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REAL-TIME SURFACE WATER QUALITY MONITORING: A REVIEW AND APPLICATION IN WATER RESOURCES MANAGEMENT

MONITORAMENTO DA QUALIDADE DAS ÁGUAS SUPERFICIAIS EM TEMPO REAL: UMA REVISÃO E APLICAÇÃO NA GESTÃO DE RECURSOS HÍDRICOS

MONITOREO EN TIEMPO REAL DE LA CALIDAD DE AGUAS SUPERFICIALES: REVISIÓN Y APLICACIÓN EN LA GESTIÓN DE RECURSOS HÍDRICOS

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ABSTRACT

Real-time water quality monitoring has proven to be an essential tool for strengthening water governance and improving water resources management strategies. This article presents a systematic review of automated monitoring practices in different countries, analyzing methodologies for data collection, calibration, and processing. Searches were conducted in scientific databases and governmental institutional portals, focusing on experiences from the United States, Canada, the European Union, Australia, Singapore, and Brazil. The analysis revealed varying levels of technological maturity among the studied countries, with the most advanced systems integrating real-time measurements with predictive models and automatic alerts. In Brazil, specific advances have been achieved, although the lack of national protocols for calibration and data integration remains a challenge. It is concluded that strengthening monitoring infrastructure and adopting standardized protocols are essential to enhance data reliability and support more effective water management decisions.

Keywords: Real-Time Monitoring. Water Quality. Calibration. Water Resources Management. Iot Sensors.

RESUMO

O monitoramento em tempo real da qualidade da água tem se mostrado uma ferramenta essencial para o fortalecimento da governança hídrica e o aprimoramento das estratégias de gestão de recursos hídricos. Este artigo apresenta uma revisão sistemática sobre as práticas de monitoramento automatizado em diferentes países, analisando metodologias de coleta, calibração e tratamento de dados. Foram realizadas buscas em bases científicas e em portais de instituições governamentais, com ênfase em experiências dos Estados Unidos, Canadá, União Europeia, Austrália, Cingapura e Brasil. Observou-se que os países analisados possuem diferentes níveis de maturidade tecnológica, sendo que os sistemas

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mais avançados integram medições em tempo real com modelos de previsão e alertas automáticos. No Brasil, identificou-se avanços pontuais, mas ainda há ausência de protocolos nacionais de calibração e integração de dados. Conclui-se que o fortalecimento da infraestrutura de monitoramento e a adoção de protocolos padronizados são fundamentais para ampliar a confiabilidade das informações e subsidiar decisões de gestão hídrica mais eficazes.

Palavras-chave: Monitoramento em Tempo Real. Qualidade da Água. Calibração. Gestão de Recursos Hídricos. Sensores Iot.

RESUMEN

El monitoreo en tiempo real de la calidad del agua se ha mostrado como una herramienta esencial para fortalecer la gobernanza hídrica y mejorar las estrategias de gestión de los recursos hídricos. Este artículo presenta una revisión sistemática sobre las prácticas de monitoreo automatizado en distintos países, analizando metodologías de recolección, calibración y tratamiento de datos. Se realizaron búsquedas en bases científicas y en portales de instituciones gubernamentales, con énfasis en experiencias de Estados Unidos, Canadá, la Unión Europea, Australia, Singapur y Brasil. Se observó que los países analizados poseen diferentes niveles de madurez tecnológica, siendo que los sistemas más avanzados integran mediciones en tiempo real con modelos de predicción y alertas automáticas. En Brasil se identificaron avances puntuales, pero aún existe ausencia de protocolos nacionales de calibración e integración de datos. Se concluye que fortalecer la infraestructura de monitoreo y adoptar protocolos estandarizados es fundamental para ampliar la confiabilidad de la información y respaldar decisiones más eficaces en la gestión de los recursos hídricos.

Palabras clave: Monitoreo en Tiempo Real. Calidad del Agua. Calibración. Gestión de Recursos Hídricos. Sensores IoT.

