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# From challenges to innovation: Expert insights on the use of Information and Communication Technologies to improve water security and river basin management

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# Abstract

Background: The growing pressure on water resources, combined with climate change, population growth, and the intensification of multiple water uses, have increased the need for more efficient, integrated, and intelligent monitoring and management systems. In this context, Information and Communication Technologies (ICT), especially those associated with Artificial Intelligence (AI), Internet of Things (IoT), Big Data, and remote sensing, hold great potential for improving water security. This study aims at identifying, based on water management experts' perspectives, the main challenges, problems, and demands to propose innovative ICT applications aimed at improving water resource monitoring, being the Piracicaba, Capivari, and Jundiaí (PCJ) river basins the research reference.

Method: This qualitative research was conducted through semi-structured interviews with 30 experts working in water resources management across various sectors, including water and wastewater companies, public agencies, river basin agencies, universities, research centres, and nonprofit organizations. The data were analysed using thematic analysis.

Results: Five key themes representing challenges and demands to improve water security were identified: data governance, data analysis, water governance, environmental education, and research, development, and innovation. From the identification of these challenges, 25 insights representing technological applications were systematized.

Conclusion: It can be concluded that information and communication technologies offer significant potential to enhance water resource management towards a future of water security.


# 1. Background

The growing pressure on water resources, resulting from population growth, urbanization, climate change, and the intensification of multiple uses of water, challenges processes of water monitoring and management in complex river basins. In this scenario, the availability of reliable, up-to-date, and accessible data gathered from multiple sources and analysed in real-time by powerful algorithmic models have become a strategic factor towards water security. According to the United Nations (2013), water security is:

The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.

The United Nations World Water Development Report emphasizes that water scarcity, extreme hydrological events, and limitations in data availability pose growing challenges to sustainable water management. The organization highlights the need for investments in monitoring and information technologies applied to the water sector (UNESCO, 2024).

In recent years, the digital transformation has enabled significant changes in the way that water resources are monitored and managed. Technologies such as smart sensors, the Internet of Things (IoT), cloud computing, big data analytics, artificial intelligence (AI), and digital twins have enabled the collection, transmission, analysis, and interpretation of hydrological data in real time, facilitating the development of smarter, more resilient, and more efficient water management systems (Daniel, et al, 2023). The digital representation of water systems contributes to the broadening of monitoring capacity, enhancing forecasting performance of critical events, optimizing resource allocation, and supporting faster and more effective decision-making processes. Daniel et al. (2023) also noted that the digital transformation of organizations responsible for water management has been driven primarily by the pursuit of operational efficiency, sustainability, and adaptation to climate change, highlighting the strategic role of Information and Communication Technologies (ICT) for safeguarding water security.

In addition, AI-based applications have shown great potential for water flow and leakage forecasting, water quality monitoring, anomaly detection, identification of potential sources of pollution, and the implementation of warning systems for real-time alerts. The integration of AI technologies, IoT, and remote sensing makes it possible to expand the spatial coverage of observations and improve the predictive capacity of hydrological models, contributing to more proactive water resource management (ZOU; JU & ZHANG, 2025; PALERMO; MAIOLO & BRUSCO, 2022; FRINCU, 2025).

In the Brazilian context, especially in highly urbanized areas and, thus, highly demanded watersheds, such as the Piracicaba, Capivari, and Jundiaí (PCJ) River Basins, which are home to approximately six million people, encompassing 76 municipalities, which accounts for 17% of Brazil's Gross Domestic Product (GDP) (AGÊNCIA PCJ, 2026), the use of these technologies becomes particularly relevant.

Although the PCJ region has robust monitoring and decision-support systems in place, the growing demand for real-time data, data integration among diverse datasets, and continuous monitoring of water security indicators highlights the need for innovative technological solutions to improve management processes of water resources. Establishing innovative technologies, however, requires a prior understanding of the challenges, bottlenecks, and demands faced by the different stakeholders directly involved in water management. The participation of experts, then, becomes paramount in the identification of their actual needs in order to generate insights for the development of solutions aligned with their institutional and operational demands.

In this context, this study aims at presenting, based on the perspectives of water resources experts, the main challenges, problems, and demands in order to foster insights for proposing innovative applications of Information and Communication Technologies aimed at improving water security, with emphasis on the PCJ River Basin.

# 2. Methods

This qualitative study, approved by the Research Ethics Committee (n. 87065825.2.0000.5481), was developed by applying a semi-structured interview guide, which was designed based on a systematic

literature review aimed at identifying, within the scientific literature in the Scopus and Web of Science databases, innovative ICT for improving water security.

The interview guide was organized into twenty questions arranged in six sections (participant identification; professional experience; general context of water resources and security; innovative technologies; water security indicators; and prospects and final comments). This study focused on the experts' responses on the challenges for water security, and their reflections and insights on the potential use of innovative ICT applications for improving water resources monitoring. This study, then, examined the extent to which experts believe that innovative ICTs can contribute to improving water security. When necessary, examples were provided of possible innovative technological applications developed in the context of water resources to engage the participants' reflections. A total of 68 experts were invited to participate in the interviews and 33 of them accepted the invitation and were interviewed. Following a first assessment of the collected data, three interviews were excluded from this analysis, resulting in a final set of 30 interviews to be included in this study. To ensure their anonymity, the participants are identified by the codes from 01AT to 30AT. The profile of the interviewees is presented in Table 1.

