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How the digital revolution is reshaping water management and policy: A focus on Spain

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ABSTRACT

The water sector is experiencing a transformative shift through digitalisation, integrating advanced technologies like IoT devices, AI, and digital twins into water management and policy practices. These advanced technologies address critical challenges such as water scarcity and hydro-climatic extreme events by improving monitoring, management, and decision-making transparency. This paper examines the impacts of digitalisation on water management and policy by analysing the Spanish case study. Findings reveal practical benefits and identify significant challenges to its adoption in the water cycle at different managerial scales. To address these challenges, we propose recommendations emphasising equitable access, capacity-building, and supportive regulatory frameworks.

1. Introduction

The water sector is currently transitioning into its so-called 'Fourth Digital Revolution'. This digital transition is substituting the last-remaining pre-digital schemes (focused on physical infrastructure and manual monitoring) by 'ultra-advanced' digital solutions guided by the principles of efficiency, resiliency, and sustainability (Walter, 2024). Digital solutions encompass a wide range of technologies and applications, including smart sensors and Internet of Things (IoT) devices, artificial intelligence (AI), cloud computing, mobile and web applications, digital twins, blockchain technology, and augmented and virtual reality. These innovations offer real-time monitoring, predictive capabilities, and automated solutions, enabling more adaptive and proactive water management strategies. This digital revolution is also playing a pivotal role in addressing global water challenges successfully, by enhancing operational efficiency, increasing the resilience of water systems, promoting sustainability principles, and improving the transparency and accountability of decision-making processes (Boyle et al., 2022; Stein et al., 2022).

Increasing water demand, climate change, and urbanisation have become critical issues. In Europe, 17 % of the population faces water stress, rising to 30 % at the global level (Berbel et al., 2020; EC, 2022). The growing demand for water, especially for agricultural purposes in water-scarce regions, will put increasing pressure on water resources (FAO, 2022). In this context, rapid and adaptive responses from decision makers in the management of the water cycle at different scales are more needed than ever. Digital technologies hold promise for addressing these challenges through real-time data collection, predictive analytics, and automated systems, eventually leading to a significant reshaping of water management and policy practices (Damman et al., 2023). The literature on the impacts of digital tools on water management is abundant, and the benefits of these technologies are more than evident. Hence, digital tools are listed as essential instruments for achieving the objectives of the recently launched EU Water Resilience Strategy by enhancing the sustainability and resilience of water systems (EC, 2025).

The ongoing digital revolution is significantly reshaping water management by improving real-time monitoring and adaptive decision-making (Alexandra et al., 2023). Technologies such as real-time sensors, IoT devices, and predictive analytics enable utilities to monitor water quality, flow rates, and storage, allowing for rapid responses to issues like leaks and water shortages (Boyle et al., 2022). For example, in some European regions, 40–60 % of water is lost before reaching consumers (EEA, 2024), but smart water networks with leak detection technologies are helping to reduce non-revenue water (Cassidy et al., 2021; Daniel et al., 2023; Amankwaa et al., 2024). Predictive analytics have also proved useful to water utilities by improving forecast demands, assessing the risk of infrastructure failure, planning maintenance, and reducing costs associated with emerging repairs and service disruptions

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(Fu et al., 2022; Grievson et al., 2022). In agriculture, precision irrigation systems optimise water use by delivering the right amount of water based on real-time data, which is crucial for managing freshwater resources (Khanna et al., 2022).

Hydropower systems can also benefit from smart sensors and digital technologies to maximise energy production and mitigate environmental impacts in rivers (Quaranta et al., 2023a). Predictive tools powered by AI and machine learning can also forecast water shortages and flood risks, identify stress points, and inform strategies to mitigate potential problems through the processing of large volumes of data (Nishant et al., 2020). Digital twins, which replicate physical water systems in virtual environments, offer a powerful tool for simulating different scenarios and testing responses to potential failures, ultimately optimising water distribution networks and supporting better planning (Brocca et al., 2024; Ostfeld and Abhijith, 2023). Furthermore, the integration of smart water systems enhances stormwater management by dynamically adjusting storage capacities during heavy rainfall, helping to prevent flooding and improve flood resilience (Tambieva and Erkenova, 2022). On the policy front, digital technologies have become powerful tools for enhancing accountability and transparency in governance by improving oversight and empowering citizens to engage actively. By leveraging digital tools, end-users can transition from reactive to proactive strategies, enabling more efficient, sustainable, and resilient water management practices (Daniel et al., 2023).

We aim to offer insights on how this digital revolution is reshaping water management and policy practices, with a special focus on Spain. Secondly, we contribute to the discussion on the challenges of this digital transformation in the water sector. Our study focuses on the case of Spain, as the efforts being deployed to foster digitalisation in the water sector have increased significantly since 2022 thanks to the Water-Cycle Digitalisation Strategic Projects for Economic Recovery and Transformation (WCD-SPERT), which will mobilise a total investment of more than 4 billion euros in the period 2022–2026 (Spanish Ministry for the Ecological Transition, 2022a). This significant effort is highly motivated by the country's high vulnerability to climate change impacts and water scarcity. Digital solutions can play a decisive role in adapting water management to overcome the climate change challenges, as emphasised by the Spanish Ministry for the Ecological Transition and the Demographic Challenge in their strategic orientations on water management and climate change (Spanish Ministry for the Ecological Transition, 2022b). Indeed, and according to the 2021 Voluntary National Review (VNR), which assesses progress towards the objectives of the 2030 Agenda (Ministry of Social Rights and 2030 Agenda of Spain, 2021), Spain is one of the most vulnerable countries to climate change due to extreme variation in rainfall and droughts and projected temperature increases. Flooding events in Autumn (2024) along the Mediterranean coastline call for urgent evidence-based adaptation measures. The success of these measures is partly dependent on digital tools to improve data reliability and predictive analysis capacities.