1 INTRODUCTION

Real-time qualitative and quantitative monitoring has established itself as a central tool for water resources management, sanitation, and environmental safety (ANA, 2022; OECD, 2020). The growing demand for rapid responses to extreme events, coupled with technological advances in sensors and digital platforms, is transforming the way managers and environmental agencies assess, interpret, and make decisions in aquatic systems (MA; YANG; ZHOU, 2022). However, challenges remain regarding sensor calibration, data comparability, and the integration of information into national and international regulatory frameworks (CONAMA, 2011; ANA, 2021).

Historically, water monitoring systems in Brazil and worldwide have prioritized quantity parameters (level, flow, and precipitation) due to the emergency nature of floods and droughts. With technological advances, however, there is increasing incorporation of real-time water quality monitoring systems, enabling a shift from a predominantly reactive model to predictive and adaptive management approaches.

The National Water Resources Policy (Law No. 9,433/1997) establishes the National Water Resources Management System (SINGREH), which integrates quantity and quality information through the National Water Resources Information System (SNIRH). Although the legislation mandates transparent and up-to-date data, the adoption of automated water quality systems is still incipient in the country.

The benefits of real-time monitoring are multiple: (i) support for crisis management, such as droughts, algal blooms, and sudden contamination events; (ii) enhancement of basin plans based on continuous time series; (iii) formulation of evidence-based, responsive public policies; and (iv) strengthening of transparency and social control. This capability is particularly strategic in the context of climate change, where extreme events alter hydrological regimes and increase the vulnerability of water supply systems.

Sensor calibration failures directly impact the reliability of real-time data. Inaccurate readings of critical parameters such as dissolved oxygen, turbidity, and electrical conductivity can lead to misinterpretations of water quality, affecting both classification under CONAMA Resolution No. 430/2011 and decision-making in basin management (CONAMA, 2011; KALBUS; REINSTORF; SCHIRMER, 2006). In scenarios involving minimum or ecological flow, calibration deviations may amplify errors in pollutant concentration estimates, resulting in misclassifications and conflicts among multiple water uses (CETESB, 2023; SABESP, 2022). International studies indicate that inadequate calibration compromises historical series and undermines institutional and social acceptance of data (OECD, 2020).

However, practical application faces challenges related to sensor reliability, periodic calibration, and laboratory validation of data. The absence of standardized protocols or neglect in maintenance may generate inconsistent reading, leading managers to make incorrect decisions, such as opening gates or unnecessarily interrupting water withdrawals. International literature shows that calibration failures can result in deviations exceeding 30% for parameters such as dissolved oxygen and turbidity (SMITH et al., 2021), compromising analyses of classification under CONAMA Resolution No. 357/2005 and effluent discharge under CONAMA Resolution No. 430/2011.

The guiding question of this article is: What is the current state of research and applications of real-time water quality monitoring, and how does it interact with water resources management in different countries?

2 MATERIALS AND METHODS

This study was based on an exploratory and descriptive bibliographic and documentary review, aiming to identify and analyze real-time water quality monitoring practices in different countries, as well as the methods employed for data processing and calibration.

The research was conducted between January and July 2025, encompassing scientific publications, institutional reports, and regulatory documents. The Scopus, Web of Science, and Google Scholar databases were used, applying combinations of the keywords "real-time water monitoring," "water quality," "real-time water monitoring network," and "hydrological data management." Articles published between 2010 and 2025 were considered, prioritizing peer-reviewed studies that presented practical applications of automated monitoring systems.

Additionally, a targeted search was conducted on official portals of government institutions and environmental agencies from the countries analyzed, including USGS and EPA (United States), ECCC (Canada), EEA and WISE (European Union), PUB (Singapore), CSIRO and Bureau of Meteorology (Australia), and ANA and INEA (Brazil). These repositories provided information on methodologies for data collection, calibration, and processing in automated monitoring networks.

The collected data were organized and analyzed qualitatively, aiming to identify operational patterns, monitored parameters, calibration practices, and strategies for integrating quality and quantity variables. Data processing followed a comparative approach, focusing on three main dimensions:

- Technological infrastructure (types of sensors, measured variables, data transmission frequency);
- Data calibration and validation protocols (frequency, traceability, audits);
- Institutional integration and use of data in water management (decision-making platforms, transparency, and public access).

The extracted evidence was systematized in comparative tables and charts, highlighting similarities, gaps, and best practices observed across different contexts. This approach allowed for an assessment of the maturity level of real-time monitoring systems and their role in supporting water resources management.

