.18 °C and a coefficient of determination (R^2) of 0.97.

The results confirm the consistency of the MultiTEMP system and its agreement with an independent reference instrument.

Figure 6 presents the spatiotemporal evolution of water temperature recorded during the monitored hydropeaking event. MultiTEMP's temperature sensors were submerged throughout the monitoring period, except for the two closest to the right and left banks (sensors S1 and S11). These two sensors were occasionally exposed when water levels were low; consequently, their values were closer to air temperature than water temperature and were therefore excluded from the analysis. Figure 6A presents the measurements obtained with the MultiTEMP system operating in automatic mode at one-second frequency, while Figure 6B shows the water temperature and depth recorded by the Levelogger sensor at a nearby location downstream from sensor S10. The temperature evolution in Figure 6B is represented using the same colour scale as in Figure 6A to facilitate comparison between datasets.

Figure 6A shows the spatiotemporal distribution of water temperature in a river section, with sensors recording a thermal gradient over time. Initially, temperatures are colder (blue tones), followed by a period of warming (red tones) and then a subsequent cooling phase. Figure 6B complements this information by representing the evolution of temperature at a specific point along with water depth. A rapid initial temperature increase is observed until stabilization occurs, followed by a decrease coinciding with depth variation.

These results suggest that thermal variability is influenced by several main factors: (i) flow dynamics, where changes in river discharge and the mixing of water masses generate temperature fluctuations; (ii) exposure to external heat sources (e.g. solar radiation), which may create vertical gradients in stratified systems, although water columns are rapidly homogenized in shallow, turbulent rivers; (iii) bed roughness, which affects flow velocity and creates thermal retention zones in backwaters and bottom structures; (iv) riparian vegetation, which modulates shading and reduces direct solar input; (v) the orientation of the river reach, which determines its exposure to solar radiation; and (vi) the inflow of tributaries with contrasting thermal regimes. Together, these factors may explain the thermal heterogeneity observed in the river section.

The findings demonstrate that high-frequency, spatially distributed monitoring of water temperature in fluvial systems is a useful, valuable tool. They describe the thermal evolution in a river