Table 1
– Interviewees profile

| ID | Affiliation | Position | Education | Work Experience |
|---|---|---|---|---|
| **01AT** | Water and Wastewater companies | Technician and Manager | Environmental Engineering | 8 years |
| **02AT** | Water and Wastewater companies | Manager | Biological Sciences | 20 years |
| **03AT** | Environmental Agencies | Technician | Environmental Engineering | 17 years |
| **04AT** | Consulting Firms | Consultant | Biological Sciences | 22 years |
| **05AT** | Universities and Research Centres | Lecturer e Researcher | Civil Engineering | 19 years |
| **06AT** | Environmental Agencies | Technician and manager | Civil Engineering | 27 years |
| **07AT** | River Basin Agencies | Lecturer e Researcher | Agricultural Engineering | 15 years |
| **08AT** | Public Sectors | Manager | Chemistry | 7 years |
| **09AT** | River Basin Agencies | Manager | Civil Engineering | 30 years |
| **10AT** | River Basin Agencies | Manager | Environmental Engineering | 16 years |
| **11AT** | River Basin Agencies | Manager | Environmental Engineering | 9 years |
| **12AT** | Universities and Research Centres | Lecturer e Researcher | Civil Engineering | 28 years |
| **13AT** | Water and Wastewater companies | Manager | Civil Engineering | 28 years |
| **14AT** | River Basin Agencies | Manager | Environmental Management | 18 years |
| **15AT** | River Basin Agencies | Manager | Civil Engineering | 15 years |
| **16AT** | River Basin Agencies | Manager | Biological Sciences | 15 years |
| **17AT** | River Basin Agencies | Manager | Civil Engineering | 1 year |
| **18AT** | Public Sectors | Researcher | Environmental Engineering | 11 years |
| **19AT** | Universities and Research Centres | Lecturer e Researcher | Environmental Engineering | 15 years |

**Source**: authors

| ID | Affiliation | Position | Education | Work Experience |
|---|---|---|---|---|
| **20AT** | Non-profit Organisations | Researcher | Environmental Engineering | 2 years |
| **21AT** | Non-profit Organisations | Researcher | Environmental Engineering | 10 years |
| **22AT** | River Basin Agencies | Consultant | Forestry Engineering | 8 years |
| **23AT** | Water and Wastewater companies | Technician | Environmental Engineering | 16 years |
| **24AT** | Public Sectors | Environmental officer | Sanitation | 1 year |
| **25AT** | Non-profit Organisations | Consultant | Chemistry | 47 years |
| **26AT** | Environmental Agencies | Manager | Environmental Management | 16 years |
| **27AT** | Water and Wastewater companies | Technician and consultant | Civil Engineering | 49 years |
| **28AT** | Environmental Agencies | Manager | Environmental Management | 3 years |
| **29AT** | Environmental Agencies | Lecturer, Researcher and Manager | Civil Engineering | 48 years |
| **30AT** | Water and Wastewater companies | Manager | Communication | 25 years |
| **Source**: authors | | | | |

From the interviewees profile, two areas of education are predominant: civil engineering (9 interviewees) and environmental engineering (9 interviewees), followed by environmental management (3 interviewees), biological sciences (3 interviewees), chemistry (2 interviewees), sanitation (1 interviewees), agricultural engineering (1 interviewee), forestry engineering (1 interviewee) and communication (1 interviewee). In terms of work experience in water resources management, most of the participants are affiliated in the public sector at Water and Wastewater companies, being 70% of those interviewed working in water resources management for more than 10 years.

The interviews were conducted and subsequently analysed by following six stages, as shown in Table 2.

Table 2
– Stages of the semi-structured interviews

| STAGE | DESCRIPTION | KEY ACTIONS |
|---|---|---|
| 1st Stage: Development and testing of the interview guide. | Design of the data gathering tool and its preliminary validation. | Elaborate a set of questions into a draft guide;<br><br>Submit the draft to peers and experts in the field for a critical review;<br><br>Conduct pilot interviews to test the interview guide effectiveness;<br><br>Revise and adapt the content based on the first results and the feedback received; |
| 2nd Stage: Initial contact with participants. | Invite experts in water resources. | Identify potential participants;<br><br>Contact the participants;<br><br>Send a formal invitation;<br><br>Set the date and time for the interview; |
| 3rd Stage: Conducting the interviews | Conducting the interview in accordance with established ethical principles and technical guidelines. | Initiate the interview at the previously scheduled date, time, and location;<br><br>Provide the participant with the Informed Consent Form (ICF);<br><br>Request the participant to read and sign the ICF;<br><br>Start recording;<br><br>Conduct the interview following the previously approved interview guide. |
| 4th Stage: Transcription of the interviews | Transcribe the spoken content into text format according to established guidelines. | Ensure the accuracy of the transcription;<br><br>Revision of the transcription by multiple team members; |
| 5th Stage: Data analysis | Analyse the collected data with emphasis on identifying relevant patterns to answer the research questions. | Compare the collected data aiming to establish patterns by identifying similarities and differences;<br><br>Associate the information obtained in the interviews to the central research questions;<br><br>Ensure that the participants' anonymity is preserved throughout the entire process; |

**Source**: authors

| STAGE | DESCRIPTION | KEY ACTIONS |
|---|---|---|
| 6th Stage: Presentation of the Results | Detailed presentation of the results. | Present the results in an organized, interpretable, and accessible manner, highlighting its relevance to the establishment of public policies. |
| **Source**: authors | | |

The participants were offered the opportunity to choose between two forms of participation: through an online interview via TEAMS platform (17 interviews) or by filling in the interview questionnaire made available via Google Forms (13 interviews). The interviews conducted via TEAMS platform were transcribed, while those completed directly on Google Forms did not require transcription. The set of interviews formed the corpus which was analysed by thematic analysis.