3 RESULTS AND DISCUSSION

Real-time water quality monitoring has emerged as an essential tool for efficient water resources management. This method enables the continuous collection of data on critical parameters, such as pH, temperature, dissolved oxygen, and the presence of contaminants, allowing immediate responses to changes in water quality. This capability is crucial for addressing contemporary challenges, such as diffuse pollution and climate-related impacts.

The introduction of real-time monitoring technologies has led to a significant transformation in how environmental information is collected, processed, and utilized. By integrating advanced sensors, communication networks, and analytical platforms, real-time monitoring provides a solid foundation for strategic decision-making. Through integrated systems, managers can quickly identify and mitigate pollution sources, minimizing impacts on ecosystems and human activities. Furthermore, the use of technologies such as machine learning and the Internet of Things (IoT) enhances the prediction of adverse events and optimizes financial and operational resources.

This approach also promotes greater transparency and social engagement. Real-time data can be shared with stakeholders and communities, strengthening participatory governance and public awareness about the importance of preserving water resources. In urban contexts, ensuring the quality of water supplied to the population and monitoring water bodies in industrial or agricultural areas is essential. These monitoring systems can act as early warning mechanisms, identifying variations in water quality caused by events such as algal blooms, industrial discharges, or changes in reservoir thermal stratification (BLUM, 2007; WU et al., 2020).

Globally, real-time monitoring aligns with the Sustainable Development Goals (SDGs), particularly SDG 6, which aims to ensure the availability and sustainable management of water. By reducing delays and uncertainties in data, it supports the achievement of targets related to health, water security, and environmental sustainability, meeting the growing demand for safe water.

Real-time monitoring utilizes multiparameter probes equipped with sensors for measuring physicochemical and, in some cases, biological variables. These stations can be installed at fixed points (banks, floating structures) or on mobile platforms. Data are automatically transmitted to control centers via GSM, radiofrequency, or satellite networks.

Periodic sensor calibration, as well as data validation and consistency checks, are fundamental to ensure the quality of generated information (MANCUSO, 2004; SMITH et al., 2021). International protocols, such as those defined by the USGS (2000), provide guidance on measurement frequency and standard operating procedures.

Recent technological advances have driven the development of more accessible and efficient real-time monitoring systems. For instance, a 2024 study presented an IoT-based system for isolated communities in the Philippines, using pH, turbidity, and temperature sensors with cloud data transmission, enabling real-time alerts via text messages (ABRAJANO et al., 2024).

It is noteworthy that most early-warning systems based on real-time monitoring have historically focused on quantity variables (level, flow, precipitation) due to the urgent need to prevent floods and droughts. However, significant progress has been made in applications related to water quality, such as controlling algal blooms, contamination, and water supply safety.

Table 1

Presents the main approaches in the literature regarding data processing of real-time monitoring for alert and decision-making systems, with a focus on the variable monitored: quantity (QTD), quality (QLD), or both (BOTH):

Location	Articles/Systems used in alert and decision	Variable Type
US USA	Dong et al. (2020) – predictive flood alert using river sensors	QTD
US USA	USGS + WQP – flood alerts and analysis of extreme events with physicochemical variables (in some regional studies)	BOTH
EU European Union	EFAS (European Flood Awareness System) – transboundary flood prediction and alert system	QTD
SG Singapore	PUB Smart Water Grid – urban network monitoring with automatic responses to quality and flow events	BOTH
CA Canada	IISD (2023) – environmental alerts with real-time sensors; prediction of contamination and algal blooms	QLD

AU Australia	CSIRO AquaWatch – prediction of poor water quality events (algae, turbidity, post-fire contamination)	QLD
AU Australia	WaterNSW – automatic alerts on flow and floods	QTD
AU Australia	HydroNET – real-time dashboards for floods, droughts, and anomalies	BOTH
BR Brazil (ANA)	HidroWeb with telemetry – flow and level alerts; some stations with quality sensors	BOTH (incipient)
BR Brasília (ADASA)	Descoberto Basin System – alerts on water withdrawal, blooms, and preventive control	QLD

Source: The Authors

3.1 MAIN MONITORED PARAMETERS

The main water quality parameters monitored in real-time include:

- Water temperature;
- Dissolved oxygen (DO);
- pH;
- Electrical conductivity;
- Redox potential;
- Chlorophyll-a (indicator of algal biomass);
- Turbidity;
- Solar radiation (important for stratification and photosynthesis).