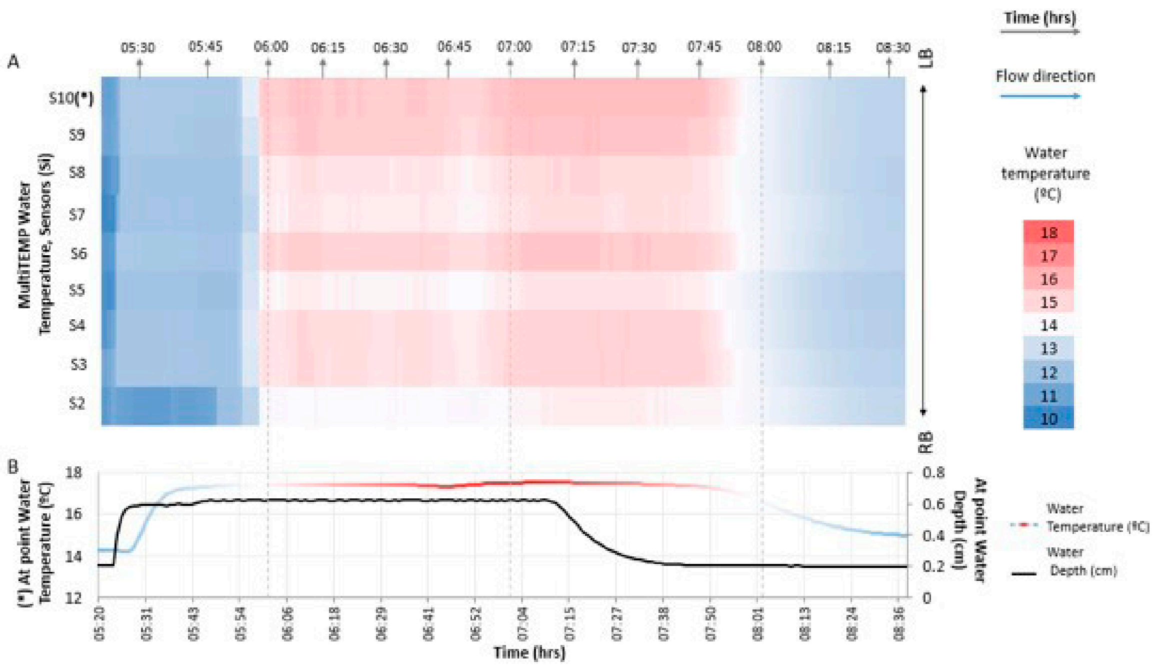

Figure 6. A) Water temperature (ºC) graph obtained from MultiTEMP during three hours of hydropeaking monitoring; B) Water temperature (ºC) and depth (cm) graph obtained from Levelogger data for the experimental basin during the hydropeaking event. (*) Localized water temperature recorded by the Levelogger (see Supplementary Material 2 for more information). *A) Gráfico de la temperatura del agua (ºC) obtenido con MultiTEMP durante 3 horas de monitorización de un evento de hidropeaking; B) Gráfico de la temperatura del agua (ºC) y de la profundidad (cm) obtenido a partir de los datos del Levelogger en la cuenca experimental durante el evento de hidropeaking. (*) Temperatura puntual del agua registrada por el Levelogger (veáse el Material Suplementario 2 para más información).*

section during a hydropeaking event, recording variability and trends in space and time, and providing detailed information for environmental management measures.

FINAL REMARKS

Water temperature is a pivotal parameter influencing physical, chemical, and biological processes in aquatic ecosystems. Accurate and comprehensive monitoring of water temperature is essential for understanding these processes, particularly in the context of global change, including anthropogenic impacts on freshwater environments.

Traditional methods of water temperature monitoring, such as in-situ measurements and satellite remote sensing, each have their advantages and limitations. In-situ measurements provide precise and detailed data at specific points or depths but are often spatially limited due to the high costs and logistical challenges of deploying multiple sensors. Satellite remote sensing offers broad spatiotemporal coverage, allowing for the assessment of surface water temperature over large areas for extended periods, although measurement frequency is constrained by revisit time. Additionally, satellite data are restricted to surface measurements and can be affected by factors like cloud cover, atmospheric interference, and land-water pixel contamination, especially in coastal and continental environments (Barton, 1995, Chang et al., 2015, Crosman et al., 2017).

Similarly, DTS systems provide high spatial resolution over long distances, but require expensive fibre-optic infrastructure, specialized acquisition units, and complex deployment logistics. Thermal infrared imaging from UAVs or airborne platforms enables fine-scale surface thermal mapping, although measurements remain limited to surface conditions and require substantial operational and post-processing efforts. WSNs and commercial multi-probe monitoring stations can provide real-time distributed observations, but their implementation cost increases rapidly as the number of sensors, communication modules, and independent data loggers needed rises.

The MultiTEMP system introduced in this study addresses several of those operational and economic limitations by providing a cost-effective, customizable, and versatile tool for high-frequency, spatially distributed monitoring of water temperature at multiple submerged points. By utilizing open-source Arduino technology and readily available components, MultiTEMP enables researchers to deploy multiple sensors connected to a single data logger, capturing synchronized temperature data across different locations and depths. Compared with conventional fixed stations or commercial distributed sensor systems, MultiTEMP reduces hardware costs substantially while maintaining high temporal resolution and spatial flexibility. The complete prototype developed in this study has an estimated cost of approximately €200, representing a substantially lower investment than most commercial multi-sensor monitoring platforms or DTS systems. This approach has significant potential to advance our understanding of thermal dynamics in aquatic ecosystems, particularly in regulated rivers where flow fluctuations can lead to rapid and complex thermal alterations.