Thematic analysis can be characterized as a flexible and useful method of analysis for qualitative research in different areas of knowledge, enabling a detailed and rich analysis of qualitative research data. Braum & Clark (2006, p. 79) define thematic analysis as "[...] a method for identifying, analysing and reporting patterns (themes) within data.".

The following steps were taken to conduct the thematic analysis: (i) careful proofreading of the interview transcripts; (ii) initial reading of the interviews and initially identification of codes aimed at answering the project's research questions; (iii) initial coding by labelling and combining patterns identified across the interviews, creating a list of topics; (iv) grouping the codes into broader categories that reflect recurring themes and suggest plausible answers to the research question, namely, 'what innovative ICT applications can be developed to improve the monitoring of water security?' (v) present and discuss the results with team members.

## 3. Results

This section presents and discusses the *thematic map* resulting from the interviews. It is suggested five categories that reflect the challenges, problems, and demands for enhancing water security as identified by the participants. Subsequently, based on the analysis of the thematic map, 25 insights, with potential to turn into real-world ICT applications for improving water security, are presented.

# 3.1 Thematic Map

The thematic map presents five categories corresponding to the challenges, problems, and demands raised by the interviewees (Table 3). Subsequently, it provided insights into the potential applications of innovative technologies for improving water resource management (cf. Section 3.2).

Table 3
– Thematic Map

| Categories | Challenges, problems and demands |
|---|---|
| **Data Governance** | Time series |
| | Data integration |
| | Data democratization |
| | Data interpretability and transparency |
| | Data sovereignty |
| **Data Analysis** | Pattern detection and prediction |
| | Turn data into information |
| | Evidence-based decision-making |
| | Warning systems for real-time alerts |
| | Interpretable and explainable systems |
| **Water Governance** | Strategic planning (watershed management plan) |
| | Facilitate intersectoral communication |
| | Integration of hydrographic data |
| | Automating reports (water situation report, water quality report, performance report, etc.) |
| | Monitoring the results and impact of strategic plans, projects, and funding |
| **Environmental Education** | The value of water |
| | Public engagement |
| | Addressing and combating *fake news* |
| | Water reuse |
| | Water loss |
| | Water tariff |
| **Research, development, and innovation** | Participatory design |
| | Partnerships with universities and research centres |
| | Technology Transference |
| | Technical Training and capacity building |

**Source**: authors

| Categories | Challenges, problems and demands |
|---|---|
| | Applied research |

**Source**: authors

## 3.1.1 Data governance

The first category encompasses processes related to **data governance** which, according to *The Global Data Management Community Framework* (2014, p. 10), involves the planning, oversight, and control of data, fostering standardization in the collection, storage, use, and reuse of data among different stakeholders. Data governance, thus, aims at ensuring data interoperability across different sectors and systems, as well as enabling accountability in the management and attribution of scientific, economic, and social value to the data collected, stored, and distributed. A recurring theme among the interviewed experts concerns the consolidation of robust **time series** of hydrological data (02AT, 06AT, 11AT, 26AT, 27AT). Time series refers to sequential hydrological data collected over long periods and stored in reliable databases, allowing it to be retrieved for a variety of purposes; for example, to detect patterns using algorithmic models of artificial intelligence. One of the interviewees explained that creating robust databases by means of consistent data gathering enables the comparison of "the rainfall and flow rate to the historical data from the last ten years [...] then we can see that, sometimes, there were significant variations and that climate change has really had a major impact on rainfall and water flow rate in the areas we are monitoring" (06AT).

The relevance of consolidating robust water time series to support reliable pattern prediction points to the importance in continuous assessment of the integrity of the sensors that collects the data. The following demands were raised by the participants: detecting failures in real-time data-collection sensors, assessing when the generation of monitoring data is insufficient (04AT, 11AT, 26AT), when the data is unreliable (04AT, 11AT), and when access to 'raw data' is hampered due, for example, private datasets (04AT, 07AT, 09AT, 11AT). To create and increase the value to the collected data, aiming at improving water resource management, require managers to access both raw and value-added data (i.e. information) which can be achieve by the integration of data and information into robust platforms that are interpretable, explainable, and transparent.

In this scenario, the experts interviewed emphasized the relevance of integrating data from different sources and sectors (08AT, 11AT, 22AT, 27AT). Interviewee 08AT stresses that **data integration** is essential for creating a database that can be accessed by diverse stakeholders to provide evidence in supporting their decisions. In addition, promoting open access to high-valued data becomes the next step towards fostering transparency in processes of data use and reuse (02AT, 06AT, 28AT). Participant 06AT celebrates the achievement of an open access system by explaining that "any person can access [the system] to visualize and download the data; any person can analyse the data for their own purpose. So, this was a major breakthrough that we're still celebrating to this day".

The experts interviewed urge to facilitate data representation by means of “translating it in a simpler language” (07AT), enabling the interpretation of the available data by multiple users (07AT, 14AT) by means of developing intuitive systems (26AT, 28AT). As highlighted by 26AT, “what I miss the most is a system that provides the public with an easy-to-understand information system: is it raining or not raining? Is this good or bad? Is the river overflowing or not? are the reservoirs low or high?”