These parameters are selected due to their relevance in indicating anomalous conditions, such as excessive algal growth, DO depletion, or the presence of undesirable compounds/pollutants, as described in Table 2 (BLUM, 2007; BRANCO, 1986; WANG et al., 2022).

Recently, monitoring systems have incorporated detection of specific contaminants, such as glyphosate. The SpectroGLY system, developed in 2024, uses visible and near-infrared spectroscopy to detect glyphosate residues in water, providing a low-cost, portable solution for real-time monitoring (AIRA; OLIVARES; DELICADO, 2024).

Table 2

Applications and significance of real-time monitoring parameters

Parameter	Significance	Application for Real-Time Monitoring
pH	Measure of hydrogen potential	Indicates chemical variations and potential contamination
Dissolved Oxygen (DO)	Amount of oxygen available in water	Assesses aquatic ecosystem health

Turbidity	Level of suspended particles in water	Detects pollution and sediment presence
Conductivity	Water's ability to conduct electricity	Indicates ion content and salinity
Chlorophyll-a	Pigment present in algae	Monitors algal blooms and eutrophication
Temperature	Thermal degree of water	Affects gas solubility and biological activity
Redox Potential	Oxidation-reduction capacity of water	Assesses chemical conditions and the presence of oxidizing substances

Source: BLUM, 2007; BRANCO, 1986; WANG et al., 2022, adapted by the Authors.

Interpretation of water quality data is enhanced through integrated analysis of parameters to guide and improve pollution alert systems. For example:

- High chlorophyll-a concentrations combined with pH elevation and DO decline suggest cyanobacterial blooms, likely due to high nutrient input;
- Redox potential decrease and increased iron/manganese indicate anoxic conditions;
- Thermal stratification can be diagnosed through vertical profiles of temperature and DO, which may result from increased suspended solids, reducing light penetration, and promoting stratification.

These correlations are validated through conventional laboratory analyses and hydrobiological modeling (ZHANG et al., 2021).

In Brazil, river pollution control analyses can use CONAMA Resolution No. 357/2005 as a fundamental regulatory reference for assessing water quality across different river stretches. This standard establishes quality criteria according to predominant usage class, allowing real-time sensor data to identify pollution plumes and correlate them with the established limits for each parameter. Consequently, even temporarily, verifying changes in water body class due to point or diffuse discharges, supporting control, inspection, and mitigation measures is possible. This approach is strategic for adaptive management and for meeting the water body classification objectives under the National Water Resources Policy.

Another critical aspect relates to minimum and ecological flow conditions. During droughts, reduced flow increases pollutant concentration due to lower dilution, potentially exceeding class limits set by CONAMA 357/2005. Simultaneously, effluents treated according to CONAMA 430/2011 standards can significantly affect low-flow water bodies, causing temporary or permanent class changes. This phenomenon is observed in Brazilian rivers during the dry season, reinforcing the need to integrate quality and quantity monitoring.

Finally, emerging technologies such as machine learning and the Internet of Things (IoT) expand analytical potential, enabling real-time anomaly detection and risk scenario prediction. For example, Abrajano et al. (2024) implemented low-cost sensors in isolated communities in the Philippines, demonstrating the feasibility of simplified alert systems in regions lacking infrastructure.

3.2 INTERNATIONAL EXPERIENCES IN THE IMPLEMENTATION OF REAL-TIME SURFACE WATER QUALITY MONITORING NETWORKS

Surface water quality is a central topic on global environmental agendas. For effective management, several countries have invested in automated real-time monitoring networks, which enable continuous acquisition of physicochemical and hydrological data. This chapter overviews the main international and national experiences in this field, highlighting operational systems, regulatory frameworks, monitored parameters, synergy between quantity and quality, applications, and integration platforms.