Furthermore, following the critical efforts being deployed by the European Commission to strengthen Europe's digital sovereignty and set the pillars for future digital leadership, Spain is determined to lead the digitalisation transformation of the water sector by implementing an ambitious national program (WCD-SPERT) to finance and promote digital water projects across the country. These efforts align with broader European strategies, including the EU Green Deal and the Digital Strategy, which aim to integrate digitalisation into environmental policies. Finally, Spain's diverse water challenges make it a compelling case for studying the application of digital solutions across different water use sectors and regions. The country encompasses semi-arid regions, densely populated urban areas, a strong and consolidated tourist sector, and an extensive agricultural sector that consumes a significant portion of its water resources. This diversity allows for an in-depth analysis of how digital technologies address distinct sectoral challenges in the water cycle at different managerial scales.

Given the rapid digital transformation in the Spanish water sector, this paper seeks to address the following research questions: 1) What are the key aspects of water management and policy being transformed by digital tools and technologies? 2) What are the primary drivers behind the digital transformation of water management? 3) Which digital tools and solutions are at the forefront of driving this transformation in water management? 4) What are the major challenges in adopting digital technologies in the water sector? and 5) What transferable lessons can be learnt from Spain's experience with digital water transformation?

Based on the outcomes from semi-structured interviews with water-sector representatives from different sectors (e.g., urban, agriculture) and management levels (e.g., river basin, region, municipality) and information gathered from the projects being financed by the WCD-SPERT national program, this study aims to answer these research questions, offering valuable insights into the impacts of digitalisation in water resources management and policy.

Although there is a long body of research on the benefits of digital tools in water management, few studies delve into how these tools are being implemented in, and impacting, a specific national context. Our work provides a real-world analysis, drawing on an analysis of national digital strategies and semi-structured interviews with stakeholders to offer practical insights on digital adoption, challenges, and strategies for success. Furthermore, it identifies critical challenges for the roll-out of digital tools in water management and policy. By addressing these challenges, this study provides valuable recommendations to accelerate digital adoption in the water sector. Finally, the lessons drawn from this research can be transferred to other water-scarce areas in the world, including other southern European countries and regions worldwide. Such lessons can be relevant for policymakers and managers looking to adapt Spain's strategies to their national contexts.

With these aims, this paper is structured as follows. The following section offers an overview of how this digital revolution is reshaping water management and policy, highlighting specific impacts. The case of Spain is then analysed in Section 3 based on semi-structured interviews with water-sector representatives from different sectors and management levels, aiming to cover the entire water cycle. This section offers practical insights on how digitalisation impacts specific management and policy aspects, its main drivers, and the type of digital solutions being implemented by different stakeholders. Section 4 focuses on the challenges in the implementation of digital solutions in the water sector. We believe that the Spanish case study provides a practical framework for understanding the challenges and opportunities associated with the digital transformation in the water sector. Finally, Section 5 provides a discussion on the lessons that can be learnt from the Spanish case study, which could help to facilitate the digital transition of the water sector in other countries and regions. This final section also proposes some areas of improvement to maximise the positive impacts of digitalisation in the water sector, as well as to offer future research avenues.

2. Digital tools as catalysts for water management and policy practice transformations

The current digital transition of the water sector is transforming how decision-makers address water challenges by enabling smarter, data-driven solutions that enhance efficiency, resilience, and adaptability in water management at different levels (e.g., urban, regional, and river basin). Compared to pre-digital efforts, which primarily relied on the construction of physical infrastructure, manual monitoring, and static policy frameworks, digital technologies are offering more dynamic, proactive, and holistic approaches for water resources management (Boyle et al., 2022). Further, digitalisation has also changed the way that policymakers design, implement, and enforce water management regulations. A summary of digital and pre-digital approaches to different water management and policy aspects is offered in Table 1.

Before the advent of digital technologies, decision-makers primarily relied on physical infrastructure improvements, regulatory frameworks, and public awareness campaigns to manage water. Historically, water

Table 1
Examples of Digital and Pre-Digital approaches to different water management and policy aspects.

Aspect	Pre-Digital	Digital
Data Analysis	Historical data, reactive approach	Predictive analytics and AI-driven insights, a proactive approach
Leak Detection	Delayed response due to manual detection	Immediate leak detection through smart sensors and automated systems
Irrigation Techniques	Manual-actioned irrigation (e.g., flood irrigation, drip irrigation)	Precision irrigation with AI and real-time soil moisture sensors
Wastewater Reuse	Limited reuse capabilities with basic treatment plants	Advanced digital systems for optimised wastewater treatment and reuse
Decision Making	Based on outdated and static data, reactive measures	Decision-making based on real-time data and predictive models
Monitoring & Enforcement	Manual inspections and periodic checks. Difficult to monitor compliance in real-time	Real-time monitoring. Enhanced enforcement through real-time monitoring, smart meters, and sensors
Public engagement and participation	Written submissions, petitions, public notices, media campaigns	Report issues and access real-time data on local water resources
Risk prevention (early-warning systems)	Manual data collection, meteorological and hydrological observations	Automate alerts for extreme weather events or pollution incidents to protect water resources and public health

Source: Own elaboration.

resources management was focused on building large-scale infrastructure like dams, reservoirs, and aqueducts to facilitate water supply and storage management. While these projects were crucial for water storage and distribution, they lacked the flexibility and efficiency required for dealing with climate variability and real-time water demand fluctuations. Government regulations and policies, such as water use restrictions during droughts or water pricing reforms, were the primary tools for influencing water consumption behavior. However, such regulatory approaches often struggled with enforcement, and policies were sometimes slow to adapt to changing environmental conditions. This adaptation limitation was mainly due to the methods for monitoring water systems, which were primarily conducted through manual inspections, sampling, and historical data analysis. This process was labour-intensive and often failed to capture real-time data, making it difficult for water managers to respond quickly to emerging shortages or inefficiencies.