Another challenging aspect of data governance is to achieve reasonable degrees of data standardization. The adoption of the FAIR principles: Findable, Accessible, Interoperable, and Reusable (Wilkinson et al, 2016), and the development of robust open data infrastructures indicates a fruitful way towards data accessibility. These measures have the potential to enhance water resources management by securing the **democratization of data**. Facilitating access to integrated datasets, in turn, would prevent rework and duplications. The participant 11AT notes that “sometimes, we discover that our colleague next door is doing the same thing as us”.

In the era of information and artificial intelligence, environmental data emerges a valuable commodity, and as such, ensuring data sovereignty, democratization, and open access becomes essential “to have more **autonomy** in deciding how water resources will be managed” (28AT).

## 3.1.2 Data analysis

The second category represents the potential to facilitate and accelerate the identification of relevant patterns in datasets to support decision-making processes and, thereby, improve water resource management. The use of artificial intelligence tools for analysing massive volumes of data (for example, by applying machine and deep learning models) enables the prediction of patterns, the design of warning systems for real-time alerts, facilitating the interpretation of monitoring data, which is fundamental to water resource management.

The experts interviewed emphasised that the use of innovative technologies for data analysis provides *scientific accuracy* in monitoring of water resources (09AT), furnishing *evidence* for decision-making processes (07AT, 10AT, 13AT, 22AT, 26AT, 27AT, 28AT), avoiding blind guesses and, therefore, replacing intuitive thinking (27AT, 28AT). In short, the use of ICTs for water resource management is assessed positively by the interviewees, as it offers support for forecasting and planning (09AT, 13AT, 16AT, 20AT, 21AT, 26AT, 27AT), fostering data management and analysis aiming at enhancing water security (10AT, 13AT, 16AT, 20AT, 21AT, 22AT, 24AT, 23AT, 30AT). Hence, understanding the potential for the responsible application of AI technologies in water resource management truly enables São Paulo State to ‘enter the 21st century’ (04AT, 11AT, 12AT).

One of the key requests made by the experts is to explore the potential of artificial intelligence for **predicting patterns** in massive databases. With the increasing investment in the acquisition of sensors for automatic data collection (to gather data on water flow, dissolved oxygen, turbidity, etc.), water and wastewater sectors have acquired massive volume of data that is impossible for human cognition alone to interpret. In this context, algorithmic models of data analysis, particularly those known as artificial

neural networks (which encompass machine and deep learning models), provide an opportunity to extract value in real-time data analysis.

For example, expert 26AT comments: “one of our ideas for the project is to use artificial intelligence tools to identify patterns in the data; we have a huge amount of data, and we want to find out what kind of patterns we can identify in it, and what kind of inferences and predictions we can make based on those patterns.”. In the same vein, interviewee 21AT explains: “Artificial intelligence tools enable the improvement of water management and security by integrating real-time and predictive data, thereby supporting decision-making processes and optimising the use of resources”.

Therefore, applying artificial intelligence models to manage water resources enables **the transformation of ‘raw data’ into information**. In other words, the monitoring data collected in real time become meaningful when interpreted within the context of water resource management. Expert 05AT explains: “[...] one has to process this ‘raw data’, which could be anything from a technician’s note, a parameter to be analysed in any given system, a laboratory analysis, a model, or even telemetry data from an automated station. This data is, then, *transformed into information*, and this *information generates knowledge* and insight for decision-making”.

Transforming data into information fosters evidence-based decision-making processes. Participant 13AT highlights that “IoT sensors, real-time monitoring systems and the use of artificial intelligence enable the continuous monitoring of water quality, levels and flow rates, as well as forecasting water demand and quickly identifying problems such as leakages or contamination. These tools provide accurate data for faster, more informed decision-making, optimising the use of water resources, reducing water loss”.

A recurring request concerns the development of innovative ICTs for designing **warning systems for real-time alerts** (01AT, 05AT, 07AT, 08AT, 09AT, 10AT, 11AT 18AT, 20AT, 26AT, 30AT). Expert 20AT summarizes: “information and communication technologies enable data to be collected, integrated and shared in real time, supporting warnings for extreme events and more efficient water management”. Warning systems could follow a ‘traffic-light system’ (11AT): to classify the detected patterns in the data on a severity scale (green, yellow, amber, red); when the warning system identifies patterns indicating critical situations – such as the risk of flooding, low levels of dissolved oxygen, or high turbidity – the system sends an alert directly to the manager, decision-maker or the population likely to be affected.

Finally, aligned with the Legislative Bill n. 2338/2023, which establishes a human centred approach for the development, promotion, and ethical and responsible use of artificial intelligence (Brasil, 2023), participants commented upon the demand in designing **transparent**, **interpretable** and **explainable** systems according to the end-user. As expert 13AT explains “the Legislative Bill n. 2338/2023 proposes a regulatory framework for the responsible use of artificial intelligence, including measures to ensure transparency, security, data protection, and accountability. It proposes risk assessments, rules for high-impact systems and the creation of a national governance framework, promoting the ethical, sustainable and responsible development of this technology, particularly for critical applications such as the control

of water supply networks". The degree of interpretability of a system should be aligned with the competencies of its end-user, as 28AT emphasises, a system "has to be very user-friendly to be able to operate it [...] it would need to have several modules: one for technicians, one for managers, and even one for the general public".