3.3 UNITED STATES

In the United States, monitoring is led by the United States Geological Survey (USGS) through the National Water Information System (NWIS), which operates thousands of real-time stations. Additionally, the Environmental Protection Agency (EPA) manages the Water Quality Exchange (WQX) platform, which integrates laboratories and automated data from various local and state agencies. Key parameters analyzed include pH, dissolved oxygen, conductivity, turbidity, temperature, chlorophyll-a, and nutrients such as nitrogen and phosphorus. There is strong synergy with quantity analysis (river flow and level), allowing correlation between hydrological events and changes in water quality.

In the U.S., water quality sensor calibration is integrated into technical protocols established by the EPA and state environmental protection agencies. The National Water Quality Monitoring Council (NWQMC) provides guidelines for periodic maintenance and calibration of equipment in the field and laboratory, including precision checks using standards traceable to the National Institute of Standards and Technology (NIST). Detailed records of calibration and periodic checks ensure that data from monitoring networks, such as those operated by USGS, maintain comparability and reliability across different watersheds. This rigor is critical for regulatory assessments under the Clean Water Act, where calibration deviations can directly impact water body classification and water quality management plans.

3.4 EUROPEAN UNION

The Water Framework Directive (WFD – 2000/60/EC) requires systematic monitoring and data integration by all EU member states. The Water Information System for Europe

(WISE) integrates water quality and quantity data, emphasizing integrated and transboundary management. The most monitored parameters include pH, temperature, dissolved oxygen, conductivity, nitrate, phosphate, turbidity, and biological indicators. Integration between quality and quantity is institutionalized, with integrated assessment mandatory in basin management plans.

In the EU, calibration practices are associated with the WFD, which mandates member states to adopt harmonized monitoring methods. Protocols are strongly influenced by technical standards from the European Committee for Standardization (CEN) and ISO, guiding both the calibration frequency of multiparameter sensors and validation and traceability procedures. Laboratory quality control systems complement field calibration to ensure data reliability for transnational watershed management plans. This standardization allows results to be comparable across countries. It supports decisions on water body classification, particularly in low-flow scenarios, where small calibration inaccuracies can lead to significant errors in ecological status assessment.

3.5 SINGAPORE

Singapore is recognized for implementing the PUB Smart Water Grid, an intelligent water monitoring network covering reservoirs and urban rivers. The system uses sensors to monitor real-time parameters such as pH, dissolved oxygen, conductivity, turbidity, temperature, and chlorophyll-a. The model stands out for integrating urban hydrological variables (level and flow), generating automatic responses in treatment plants and drainage systems. Combined data are strategically used to ensure water security and prevent algal blooms.

In Singapore, calibration is treated as a strategic step within the integrated water management system led by the Public Utilities Board (PUB). The country adopts strict preventive and corrective calibration protocols based on ISO standards and supplemented by internal metrological traceability requirements. Given the high population density and dependence on limited water sources, the reliability of real-time data is essential to anticipate pollution risks and manage critical low-flow events. Calibration deviations are treated as operational safety failures, and the use of redundant sensors and cross-validation systems reinforces the reliability of data used to meet drinking water and receiving water quality standards.

3.6 CANADA

The Canadian government, through Environment and Climate Change Canada (ECCC), maintains a hydrometric network with real-time data accessible to the public. Sensors monitor parameters such as temperature, pH, conductivity, DO, turbidity, and, in some locations, nutrients and metals. Synergy between quantity and quality is evident, as stations integrate level, flow, and physicochemical sensors. The platform is widely used for flood forecasting, reservoir management, and environmental alerts.

In Canada, calibration protocols are conducted under the National Water Quality Monitoring Program (NWQMP), coordinated by ECCC. Detailed guidelines for sensor calibration and verification are followed in automatic stations and field campaigns, with traceable and auditable documentation required. Interlaboratory comparisons are also used to ensure consistency across provinces and territories. The main concern is to ensure that data support environmental protection policies under the Canadian Environmental Protection Act and Canadian Water Quality Guidelines. In minimum or ecological flow conditions, calibration failures may lead to inadequate ecological risk classifications, directly affecting the management of sensitive aquatic habitats.