In water-intensive sectors like agriculture, flood irrigation was widely used, leading to significant water loss. Efficiency programs relied on basic improvements like drip irrigation and canal lining, but without real-time data, these methods could not maximise water-use efficiency or adjust based on evolving environmental conditions. In the case of the urban sector, efforts were focused primarily on infrastructure improvements and public awareness campaigns. Raising awareness through campaigns to encourage water conservation (e.g., encouraging shorter showers, fixing leaks, etc.) was common but had limited effectiveness in altering long-term water-use behaviour without data-driven insights to guide action.

Digital technologies have introduced precision, automation, and real-time decision-making into water management, enabling a more targeted approach to specific needs and problems derived from climate challenges (Alexandra et al., 2023; Daniell et al., 2022). Digitalisation of the water sector has shifted the focus from physical infrastructure and supply augmentation towards the principles of cost-efficiency and sustainability as key determinants of water resources management. Technologies, such as IoT sensors, are now being used to continuously monitor water flows, detect leaks, and assess infrastructure conditions (Furones and Monzón, 2023). The integration of smart sensors into urban water systems is contributing to the identification and repair of leaks more rapidly, preventing substantial water wastage. Unlike manual monitoring, these sensors provide real-time data on water pressure, quality, and consumption, allowing decision-makers to optimise distribution, address inefficiencies immediately, and define more tailored management measures and policies (Water Europe, 2022).

A significant shift in the current 'fourth' digital revolution in the water sector has come from the use of big data and AI-powered predictive models (Boyle et al., 2022). These tools analyse vast amounts of historical and real-time data to predict water availability, demand, and drought conditions with high accuracy. For example, AI models can optimise irrigation schedules based on soil moisture data, weather forecasts, and crop water needs, ensuring that farmers use only the necessary amount of water. Predictive analytics provide water managers with valuable insights to forecast droughts or water supply shortages weeks or months in advance, enabling more strategic resource allocation (Botín-Sanabria et al., 2022; Daniell et al., 2022). In contrast, pre-digital strategies often relied on static assumptions and historical averages, which could not account for fast-changing environmental conditions. Further, the automation of water systems allows for real-time adjustments in water supply based on demand. For instance, SCADA (Supervisory Control and Data Acquisition) systems enable remote monitoring and control of water treatment plants, reservoirs, and pumping stations. Thus, water systems can react dynamically to real-time data, automatically increasing or reducing water supply based on factors like weather or usage spikes (Beal and Flynn, 2015). Pre-digital efforts required manual interventions, where infrastructure changes or repairs were often delayed due to slow detection or human error, exacerbating the impacts of water shortages.

Socioeconomic impacts of hydro-climatic extreme events are increasing as a result of climate change, and digital solutions can significantly contribute to risk reduction and the protection of public health. The integration of hydro informatics on hydro-economic modeling is improving model capacity to enhance decision-making on water resources management under rapidly changing climatic conditions (Expósito et al., 2020). Further, early warning systems equipped with digital technologies are becoming essential for saving lives and preventing disasters. Copernicus CEMS is offering new opportunities for real-time data to enhance water-related risk responses, such as the European Flood Awareness System (EFAS). Drought early warning systems equipped with real-time smart sensors and AI-predictive technologies can also allow authorities and water users to act before the most severe impacts occur. At the European level, the European Drought Observatory (JRC, 2021) and the EDORA Drought Impact Database and Drought Risk Atlas (JRC, 2023) are also helping EU countries with valuable drought forecasting and monitoring capacity. In the same way, different Spanish river basin authorities are developing digital solutions for drought monitoring and assessment in their respective territories.

Digital systems have also transformed the efficiency and scalability of wastewater treatment and reuse, thus accelerating the transition of the water sector towards circularity (Hernández-Chover et al., 2022; Ruiz-Ocampo et al., 2023). Water treatment plants now use digital water quality monitoring and AI algorithms to optimise chemical use, energy consumption, and treatment times, making the process more sustainable and efficient. Reclaimed water is becoming a crucial source for agriculture and industrial processes, helping to reduce the demand on freshwater resources (Expósito et al., 2024). By comparison, older systems of wastewater reuse were not integrated with digital technologies, making them less efficient and more challenging to scale in response to water scarcity (Radini et al., 2023).

Finally, it is worth mentioning the potential of blockchain technologies for the implementation of water trading schemes. This technology is emerging as a tool for transparent water exchange and allocation (Sriyono, 2020). Blockchain can provide secure, real-time records of water usage and rights, helping manage shared resources in river basins or across regions (Buyssens and Viaene, 2024). This capability may be particularly relevant to areas facing over-extraction and transboundary water disputes. In contrast, earlier efforts to manage shared water resources often relied on bureaucratic agreements and could not ensure transparency or equitable distribution in real-time, leading to potential conflicts and inefficiencies.

As previously mentioned, digitalisation has also impacted operational water management. Digitalisation allows decision-makers to base decisions on accurate, real-time data rather than on estimates or outdated statistics (Alexandra et al., 2023). By having access to data, predictive analysis, and up-to-date information, water management authorities can respond more effectively to water crises, issuing targeted water use restrictions rather than broad mandates that may not be suitable for all areas. Pre-digital policies often relied on broad, top-down approaches, leading to inefficient allocation of water resources during periods of scarcity. Furthermore, the integration of digital tools makes it easier to monitor compliance with water regulations (Michalec et al., 2022). Smart meters and IoT sensors provide authorities with real-time data on water usage, helping to avoid over-exploitation and unsustainable use of water resources whilst also promoting transparency and accountability. Digitalisation is thus facilitating a more effective enforcement of regulations, as well as the design of innovative policies aimed at providing effective targeting and rigorous impact evaluation (Balogun et al., 2020).