## 3.1.3 Water governance

**Water governance** can be described as a set of political, legal and social systems that offers guidance for decision-making processes on the use and management of water resources (Santos, 2026). According to the Sustainable Development Goal (SDG) n. 6 – clean water and sanitation – proposed by the United Nations, water governance aims to "ensure availability and sustainable management of water and sanitation for all" (United Nations). The Organisation for Economic Co-operation and Development (OECD) highlights that the water crisis can be described as a governance crisis given the importance of engaging in a multi-level approach to safeguard water security across the globe. A sustainable management of water resources, then, requires strategic planning, the establishment of constant dialogue with a wide range of sectors (public and private companies, third sector, civil society, etc.). Evaluating the results of proposed plans and actions, and funding investment also becomes paramount to processes of water governance.

An agenda for water governance encompasses the resolution of conflicts over water use, massive investments in **water reuse**, and the **diversification of sources for water supply**. In the Brazilian context, expert 12AT summarizes: "Brazil is suffering from droughts; not only from droughts, but also from water scarcity. Many sectors are using water, which is giving rise to conflicts over its use. With the aim of mediating these conflicts, water reuse is part of the solution; another part of the solution is to diversify the sources of water supply.".

In a future characterised by water insecurity, climate change, weather unpredictability and extreme events, water governance involves well-established **strategic planning**, known in the field of water resources management as **River Basin Plan**. A good strategic planning should provide a set of clear objectives and specify quantifiable targets that support the development of feasible actions that, in turn, can be assessed, evaluated and revised. The development and implementation of the strategic actions, then, is monitored to assess the extent to which the aims are being met, whether any unexpected event has occurred, and/or which of the proposed strategies should be revised.

In the context of water and wastewater companies, expert 02AT strongly emphasizes the relevance of strategic planning: "I'm fighting over getting at hiring a strategic planning consultancy that will cover the company as a whole and, within each department, establish specific management indicators to help us with decision-making processes.". In the context of São Paulo State, the aim is to integrate strategic planning across multiple sectors in order to establish "a state-level plan for water resources management" (26AT).

Tracking and assessing the progress of **strategic plans, projects and funding** proposed by the river basin plan, thus, become a key factor for water governance. This assessment is done by means of specific indicators that measure “the execution, evaluation and implementation of the plan” (26AT). These indicators should be presented in water situation reports and bulletins, as expert 27AT explains: “There is another management tool, namely the water situation report, in which you produce an annual report detailing the condition of water resources in each river basin and, subsequently, at state level, the state report”. Whereas reports are launched annually, **bulletins** and **water quality reports** detailing the status of water resources can be published annually, monthly, biweekly, weekly or even daily. Therefore, well-structured and self-explanatory **reports** become an **effective communication strategy**, both for **facilitating intersectoral dialogue** and for improving communication with the public.

The implementation of innovative ICT can support the evaluation of the progress of River Basin Plans, the assessment of what has been implemented, what needs to be revised or changed. In sum, ICT could inform decision-making process of water resource managers enhancing water governance.

## 3.1.4 Environmental Education

Ensuring water security also involves **environmental education** measures aimed at raising public awareness of water security and insecurity by informing and educating people about the sustainable use of water resources, as well as encouraging active participation in the public debate and the management of natural resources.

Environmental education involves informing the public about the decisions, values and actions related to water resources by an open dialogue aiming to foster critical thinking regarding the complexities involved in water management. Whenever possible, the public should get involved in water resource management, empowering citizens to become active participants and thereby promoting transformative environmental education. Loureiro (2003) explains that: “to educate for transformation is to act consciously within social processes that are conflictingly shaped by social actors who have different ideas of society and which claim the natural resources, both materially and symbolically, in unequal ways”. Broadening the perspectives about water, as a valuable natural resource, along with striving for environmental justice and equity, is also part of environmental education.

**Awareness campaigns** to reduce water consumption (02AT) considering the diversity of demographic groups (30AT) aims at providing information on the economic, electric, and chemical costs of water treatment (30AT). Another measure of environment education is to inform about the importance of diversifying the sources of water supply and educating the public on the safety of water reuse methods (12AT). The interviewee 28AT highlights the importance of raising public awareness of the multifactorial causes of water scarcity, while educating people on the complexities involved in water resource management.

Another suggestion, given by participant 30AT, is to inform the public about the investments in environment conservation and infrastructure, explaining the reasons for and the impact of their

interventions. The participant also emphasises the importance of increasing water and sewage fees (30AT), arguing that environmental education alone is not enough to ensure that the public values water as an essential resource: “If [environmental education] is reflected in the price, people will automatically take action. If it isn’t reflected in the price, and we rely solely on raising environmental awareness, I don’t think that’s enough” (30AT). While raising water tariff can be key to reduce water consumption, social inequalities must be considered to safeguard social justice.

In synthesis, environmental awareness initiatives involve underscoring the **value of water**, educating people about climate change and its impact on the availability of water resources, dissolving popular myths and combating fake news. Transformative water education places citizens at the heart of the debate, as active participants in water monitoring and management, reflecting on feasible strategies for a future with water security for all members of society. Educating people about the value of water means providing information that encourages them to reflect on the complexity involved in its cycle: “water is part of a complex network, a dynamic process [...] therefore, water must be understood in its entirety, throughout its entire cycle.” (30AT).

## 3.1.5 Research, development, and innovation

This paper proposes applications of innovative information and communication technologies (as insights; cf. section 3.2) to address the challenges and demands described above. To invest in research, development and innovation requires methodological, ethical and social consideration from designing prototypes of new technologies, through to their implementation, technical training, and subsequent maintenance.