3.7 AUSTRALIA

Australia operates the Water Data Online system, coordinated by the Bureau of Meteorology. The platform collects real-time data on flow, water levels, and quality in rivers and reservoirs. Key monitored parameters include pH, temperature, DO, conductivity, and turbidity. Integration with rainfall data and hydrological forecasting supports water resources management in arid regions and the anticipation of extreme events.

In Australia, sensor calibration is regulated under the National Water Quality Management Strategy (NWQMS) and aligned with the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ, 2000). Due to high climate variability and prolonged droughts, accurate readings under minimum flow conditions are especially critical. National protocols require regular calibrations both in the field and laboratory, with independent technical audits in large-scale monitoring projects. Sensor integration with hydrological modeling systems emphasizes the need for robust and calibrated data, as measurement errors may distort ecological risk assessments and compromise watershed management plans under water scarcity conditions.

3.8 BRAZIL

In Brazil, water quality monitoring is regulated by CONAMA Resolution No. 357/2005, focusing on laboratory data. However, the National Water and Basic Sanitation Agency (ANA) and state agencies are expanding automated networks. ANA operates approximately 300 automatic hydrometric stations and points measuring parameters such as conductivity, temperature, and DO. Although still incipient, efforts are underway to integrate quantity (flow, level) and quality data in systems such as HidroWeb.

In Brazil, calibration of sensors used in water quality monitoring networks remains a major challenge for obtaining reliable and comparable data. Although the National Water Quality Monitoring Network (RNQA), coordinated by ANA, has operational protocols for data collection, storage, and transmission, there is currently no national standardized protocol for calibration and periodic verification of multiparameter field sensors. This leads to heterogeneous practices among states and concessionaires, with calibrations often limited to internal routines, without integration into a unified regulatory framework. Lack of standardization can result in systematic deviations in critical parameters such as dissolved oxygen, turbidity, or electrical conductivity, compromising environmental condition assessments, especially under low-flow conditions or monitoring of effluents in compliance with CONAMA Resolution No. 430/2011. In this context, calibration discussions in Brazil remain fragmented, relying on manufacturer recommendations and isolated best practices. To ensure real-time monitoring reliability meets environmental and water resources legislation standards, institutional advances are required.

Recent experiences show relevant advances in real-time monitoring in Brazil. In the Paraíba do Sul River Basin, multiparameter probes are employed in critical stretches to assess water quality dynamics based on point discharges and flow regulation, continuously monitoring dissolved oxygen, pH, conductivity, and turbidity. The data support reservoir operation and minimum flow definition, particularly during droughts, although challenges remain in calibration and maintenance in high organic load environments (ANA, 2021; INEA, 2022).

In the Cantareira System, managed by Sabesp with CETESB oversight, automatic probes monitor parameters at strategic points, integrated into adaptive management of São Paulo's metropolitan water supply. The data enable rapid decision-making for water crisis prevention, optimization of treatment plants, and control of water quality delivered to the population, particularly during prolonged droughts (SABESP, 2022; CETESB, 2023). Both cases indicate that, even amid calibration uncertainties, real-time monitoring consolidates as a decision-making tool and supports water resilience.

3.9 STATE OF RIO DE JANEIRO

In the state of Rio de Janeiro, water quality monitoring is coordinated by the State Environmental Institute (INEA) through the Water Quality Monitoring Network (RMQA). Historically focused on manual sampling, the network began automating strategic points in recent years, supported by partnerships with universities and concessionaires. Currently monitored parameters include pH, conductivity, turbidity, DO, and temperature, with some pilot stations integrating flow and level data.

For example, monitoring of the Guandu River began in the 1990s with manual sampling campaigns, evolving from 2015 with the installation of multiparameter probes. Currently, data are used for preventive quality control in the Guandu-Lameirão water intake system, integrated into the metropolitan supply system.

3.10 COMPARATIVE ANALYSIS OF MONITORING NETWORKS

The comparison between Brazil and developed countries highlights a regulatory deficit in Brazil. While the U.S., European Union, Canada, Australia, and Singapore have established robust and auditable calibration systems, Brazil largely relies on isolated best practices and manufacturer recommendations. This gap compromises the reliability of time series data and reduces the capacity to integrate national monitoring into global databases, as shown in Table 3.