In summary, the current digital transformation of the water sector represents a fundamental shift in how decision-makers are managing water resources at different scales. Digital technologies offer more flexible, proactive, and targeted solutions than traditional approaches, enabling a more sustainable use of resources, enhancing water-system resilience, and facilitating a more effective and transparent water governance. Despite its many benefits, it is worth noting that digitalisation also presents challenges and limitations that need to be addressed, such as equity concerns (not all regions or stakeholders have equal access to digital technologies, exacerbating inequalities in water management); data privacy and security (protecting sensitive water data and preventing cyberattacks on water infrastructure); technological integration and data interoperability (outdated infrastructure, lack of capacity); fragmentation of governance and regulatory frameworks across multiple sectors (which can hinder the deployment of standardised digital solutions); need for greater investment in infrastructure and technological skills to enable the effective implementation of digital technologies in water management systems, among others (Stein et al., 2022; Damman et al., 2023). These challenges will be further discussed in subsequent sections.

3. Insights from Spain

The Recovery, Transformation and Resilience Plan (PRTR), launched by the Spanish government in 2022 after the Covid crisis and financed by the Next Generation EU recovery funds, defines the digitalisation of the water cycle as a strategic topic to augment Spain's economic recovery and resilience. As a result, the Water-Cycle Digitalisation Strategic Projects for Economic Recovery and Transformation (WCD-SPERT) program was launched in 2023. It aims to finance public & private projects for the modernisation of water management schemes across the country at different levels (i.e., municipality, regional, river basin, and nationwide) through the use of digital technologies (Spanish Ministry for the Ecological Transition, 2022). This program promotes the formation of public-private partnerships between water service operators, research and technology providers, and water management decision-makers. Further, the program's strategic priorities were set with the collaboration of public and private representatives from urban, industrial, and agricultural sectors, as main water users, and other societal groups. The WCD-SPERT primary focus is not just on addressing the immediate needs of these economic sectors but also on preparing Spain's water systems for future challenges linked to climate change, population growth, and increasing demand in a context of growing water scarcity.

This section aims to offer an overview of the impacts of the current digital revolution on different aspects of water resources management and policy, considering the entire water cycle. Information has been obtained from two sources: Firstly, from semi-structured interviews with representatives and decision-makers from different sectors (agricultural and urban) and institutions related to the management of water resources at various administrative levels, such as the Spanish Ministry for the Ecological Transition, regional water agencies, basin authorities, and municipal utilities. These interviews were carried out between May and October 2024, utilising a questionnaire followed by an interview to discuss the results. The main objective was to gather their opinion on how digitalisation is reshaping specific aspects of water management and policy, highlighting particular digital tools and solutions being implemented in their organisations, the drivers for this transformation, and the challenges encountered. Secondly, information on the financed projects by the WCD-SPERT program has been analysed. Although several interviewees highlighted projects funded by this WCD-SPERT program in their respective organisations, the consultation of the program has provided additional information on the types of digital solutions being implemented by other organisations. We believe that the information gathered from these two complementary information sources, consulted representatives, and the WCD-SPERT program, provides valuable information on how the current digital revolution is impacting water management practices in Spain.

Based on the gathered information, our study categorises the key impacts of digital tools in water management in Spain into four main aspects: (1) Monitoring and Data Collection, which enhances water quantity and quality tracking; (2) Predictive Analytics and Decision Support, which improves forecasting and resource allocation; (3) Efficiency and Resource Optimisation, which promotes water reuse and conservation; and (4) Stakeholder Engagement and Governance, which increases transparency and participation. This study highlights how digitalisation is reshaping modern water management practices in the country, aiming to answer our research questions related to the main aspects of water management impacted by digitalisation, its primary drivers, and the specific digital tools and solutions being implemented. Specific examples of digital tools and their practical applications are also provided.

1. Monitoring and Data Collection.

Digital technologies such as smart sensors, SCADA (Supervisory Control and Data Acquisition) systems, and IoT solutions provide continuous updates on water flows and quality. At basin or regional scales, consulted organisations highlighted that thanks to Automated Hydrologic Information Systems (SAIH in Spanish), which integrate thousands of sensor inputs, River Basin Authorities can improve forecasting processes and make informed decisions on water allocation, drought management, and flood control. GIS-based tools and IoT sensors in the Canary Islands further enhance desalination plant monitoring, reducing distribution losses and allowing real-time operational adjustments (Fernández Moniz et al., 2020). The data acquired through these diverse systems provides an accurate and dynamic picture of water systems, improving predictive analytics for droughts, floods, or water over-abstraction. In the Guadalquivir basin, as in other Spanish river basins, real-time water quality monitoring systems are being used to track pollutants, ensuring compliance and the identification of pollution sources. At the local scale, municipal water utilities, such as those of Madrid, Seville, and Barcelona, have reported that water-leakage losses have reduced by up to 20 % thanks to the implementation of smart water meters and network sensors (Spanish Institute of Statistics, INE). Most of the digital projects financed by the WCD-SPERT at the municipality level include the integration and improvement of SCADA systems to enhance the management of water supply networks.

Additionally, digital tools play a critical role in monitoring water quality in real time, allowing for immediate action when contamination is detected. Real-time water quality monitoring is improving pollution control in Spanish river basins and municipalities, with automated stations detecting contaminants in rivers, reservoirs, and groundwater.