Firstly, potential technological applications should be developed in collaboration with its potential users. This process, as explained by 28AT, is called **participatory design**: “Listening to the technical staff, listening to the managers, and listening to those who are likely to use the tool is, in itself, a collaborative way of designing the decision-support system”. Once a technology has been developed, the interviewees strongly emphasise the importance of **technical training** to ensure its effective implementation and appropriate use (03AT, 04AT, 05AT, 06AT, 07AT, 09AT, 10AT, 11AT, 13AT, 14AT, 20AT, 18AT, 22AT, 26AT, 29AT). The participant 11AT highlights that as in any area, water resource management requires technical training in the use of AI tools: “AI is going to be here to help [...] so this becomes another skill to look for when recruiting. This demand for **technical training in AI**, whether for technologies in water resource management or in any other field (law or any other use), we will need to be literate in this area”.

A fair, equitable and sustainable development of innovative ICT involves cost-free **technology transference** across sectors, making it openly available and accessible to a wide range of users (02AT, 05AT, 06AT, 08AT, 09AT). Consequently, there is a recurring demand for these technologies to have a user-friendly interface that is easy to interpret, so that people with or without technical training or specialised knowledge can access, understand and benefit from it (07AT, 14AT, 16AT, 28AT).

A technical challenge associated with the use of artificial intelligence (mainly unsupervised deep learning models) concerns their inherent lack of **explainability**. In other words, there is an increasing demand not only for user-friendly design, but also for **transparency** in the model's internal logic. This is known as the **black-box problem**: "nobody understands how this stuff works, nobody understands how to operate it, nobody knows what's in there, nobody knows what it runs" (28AT). For this reason, in strategic areas such as public safety, public health and water resources management, developing transparent and interpretable models becomes an essential requirement.

Adopting best practices in research, development and innovation also involve solid partnerships to foster fruitful collaboration among universities, public and private sectors, and nongovernmental organizations (03AT, 05AT, 07AT, 08AT, 09AT, 10AT). Expert 09AT reiterates: "what we need, and what we have been striving for, is to bring the university's expertise to the River Basin Committee, so that we can bring these two institutions closer together and establish more robust parameters, supported by scientific precision, rather than relying on speculations."

In sum, strong partnerships among different sectors of society provide support for the sustainable and responsible development of technologies that, in fact, can be implemented in real-world contexts within water resource management. Participatory design, technical training, and technology transference provide a fruitful pathway towards the development and implementation of innovative ICTs to improve water security.

## 3.2 Insights and innovative ICT applications for improving water security

Based on the challenges, problems and demands identified, the interviewees suggested solutions in form of insights and technological applications to assist water resource management and enhance water security. By reflecting on the interviewees' demands and proposals for new technological applications, as well as discussions within the research group that conducted this study, 25 potential insights, applications, projects and innovative ICT possibilities for improving water security were identified, which are described below.

**a) Systems for monitoring the impacts of climate change (03AT)**

Systems for qualitative modelling (i.e. models that deal with qualitative, not strictly quantified data, such as satellite imagery) and AI tools (such as machine and deep learning algorithms) to analyse existing databases, propose parameters and monitor the consequences of climate change in hydrology.

**b) Water scarcity warning and risk management system (03AT)**

AI applications for data monitoring and pattern detection that provide early warning signs of potential water scarcity to issue alerts to enable strategic decision-making, better management of the resources, and risk mitigation measures, such as rationing, prioritising water use, increasing water resource rates, and introduce diverse water pricing schemes according to water availability and population demography.

**c) Technological application to assess the effectiveness of water awareness campaigns, to combat fake news and to evaluate user satisfaction in real time (02AT)**

AI application developed for public communication, aiming at demystifying and combating fake news. For example, training algorithms to detect the spread of misinformation and generate alerts for the relevant authorities. Training algorithms, such as sentiment analysis to assess public opinion on the water and wastewater services. Evaluating the results of awareness campaigns; for example, comparing the reduction in water usage before and after large-scale awareness campaigns in a specific region, and/or focusing on a particular company or industry.

**d) Integrated monitoring system with real-time warning signs (09AT, 10AT e 27AT)**

To develop a platform that integrates and combines information on drought monitoring, river flow, satellite imagery and weather forecasts to improve water resource management in planning strategies to enhance water security. Monitoring data in real time and generating warning signs for potential scenarios which require attention will enable better management and decision-making processes. The use of AI tools aims to support the elaboration of reports, bulletins and river basin strategical plans, by means of disclosing information on the river condition, water quality, facilitating data analysis, and enabling evidence-based water resource management. By integrating data from radar, telemetry and observation stations, the reliability of the information gathered provides robust support and evidence for decision-making processes in water management.

**e) System for monitoring the implementation of river basin management plans (11AT)**

Using of technology to facilitate the organisation of water resource funding initiatives, to monitor how much has been invested in programmes, projects and initiatives, to identify gaps that hinder water management, and to assist the development of new action plans to be described in the river basin plans. This application aims at integrating data on every financial intervention (public or private) carried out in the river basin in order to compare the extent to which the results align with the planned objectives.

**f) Machine vision applications for monitoring floating solid waste (10AT)**

Use machine vision algorithms to assess, monitor and track the amount of solid waste in hydraulic structures (for example, in dams). This technology aims to assist the detection of floating solid waste in critical areas, analysing the results of action plans conducted to reduce solid waste. Through real-time data collection, this application will be able to generate warning signs (alerts) regarding diffuse pollution and predict the impact of such waste to critical areas.