Table 3

Comparison between International and National Real-Time Monitoring Networks

Country / State	System / Platform	Common Parameters	Quality/Quantity Synergy	Coverage	Public Availability
USA	NWIS + WQX	pH, DO, conductivity, nutrients, turbidity	High	National	High
European Union	WISE + WFD	pH, DO, nitrate, turbidity, biological indicators	High	Transboundary	High
Singapore	PUB Smart Water Grid	pH, DO, chlorophyll-a, turbidity	High	Urban	High
Canada	ECCC Hydrometric	pH, DO, conductivity, turbidity, metals	High	National	High

Australia	Water Data Online	pH, DO, temperature, turbidity	High	National	High
Brazil	ANA + State Networks (HidroWeb)	Temperature, DO, conductivity	Medium	National	Partial
Rio de Janeiro	INEA - RMQA	pH, DO, turbidity, temperature	Medium	State	Partial

Source: Authors.

4 CONCLUSION

Real-time water quality monitoring represents a milestone for water governance, enhancing response capacity and adaptability to environmental and climatic pressures. Its effectiveness, however, depends on data reliability, integration between quality and quantity, and periodic sensor calibration. Neglecting these aspects can lead to misinterpretations, driving inadequate technical and policy decisions.

Analysis of international experiences reveals significant advances alongside common challenges, including biofouling, calibration inconsistencies, and regulatory limitations under low-flow conditions. In Brazil, these challenges are particularly relevant due to strong hydrological seasonality and the need to integrate automated data with national water quality standards and effluent discharge regulations.

The comparative analysis shows that countries such as the U.S., EU, Canada, Singapore, and Australia have established sensor calibration protocols based on international technical standards and robust regulatory frameworks with metrological traceability (OECD, 2020). In Brazil, despite progress promoted by the National Water Quality Monitoring Network (RNQA), there is no standardized national protocol for field calibration of multiparameter probes (ANA, 2022; INEA, 2022).

In the U.S., traceability to NIST and Clean Water Act regulatory requirements ensure reliability; in the EU, harmonized standards under the Water Framework Directive guarantee comparability among member states (OECD, 2020); in Singapore, calibration is treated as an operational safety requirement, with sensor redundancy and periodic government audits (OECD, 2020; NASA, 2023); in Canada, metrological control is reinforced through audits and interlaboratory comparisons; and in Australia, calibration operates under the National Water Quality Management Strategy, which includes specific guides for calibration and technical audits integrated into national strategies to address droughts and low-flow regimes (OECD, 2020).

In contrast, in Brazil, calibration, although included in technical manuals of agencies such as ANA and CETESB, is applied in a fragmented manner and without a uniform normative protocol. This weakens data comparability between basins and compromises integration with regulatory limits, such as those defined in CONAMA Resolution No. 430/2011. This gap highlights the need for national alignment with international best practices to ensure greater reliability and applicability of data in classification and water resources management processes, particularly in critical minimum or ecological flow scenarios.

Future perspectives include the use of nanosensors and biosensors for detecting emerging contaminants at low concentrations (LI; ZHANG; WANG, 2021), artificial intelligence for automatic sensor calibration, reducing errors and deviations (MA; YANG; ZHOU, 2022), and remote sensing integrated with in situ stations, creating hybrid monitoring networks (NASA, 2023). Such advances allow for greater coverage, precision, and resilience of water surveillance networks, especially in hard-to-reach regions or areas prone to extreme events (OECD, 2020).

Real-time monitoring is essential for climate resilience and urban water security, enabling rapid responses to floods, droughts, or cyanobacterial blooms (ANA, 2022; SABESP, 2022). In the sanitation sector, it optimizes water treatment, ensures supply reliability, and complies with legal standards for effluent discharge and potability (CONAMA, 2005; CONAMA, 2011). Thus, these technologies contribute to climate adaptation, water security, and urban sustainability.

It is therefore recommended that monitoring plans consider:

(i) robust calibration and validation protocols;
(ii) integration between quality and flow parameters;
(iii) incorporation of predictive models based on continuous time series; and
(iv) regulatory alignment between discharge limits (CONAMA 430/2011) and water body classification (CONAMA 357/2005), especially in low-flow scenarios.

Such measures are fundamental to ensure that real-time monitoring fulfills its role as a strategic tool for water sustainability.

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