2. Predictive analytics and decision support.

Continuous monitoring and real-time feedback support predictive analytics and dynamic decision-making. In agriculture, consulted organisations confirmed that smart irrigation systems help them to adjust water use based on soil moisture and weather forecasts, maximising water-use efficiency and optimising costs. They noted that the digitalisation of the Spanish agricultural sector is also being promoted by the Spanish Ministry for Agriculture with a €2.4 billion investment and covering 700,000 ha in the period 2022–2027.

At the river basin scale, drought management has traditionally been a reactive process, with water restrictions imposed only after reservoirs reach critically low levels. However, digitalisation is transforming this process by enabling authorities to forecast drought conditions weeks or even months in advance. Several basin authorities reported that they are developing and upgrading AI-powered decision-support systems to enhance resource distribution in a way that balances human and environmental needs, to monitor drought conditions, and to predict water availability in their Drought Monitoring Platforms. This approach allows for proactive measures, such as adjusting water allocations, enforcing restrictions earlier, or investing in alternative water sources. In basins such as Segura, Tagus, and Ebro, satellite-based monitoring and AI models will help predict droughts and guide water allocation (WCD-SPERT). In Catalonia and Andalusia, real-time data is helping authorities minimise drastic water cuts by targeting specific areas, balancing human and environmental needs. The HIDRO-MET system, implemented by the Catalonian Water Agency (ACA), integrates real-time rainfall and river flow data with hydrological models to predict floods, issuing early warnings to municipalities, helping them prepare for and respond to flood risks. On a broader scale, the EU's Copernicus Emergency Management Service (CEMS) provides flood forecasting and early warning across Europe, leveraging meteorological and hydrological data.

In urban settings, predictive models like GoAigua (in the region of Valencia) allow utilities to adjust water pressure dynamically based on real-time demand and weather forecasts, ensuring that water is distributed efficiently while minimising waste. In the city of Seville, the water utility EMASESA has implemented a predictive modeling tool (i.e., Aquasig) that simulates scenarios in the drinking water network, helping maintain chlorine levels and prevent contamination.

3. Stakeholder engagement and governance.

The fact that digital platforms facilitate citizen involvement in water management, enhancing transparency and cooperation with other stakeholders and societal groups, has been widely recognised by consulted organisations. These platforms provide a transparent flow of information, fostering collaboration and reducing conflicts in the management of water resources, especially in those locations with chronic water scarcity. In the city of Valencia, a mobile app allows citizens to track their water use, report leaks, and receive updates on local water conditions, fostering conservation. At the basin level, Spanish basin authorities are developing digital platforms where stakeholders can share concerns and contribute to river basin management plans, promoting participatory governance. Further, most of the funded digitalisation initiatives by the WCD-SPERT include the improvement of their governance frameworks as an expected outcome of the digitalisation transformation, including digital platforms to facilitate participation, information exchange, and collaboration with other water management organisations.

Most of the consulted organisations affirm that digitalisation enables cross-sectoral integration and public-private partnerships by breaking down data silos and ensuring that all sectors and agents have access to shared data on water resources, thus facilitating decision-making at different management levels. Collaborative approaches between public and private agents, such as public basin authorities working with private water utilities, ensure that the development and deployment of digital water solutions are supported by initiatives that foster innovation while protecting water resources. This type of collaborative initiative has been significantly encouraged by the WCD-SPERT. Different Spanish governmental institutions are making significant efforts to promote public-private partnerships to bring together stakeholders from various sectors to collaborate on water digital solutions. These partnerships allow for the sharing of knowledge, technology, and resources, accelerating the adoption of digital tools across the water sector and facilitating the "green-digital" transition promoted by EU policy strategies. For example, the regional water agencies of Catalonia and Andalusia are actively supporting these initiatives to drive sector-wide digital transformation. Further, Spanish innovation hubs, such as Cetaqua and the Digital Water Innovation Hub, have been identified as excellent instruments to facilitate collaboration between research institutions and technology companies, accelerating the adoption of digital water management tools.

4. Efficiency and resource optimisation.

Digital tools are increasing the efficiency and flexibility of water systems, allowing the optimisation of resource allocation and the management of storage and distribution networks. Consulted organisations of the irrigation sector highlighted AI-driven solutions, such as those developed in Valencia (i.e., IDRICA), Murcia (i.e., Digital Data Farm), and Malaga (i.e., AGROW), as transformative tools to optimise water usage, reducing the amount and timing of water applied. At the river basin level, rainfall-runoff simulation tools like SIMPA (developed by the Spanish Centre for Research and Development of Water Infrastructure, CEDEX) help forecast water availability, aiding decision-making during dry periods in basins such as Segura and Júcar. Segura and Júcar river basin authorities have long experience in the use of these decision-support systems to manage water resources during dry periods. In the case of the Guadalquivir basin, the Guadalquivir 4.0 project uses real-time data to manage water reservoirs dynamically, optimising retention during heavy rainfall and ensuring efficient distribution during dry periods. As highlighted by these River Basin Authorities, these digital solutions not only enhance resource allocation, but also the overall water system's ability to cope with climate-induced variability. Further, such systems also play a role in protecting critical ecosystems, such as the Doñana National Park (in the Guadalquivir basin), by ensuring balanced water releases.

In urban settings, smart water networks incorporating AI and blockchain solutions improve supply management and reduce non-revenue water losses, as demonstrated by Aquadvanced (Barcelona) and Aquasig (Seville). In regions such as Murcia, digital solutions are enhancing water reuse for agricultural and industrial applications, ensuring reliable water availability while reducing pressure on natural reserves. Projects like Circular Toolkit (developed by CETAQUA) and AQUATIM (developed by the water utility Aqualia) are improving water circularity and increasing water-use efficiency.