**g) Real-time watersheds monitoring applications**

As an alternative to satellite image (which can be affected by cloudy weather or lack fine-grained resolution), relevant factors which affects watersheds behaviour can be monitored using data extracted

from security cameras. Based on this data collection, it is possible to apply machine vision algorithms to detect floating debris in water streams, potential flooding and sources of contamination, water loss, etc.

**h) Flood and water level rise warning systems in coordination with the civil defense service (10AT)**

Use of data gathering technologies and AI tools for real-time data analysis to issue warning signs regarding floods, predictions of fast water level rise (for instance when opening dam gates) in coordination with the civil defence authorities. Classification of the criticality of water levels and tailored trigger warning alerts for managers, technical staff, and the civil population residing at flood risk areas.

**i) Application for simulating land use and occupation (02AT, 10AT)**

The use of ICT to monitor watersheds aiming at detecting and preventing the spread of potential unauthorised land use and occupation. Data can be collected via satellite images and surveillance drones. The integration of data from different sources, combined with an AI application for data analysis, has the potential to assist decision-making processes in coordination to environmental agencies, decreasing the risk of damaging water catchment areas by irregular land occupation.

**j) Application to automating reports on water quality and quantity (11AT)**

To develop an AI application that integrates data on rainfall, the rainfall-to-flow ratio, dissolved oxygen, turbidity and other relevant parameters, in order to automate the generation reports drawn from various data sources, such as, for example, São Paulo State Environmental Company (CETESB), Metropolitan Water and Energy Company (EMAE), São Paulo State Wastewater Company (Sabesp), and São Paulo State Water Agency (SP Águas).

**k) Application for detecting faults in sensor data collection (11AT)**

Develop an AI tool to monitor data collection in order to identify potential sensor faults and, thereby, prevent the historical time series from being compromised. This can be achieved by detecting data gaps, by using cameras to monitor the integrity of the sensors, monitoring the power source supplying the sensors, checking the internet connection (in the case of IoT devices) or checking the river gauge to measure the sensor's contact with the water. This application will enable to safeguard processes of data integration, early warning systems, and to detect potential causes of failures in data collection. This monitoring device will be paramount for acquiring reliable, high-quality data, which, in turn, will facilitate the development of robust algorithms for data analysis.

**l) The use of chatbots to communicate with the public (11AT)**

Develop a chatbot to facilitate public access to information about water resources in their region, such as potential disruptions to the water supply. For example, by providing their national identity and property registration number, members of civil society would be able to retrieve information using an AI interface.

**m) Dashboard of integrated data (11AT)**

Develop data visualisation user-friendly platform via self-explanatory dashboards. This application would enable users to drill down or drill up clusters of data to narrow or broaden access to information available from different stakeholders and sectors, thereby facilitating the decision-making processes.

**n) Water license management system**

This system aims to integrate information on granted water allocation permits (water licenses) in relation to the projections of water availability in order to support evidence-based decisions regarding requests for new and renewal water licenses. Such a system would be design in order to correlate the following variables: (i) data on existing water allocation permits, (ii) water availability in the given region, (iii) projections of water availability (short, medium and long term forecasting), and (iv) the actual use of the licensed water. This would enable continuous assessment of water use in relation to the quantity authorised by the permit, allowing rigorous inspection and correct adjustments when needed.

**o) Smart irrigation**

Develop a system that uses AI applications for the efficient management of irrigation processes. Knowing how and when to irrigate crops can be a powerful tool for preventing water and electricity loss (30AT), soil runoff and erosion. An innovative solution would be to link irrigation systems via IoT with real-time meteorological data (relative humidity and rainfall forecasts) to adapt irrigation processes to environmental conditions. One could consider the possibility of using machine vision (remote sensing, or surveillance cameras) to monitor soil erosion (27AT and 30AT). In addition, the system would enable the use historical data to establish correlations between erosion and irrigation methods, and between irrigation methods and soil runoff. Thus, the most appropriate type of irrigation could be implemented for the sustainable use of water and electricity while preventing soil damage.

**p) Integrated system for monitoring and reducing water consumption**

Design and conduct a survey to represent a population's demographics (age, gender, economic status, etc.) in relation to their water consumption data in order to target environmental awareness campaigns to specific profiles and consumption habits. Engage in partnerships with companies to implement pilot awareness campaigns aiming at reducing, in the case of São Paulo State, human water consumption. Whereas most river basins in Brazil supplies water for agriculture and industry, the greatest demand for water in the State of São Paulo is for human consumption; as such, awareness campaigns can be powerful allies in reducing water consumption.

**q) e-PCJ: citizen science project to monitor the PCJ river basin**

Design mobile apps to engage the general public (citizen science) to report issues that may affect water security, such as the condition of rivers, lakes and beaches in their region, tap water quality, potential incidents that could jeopardise water security, for example oil spill. Using AI applications, the system analyses the information gathered to issues warnings to regulatory authorities, thereby reducing delays in the decision-making process.

**r) Data governance implementation**

This system aims to facilitate data sharing for use across different sectors (water resources, energy, internet, gas, etc.), which may, in turn, add value to the data and transform it into information. This information (data processed within a specific context) could, in turn, be available within the system so that it can be accessed, thereby avoiding redundancy (duplication of effort). This proposal aims to improve data governance in the state of São Paulo with a view to the *democratic access* of data and information.