The system is based on DS18B20 digital temperature sensors, which offer an accuracy of ±0.5 °C over a range of −10 °C to +85 °C at an affordable cost (€6). These sensors are suitable for most freshwater environments, providing the reliable and consistent measurements essential for precise thermal profiling. Sensors are coupled using different Arduino compartments and boards. Data are stored on removable memory cards in standard formats (e.g. CSV), facilitating retrieval and analysis. Open-source software tools can be used for data processing, and the system's firmware can be modified to include additional functionalities, streamlining data handling and promoting integration with existing data analysis workflows. An additional advantage of MultiTEMP is the integration of GNSS positioning into the monitoring platform, allowing georeferencing of the sensor array and facilitating rapid deployment and relocation in the field. Furthermore, the same sensor chain can be configured either vertically (e.g. in lakes or reservoirs) or horizontally across river sections, increasing adaptability compared to fixed single-point monitoring systems. The use of open-source firmware enables researchers to modify acquisition frequency, sensor spacing, and operational modes without proprietary software restrictions.

Successfully deployed in a hydropeaked river reach, MultiTEMP has elucidated rapid spatial and temporal patterns in water temperature changes caused by hydropeaking events (specifically, rapid flow fluctuations for hydroelectric generation). By providing high-frequency data, MultiTEMP has enabled the examination of spatiotemporal thermal patterns during changing conditions (i.e. flow). All sensors capture data at the same time and are kept in the same location thanks to the metal chain (weight and adaptation to the bed). Unlike systems based on independent loggers, MultiTEMP acquires synchronized measurements from all sensors using a single controller and data logger, simplifying deployment, maintenance, and data management. These capabilities are crucial, for instance, for understanding the impacts of flow regulation on aquatic habitats and for informing environmental management strategies.

While the MultiTEMP system offers significant advantages, certain limitations should be acknowledged. Sensor accuracy may diminish over time due to drift, so regular calibration/validation or replacement may be necessary to maintain precision and ensure data reliability. Although the system is energy-efficient, battery life may limit deployment duration, especially in remote locations, requiring careful planning for long-term monitoring campaigns. Despite waterproofing measures, extreme environmental conditions (e.g. strong currents, debris impact, extreme temperatures) may pose challenges to the system's durability and functionality. To address these limitations, future enhancements are proposed. Incorporating wireless communication modules (e.g. GSM, LoRa, Wi-Fi) would enable real-time data transmission, facilitating immediate data analysis and decision-making. Adding solar panels could extend deployment duration by providing a renewable power source, reducing the need for frequent battery replacements. Integrating sensors for other parameters, such as dissolved oxygen, conductivity, or pH, would expand the system's utility and provide a more comprehensive understanding of aquatic environments. Developing mechanisms to improve depth precision and sensor placement would enhance vertical profiling capabilities, particularly in deep or stratified water bodies. Upgrading the system's materials and protective enclosures could enhance resistance to harsh environmental conditions, increasing longevity and reliability. Beyond conventional aquatic systems, such developments would further enhance the applicability of the MultiTEMP system in environments inaccessible to airborne infrared thermal sensors, such as subaquatic or highly turbid settings, including hydrothermal spring systems. In such environments, the system could be used to characterize temperature gradients and mixing dynamics between hydrothermal discharge and surrounding colder waters.

The flexibility, affordability, and adaptability of MultiTEMP make it a valuable tool for a wide range of applications in limnological and environmental research. Continued refinement and expansion of such systems will further empower researchers and resource managers to address pressing ecological challenges, ultimately supporting the sustainability and health of aquatic environments.

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AUTHOR CONTRIBUTIONS

E.C.:: Methodology, Formal Analysis, Writing – Original Draft Preparation; M.B.: Methodology, Hardware, Software, System Design; R.J.B.: Funding Acquisition, Visualization, Supervision, Validation; A.P.: Conceptualization, Methodology, Supervision, Validation; D.V: Conceptualization, Resources, Software, Supervision, Validation.

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