With regard to the main drivers of this digitalisation transformation in the water sector, consulted organisations have highlighted increasing water scarcity and the adverse effects of climate change as the most important. As previously commented, Spain faces pronounced challenges due to climate variability, including severe droughts and unpredictable rainfall patterns. As noted by the respondents, digital solutions are helping to increase the climate resilience of water systems, ensure sustainable resource utilisation, and enhance monitoring and forecasting capabilities, thus enabling more effective responses to these climatic challenges. Secondly, all consulted decision-makers agree on the crucial role played by the decisive governmental support through the WCD-SPERT program. This program is helping to allocate substantial public and private investments to modernise water infrastructures and processes in a wide range of water organisations at different managerial scales, from river basin to local agents. Thirdly, the fast development of technologies such as IoT, AI, and cloud computing is revolutionising all aspects of our lives, including the way water resources are managed. The rapid reduction in the implementation costs and the easier access to these technologies facilitate their adoption by water operators at different managerial scales. Related to this fast development and integration of digital solutions by water organisations, the greater ability to increase capacity building within these organisations is also showing to be a key driver. Finally, the need for regulatory compliance with environmental legislation is also playing a driving role in this digital transition. Aligning with EU directives and global sustainability goals, Spain is committed to improving water quality and management practices. With this aim, digital solutions are facilitating compliance with these regulations by providing accurate data and streamlined reporting mechanisms.

Although some specific digital solutions have already been commented on, the analysis of the projects financed by the WCD-SPERT program provides additional information on the most popular digital solutions (and technologies) being developed and implemented by the Spanish ecosystem of water management organisations. Upon this information, these solutions can be classified into five main groups (or types). Specifically, the development of digital urban water networks (which might, but not always, also be accompanied by the integration of a digital twin), the implementation of smart irrigation systems in urban and agricultural locations, and the development of digital decision-support systems at basin scales, have been identified as the most widely embraced solutions by the Spanish water sector. Table 2 provides some examples of these solutions, together with information on the type of technologies and location.

In summary, consulted Spanish decision-makers have highlighted the way that digital technologies are transforming water management in Spain, driving improvements in the efficiency, sustainability, strategic management, and resilience of complex water systems. Tools such as smart sensors and IoT platforms enable real-time monitoring and predictive analytics across urban and agricultural sectors. In urban areas, smart water systems in cities like Madrid, Seville, and Barcelona have significantly reduced water-leakage losses (Díaz-Cano et al., 2025). Similarly, smart irrigation platforms allow optimising water use, alleviating pressure on freshwater sources. At the river basin scale, Spanish basin authorities also benefit from the use of digital tools through the improvement of functionalities for the monitoring of water flow and quality, and enabling more informed decision-making. Similarly, predictive tools often provide accurate forecasts of rainfall and runoff, and satellite and AI-driven platforms improve the management of drought and floods, thus allowing for improved weather alert systems. At the reservoir level, digital tools enhance reservoir operations, allowing for dynamic water storage and release based on real-time data. Finally, another relevant area that has benefited from the use of digital tools is public engagement and governance. Thanks to the development of digital platforms, stakeholders and societal groups can easily access information and contribute to decision-making.

4. Challenges in the adoption of digital solutions in the water sector

The digital transformation of Spain's water sector clearly shows the commitment of Spanish authorities and stakeholders to equip the water sector with cutting-edge technologies and digital solutions to face the main water challenges in the country. Further, digitalisation of this strategic sector is crucial to guarantee Europe's competitiveness and digital independence, and adaptation to climate change (EC, 2022). To meet the objectives outlined in the Commission's Digital Compass, the

Table 2
Leading digital solutions are being implemented in the Spanish water sector.

Type	Location	Technological solution	Description
Digital Urban Water Networks	Madrid, Barcelona, Valencia, Zaragoza	Smart IoT meters, real-time monitoring, data analytics	Urban water management can be upgraded through the use of real-time data and integration of predictive analytics to support decision-making, leak detection, and enhance the operational efficiency of water utilities.
Digital Twins for Urban Water Systems	Barcelona, Seville, Canary Islands, Balearic Islands	Digital twin, AI-based simulations	Digital twin technologies to model extensive water networks and enable simulation and prediction of water flows (in quantity and quality) in different water availability and climatic scenarios, including extreme events. They allow the optimisation of water production and distribution, including conventional and non-conventional water sources (e.g., desalinated and reclaimed water).
Smart Urban Irrigation Systems	Malaga, Valencia	Precision irrigation, IoT, data analytics	Integration of IoT devices for smart irrigation in urban parks, reducing water consumption and optimising irrigation schedules based on weather and soil data.
Smart Agricultural Irrigation Systems	Duero, Ebro, Jucar and Guadalquivir river basins	Remote sensing, AI-based analytics	The use of IoT devices, AI, and machine learning to enable simulation and prediction of water requirements based on soil and climatic conditions, as well as to monitor irrigation return flows and aquifers. These technologies also help to improve the management of irrigation infrastructures and optimise fertilisers.
Digital Decision Support Systems at Basin Scale	Ebro, Tagus, Segura, Guadalquivir river basins	Remote sensing, AI-based analytics, satellite data	Upgrading of the current Automated Hydrologic Information Systems (SAIH in Spanish) through advanced remote sensing technology, AI analytics, and the use of satellite imagery to monitor water flows and bodies, but

(*continued on next page*)

Table 2 (*continued*)

Type	Location	Technological solution	Description
			also to predict water availability in a major river basin. Real-time data helps optimise water flows and prevent over-extraction, improving the basin's resilience and sustainability. Simulation and predictive capacities allow the simulation of conditions to avoid adverse impacts in the event of drought or flooding.

Source: Own elaboration.

EU must significantly increase investments in essential digital technologies, including cybersecurity, cloud computing, AI, data spaces, blockchain, quantum computing, and semiconductors, as well as enhancing digital skills (EC, 2021).