**s) Platform for self-management of water loss (30AT)**

Develop systems that use IoT sensors to detect water loss in homes, commercial and industrial premises. When an anomaly is detected, the system would send alerts directly to the owner's mobile phone notifying that the integrity of the internal network can be damaged. The system identifies anomalies in water consumption based on the consumption patterns of households, businesses, industry, etc.

**t) System for water consumption tariff flag (29AT)**

Propose to diversify the rate to calculate water tariffs according to different tiers based on the region's water availability (for example, the volume level of reservoirs). One option would be to adjust the tariff according to monthly per capita consumption to encourage water saving (the more you use, the more you pay; the less you use, the less you pay). To foster environmental justice, the social-economic status of the population should be considered.

**u) Application of disease prediction in public health using sewage data (29AT)**

Use sewage samples to identify diseases that may affect public health and create heat maps of critical areas. Develop an AI application to analyse the data in order to accelerate sanitary measures.

**v) Virtual reality to promote environmental education and engagement (02AT)**

Design virtual reality devices to engage the public in discussions about sustainability and water resources in a fun, yet scientific way, thereby promoting transformative environmental education.

**x) Digitalization of archived documents to fill in time series gaps (04AT)**

Retrieve historical data by means of digitalising documents containing time series information; conversion of images into text using an optical character recognition and applying natural language processing algorithms to organise and classify the texts by subject.

# 4. Discussion

This paper has presented, based on experts' perspectives, the main challenges, problems and demands enabling insights for the development of innovative applications of Information and Communication Technologies (ICT) to improve water security, in the context of the PCJ river basin. The results showed that the challenges identified go beyond purely technological solutions, involving interdependent aspects related to data governance, data analysis, water governance, environmental education, and research, development and innovation. These five categories are key elements in strengthening water security in a context characterised by climate change, increasing pressure on water resources, and the growing complexity of decision-making processes.

In the context of data governance, the availability of reliable time series, integration between different databases, the democratisation of information, transparency and data sovereignty are fundamental for the development of decision-support systems. The fragmentation of information in diverse datasets and communication barriers across public and private institutions still represent significant obstacles to water resource management. In order to transform data into information, powerful artificial intelligence tools can be applied to analyse massive amount of data which, in turn, scaffolds the development of warning systems for real-time alerts. The possibility to analyse real-time data enables decision-making processes, supported by up-to-date evidence, to be more precise and efficient.

Innovative ICT have also the potential to play an important role in water governance by assisting the monitoring of river basin plans, projects, investments as well as assessing management indicators, fostering evidence-based decision-making processes. The elaboration and dissemination of water condition reports and bulletins enhance administrative efficiency and facilitate the communication among different stakeholders in the water resources management. As an ally to water governance, environmental education complements efforts based on technological innovation to enhance water security. Experts emphasised that water security depends not only on the availability of efficient monitoring tools, but also on the ability to communicate and engage with the public. Initiatives focused on public engagement, combating misinformation, investing in citizen science and promoting awareness campaigns increase public participation in water resources management, strengthening governance towards a future of water security.

Emphasis was given for strengthening the cooperation among universities, research centres, water and wastewater companies, and end-users of technological systems. This result reinforces that the development of innovative solutions should be driven by participatory design, followed by technical training programs, technology transfer initiatives. Thus, the collaborative development of ICT has the potential to enhance their effectiveness, implementation, maintenance and long-term sustainability.

The key contribution of this study is the proposal of 25 insights into technological applications to support different stages of water resource monitoring and management. The proposals range from warning systems for real-time alerts, data governance platforms, citizen science projects, automated reporting, water license management, smart irrigation, and digital environmental education. These

insights constitute an initial portfolio of opportunities for the development of innovative solutions aligned with the real needs identified by the experts.

Among the limitations of this study, the results reflect mainly the perception of experts working within the context of the PCJ river basins and, as such, there may be different challenges and priorities in other river basin regions. Furthermore, the insights presented are forward-looking in nature and require further studies into technical, economic, institutional and regulatory feasibility for their effective implementation. In future research, it is recommended that a more in-depth assessment be carried out of each of the proposed applications, including analyses of technological feasibility, prototyping, experimental development and validation in real operational environments.

# 5. Conclusion

It is concluded that strategies to improve water security require an integrated approach that combines technological innovation, data governance, public engagement, capacity building, technology transference, and continuous cooperation between different sectors of society. Information and communication technologies offer significant potential to enhance water resource management towards a future of water security.

# Abbreviations

AI
Artificial Intelligence
GDP
Gross Domestic Product
ICF
Informed Consent Form
ICT
Information and Communication Technologies
IoT
Internet of Things
OECD
Organisation for Economic Co-operation and Development
PCJ
Piracicaba, Capivari, and Jundiaí
SDG
Sustainable Development Goal

# Declarations

**Ethics approval and consent to participate:**

This research was approved by the Research Ethics Committee of at the Pontifical Catholic University of Campinas (PUC-Campinas), n. 87065825.2.0000.5481. Participation in the interviews was voluntary, and informed consent was signed by all the participants involved.

**Consent for publication:**

not applicable.

# Competing interests:

The authors declare that they have no competing interests.

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# Author Contribution

MVR Conceptualization, Methodology, Investigation, Writing -original draft; OMF Conceptualization, Methodology, Investigation, Writing - original draft, Supervision, Funding Acquisition; DFM Methodology, Investigation, Supervision; RDPA Investigation; All authors discussed, reviewed and edited the manuscript.

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# Data Availability

The dataset generated and analysed during the current study is not publicly available to secure individual privacy and the anonymization of the participants but are available from the corresponding author on reasonable request.

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