Despite the potential for digital tools to revolutionise water management, consulted organisations have highlighted several challenges that might affect their widespread adoption. One key challenge is the difficulty in quantifying the full benefits of these technologies. This uncertainty creates hesitancy among decision-makers, who struggle to justify investments without clear evidence of long-term value. This fact has been reported in the literature, e.g., Quaranta et al. (2023b), who argue that the full acceptance and integration of digital solutions often depend on the technical and operational capacities of users.

A second challenge relates to the substantial upfront investment needed for equipment acquisition (as specially highlighted by the regional government of Andalusia). For local governments and organisations with limited budgets, these costs can be prohibitive. Moreover, ongoing expenses, such as maintenance, updates, and staff training, add to the financial strain, deterring broader adoption. Several organisations at different managerial levels emphasised that without clear financial incentives or evidence of cost savings, organisations may remain reluctant to allocate resources to digital transformation. This issue is of special relevance for small water utilities and stakeholders (e.g., irrigation communities and municipalities), which often lack the financial (and human) resources to carry out digital upgrading. In this sense, the Spanish WCD-SPERT constitutes an effective instrument to provide these needed financial resources, as highlighted by most of the respondents. Additionally, the Spanish Ministry for the Ecological Transition highlighted that inconsistent data management practices result in challenges with data exchange and interoperability.

Beyond financial and technical challenges, cultural and institutional factors further complicate the adoption of digital tools. Traditional water management practices, deeply rooted in local communities, often resist change. In this sense, several consulted organisations expressed concerns that digitalisation might disrupt established practices, bypass community-driven management, or require restructuring teams to create new roles for overseeing technology implementation. This lack of trust in digital tools providers and the disruption of familiar processes can hinder or even prevent the integration of innovative solutions.

Another relevant challenge highlighted by the Spanish Ministry for the Ecological Transition relates to the limited access of citizens and water management authorities to digital tools, in particular in rural and marginalised communities. This lack of access can lead to further exclusion, leaving already vulnerable communities without the ability to influence water policies or benefit from technological solutions, such as real-time water monitoring or early warning systems. Closely tied to the issue of access is the challenge of digital literacy. The successful use of digital tools often depends on the ability of users to interpret and navigate complex tools, which requires a certain level of technical knowledge.

The vast range of solutions available on the market affects this paradigm shift, as potential users struggle to determine which tools are the best fit for their needs. This diversity can create confusion and indecision, and end-users may lack the expertise or resources to evaluate and select the most appropriate tool. Consulted organisations highlighted that the understanding of how these tools can help identify and create value chains within water management usually requires internal organisational changes. Consequently, the potential to leverage digital tools for value creation, such as improving efficiency, reducing costs, or enhancing service delivery, is not always immediately apparent, especially in local and rural contexts. As a result, the digital transformation may be delayed or scaled back.

Finally, regulatory and policy challenges are notable, since this digital transformation also calls for new regulatory needs, as well as secure and sustainable governance schemes. As indicated by surveyed respondents, the policy environment needs to be supportive to accelerate the adoption of digital tools. Inadequate policies, regulations, and incentives can slow the integration and acceptance of digitalisation in a sector that is very sensitive to social concerns, such as the water sector. In this sense, policymakers should develop adequate regulations and support frameworks to minimise any potential negative impacts of digitalisation related to access inequality, data privacy and security, and technological integration. Moreover, the protection of sensitive water-related information and the prevention of cyberattacks on water infrastructure are attracting growing public concerns. Water authorities and operators must ensure that their digital solutions are secure and reliable. Further, integrating new digital systems with traditional water management practices can be challenging, particularly in some sectors (e.g., agriculture) and areas (e.g., small municipalities) that are still reliant on outdated infrastructure, and that might require specific initiatives and programs focused on their needs, as addressed by the Spanish WCD-SPERT program. Survey results indicate that the adoption of digital tools brings changes to established workflows and practices. These changes can lead to reluctance among some end-users who may perceive these transformations as disruptive or challenging to adapt to.

Policymakers must develop legal frameworks to manage data privacy, cybersecurity risks, and the equitable distribution of digital water solutions (EC, 2022). As also suggested by consulted organisations, the adoption of smart technologies also requires revisions to existing water regulations, such as the Urban Wastewater Treatment Directive and the Drinking Water Directive in the EU, to ensure they leverage the potential of digital innovations in the establishment of targets and standards. Furthermore, digital solutions must align with broader environmental policies, such as the EU's Zero Pollution Action Plan and the Circular Economy Action Plan, to promote sustainable water management.

5. Discussion and concluding remarks

The analysis of the digital transition of the Spanish water sector offers valuable insights for other regions and countries facing similar water management challenges. Although areas in the USA, Israel, Australia, and other European countries are also transitioning to profound digital transformations in their respective water sectors, some key lessons can be extracted from the Spanish case study, which might help to enhance the positive impacts of digital solutions on water management practices. In this sense, we would like to highlight the following aspects.

The results described in this paper demonstrate the importance of embedding digitalisation into existing water governance structures to enhance resilience to climate change and increasing water demands. They also offer a roadmap for regions or countries aiming to modernise their institutional frameworks while ensuring equitable and sustainable access to water resources. Developing a comprehensive digitalisation plan, such as WCD-SPERT, that encompasses all aspects of the water cycle is crucial. Spain's holistic approach helps to ensure that digital tools are effectively integrated into existing infrastructure and governance frameworks at different managerial scales (e.g., local, regional, basin), thus enhancing resilience of the overall water system.

Another valuable insight is the promotion of collaboration between governmental bodies, private operators, and technological agents to accelerate innovation and its implementation. Spain's public-private partnerships are facilitating the deployment of cutting-edge technologies, demonstrating the effectiveness of cooperative frameworks in improving accessibility and applicability of these digital solutions. As reported by the European Office of Patents (EPO) in a recent study, Spain is highly specialised in the development of water-related innovations and technologies, achieving a revealed technology advantage (RTA) index of 2.3 (highest among EPO member states) (European Patent Office, 2024). This high RTA index reveals that Spain's overall innovation capacity is highly focused on the development of water-related technologies.

The analysis carried out in this study has contributed to identifying the benefits and challenges of digitalisation in the water sector, where smart systems are already being implemented to optimise water use, manage river basins, and protect water quality, among other aspects. Nevertheless, further attention (and research) is needed to identify and minimise potential negative impacts for society and the environment derived from this digitalisation revolution. While digital tools offer functionalities for enhancing water management, their successful implementation faces a variety of challenges. From a technological standpoint, the wide diversity of digital solutions available and the lack of standards often lead end-users to revert to more traditional methods. Socioeconomic challenges are varied and revolve around issues of access, equity, and the financial sustainability of digital tools, which can disproportionately affect vulnerable communities and exacerbate existing inequalities. Moreover, insufficient technical capacity and a lack of experience in implementing digital technologies continue to hinder their widespread adoption, particularly in smaller utilities.

Addressing these challenges calls for a multifaceted approach that integrates technological improvements, including cybersecurity and data ownership, funding mechanisms, and capacity-building efforts. Based on this perspective, the following areas for improvement are needed to enhance the adoption and usefulness of digital tools.

- Ensuring the development of more cost-effective, user-friendly, and simpler digital tools to encourage their use and ensure that the digital transformation is more accessible to a broader range of stakeholders, including smaller utilities with limited technical expertise.
- Enabling communication with end-users (e.g., water utilities, policymakers) from the outset of the design process; this will allow end-users to be fully acquainted with the functionalities of the tools and their potential benefits. Involvement from the early stages of the design process will also ensure that the final product is fully aligned with the actual needs of end-users.
- Enhancing awareness and education as a way to improve digital literacy. End-user confidence in digital tools could be enhanced through showcasing successful applications. In this sense, Living Labs could be used as a platform to assess the contribution of digital tools to "value creation" (i.e., to the delivery of tangible and measurable benefits such as improved decision-making, cost savings, enhanced sustainability, and better public engagement).
- Establishing data frameworks setting out clear guidelines on data ownership and sovereignty.
- Development of supporting regulations, policy frameworks, and instruments, e.g., targeted funding and grants that boost the adoption of digital tools.
- Setting up monitoring and evaluation frameworks through Key Performance Indicators (KPIs) to track the effectiveness of digital tools in water management, justify investments, and identify options for further improvement. Some of the KPIs already proposed in the literature include non-revenue water percentage, energy efficiency, asset utilisation, carbon footprint, water reuse rate, and advanced monitoring.

Adequate consideration of these specific areas of improvement might help to maximise the positive impacts of digitalisation in water cycle management. Published evidence based on impact assessments of digitalisation in water resources management is still scarce, indicating that more research is needed. This research should offer practical learnings on how to address digital challenges and public concerns on the use of these tools, and highlight potential benefits that digitalisation can bring to address global water challenges, such as those derived from climate change and growing water demand. This study has aimed to fill this gap by offering practical insights from the current digitalisation transformation of Spain's water sector.

Digitalisation is a central priority at the European level, with the EU Digital Strategy playing a pivotal role in shaping the future of Europe's economy and society. Launched in 2015, this strategy provides a comprehensive roadmap to drive the digital transformation while aligning with the EU's broader goals, including achieving a climate-neutral Europe by 2050. As countries across Europe work toward these ambitious goals, the findings presented in this paper offer valuable insights and practical guidance for those aiming to implement the EU Digital Strategy. By addressing both the challenges and best practices encountered during digitalisation efforts, the Spanish case study can help other countries anticipate and mitigate similar issues in their digital transformation processes. It is therefore a resource for navigating the complexities of the digital transition. Moreover, this study showcases a range of successful digitalisation initiatives at different managerial scales, offering practical examples that can serve as models for other European regions and nations.

This study has primarily focused on the current applications of digital tools in Spain for monitoring, predictive analysis, and optimising water use. However, these tools will likely play a significant role in anticipating and shaping future policy scenarios. Digital tools will facilitate the continuous collection and analysis of data, enabling the creation of a comprehensive historical database from sensors, IoT devices, or remote monitoring systems. This wealth of data will allow decision-makers to track long-term trends. As data continues to accumulate, it will become essential in future water decision-making processes, enabling more sound strategies. For example, the water quality monitoring system in the Ebro River Basin, outlined in Section 3, has already demonstrated the power of data in pollution detection, and in the future, AI-driven predictive models could allow authorities to adjust regulations based on real-time contamination risks proactively. Similarly, the precision irrigation systems in Andalusia show how data-driven approaches improve water efficiency today, but in the future, these insights could support flexible, market-based water trading schemes that reward conservation.

Finally, it is worth noting that this study presents some relevant limitations. The information used is limited to the self-reported data gathered from a group of water management organisations. Although we got responses from organisations representing the entire water cycle at different managerial scales, these might partially represent the whole of the Spanish landscape of water organisations. To address this limitation, we also analysed the information content in the digitalisation projects financed by the Spanish WCD-SPERT, which covers the entire Spanish territory and provides reliable data on a broad sample of projects at different managerial scales. Another limitation refers to the impact assessment of these digitalisation projects, since these are still being implemented, and some of the information given by the interviewees refers more to expected outcomes than real ones. A comprehensive assessment of the impacts derived from these significant digitalisation efforts and investments will require further future research.

CRediT authorship contribution statement

Alfonso Expósito: Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Esther Díez Cebollero:** Writing – review & editing, Validation, Visualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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