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A practical roadmap for the digital transformation of urban water systems – using insights from a Swedish utility to chart the path forward

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ABSTRACT

Urban water systems are facing growing challenges, including climate change and aging assets. Digital transformation presents opportunities to address these issues. However, water utilities often encounter barriers such as fragmented initiatives, organizational inertia, and lack of systems interoperability, limiting the scalability and impact of digitalization efforts. This paper presents a strategic roadmap for the digital transformation of water utilities, developed through a literature review and a case study of Vakin, a water utility in Sweden. The findings highlight that organizational and cultural factors are as critical as technical solutions for successful transformation. The study presents arguments that digitalization must be driven by organizational needs and framed within a systems-thinking perspective, resembling strategic organizational development rather than isolated projects. This paper also argues that digital transformation needs to resemble strategic organizational development more than a digitalization project. The proposed approach fosters flexibility, interoperability, and a culture of prototyping and continuous improvement, providing a structured framework for utilities to navigate digital transformation and enhance sustainability.

Key words: asset management, data management, digital culture, digitalisation, IoT, utility management

HIGHLIGHTS

- Organizational and cultural change is harder than technical transformation.
- Digitalization needs to be needs-driven and based on systems thinking.
- A strategic roadmap for the digitalization of water utilities is proposed.
- Emphasizes phased steps and actions for utilities at different digital maturity levels.

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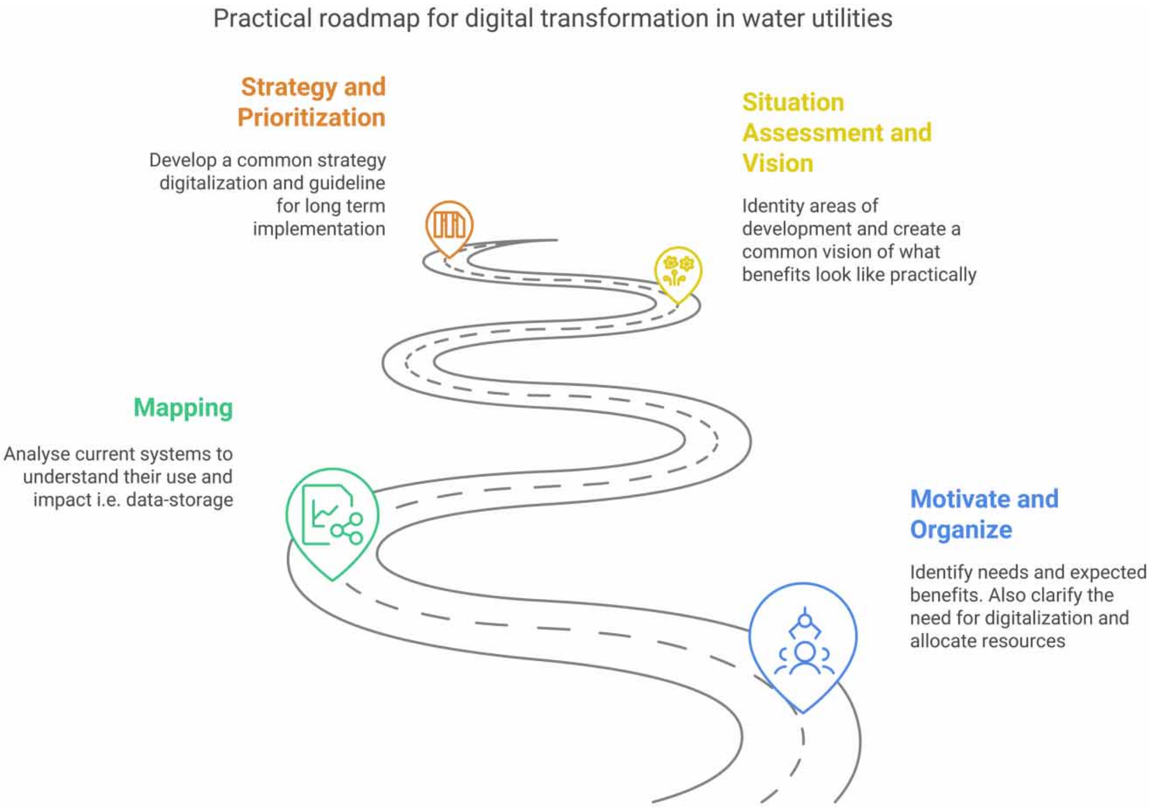
GRAPHICAL ABSTRACT



1. INTRODUCTION

Digitalization is a transformative global trend reshaping various sectors, including the water industry (Arnell *et al.* 2023). To address the escalating challenges such as climate change impacts, aging infrastructure, and the shift towards circular systems, embracing digital technologies has become essential (Goel *et al.* 2024). Urban water systems (UWS), encompassing the production and supply of drinking water, wastewater collection and treatment, and stormwater management, are critical infrastructure for urban societies. Their extensive scale, long operational lifespans, and dispersed nature have historically made comprehensive monitoring and automation challenging (Arnell *et al*. 2017; Sarni *et al.* 2019; Therrien *et al.* 2020; Arnell *et al.* 2021). In many industrialized regions, aging infrastructure and insufficient reinvestments exacerbate these challenges, leading to issues such as water leakage, declining water quality, and non-compliance with environmental and service standards (Selvakumar & Tafuri 2012; Svenskt Vatten 2020). In Sweden alone, the replacement cost of UWS is estimated at 820 billion SEK (€82 billion), with annual reinvestments of 23 billion SEK (€2.3 billion) required for sustainable asset management (Svenskt Vatten 2020; Najar & Persson 2023).

Digitalization in UWSs presents significant opportunities to address these challenges by enabling integrated data management, real-time monitoring, and predictive maintenance, ultimately improving operational efficiency and sustainability (Fu *et al.* 2023; García Baigorri *et al.* 2024; Kerimov *et al.* 2025). It supports circular water management approaches, optimizing infrastructure use and recovering resources from wastewater (Soo *et al.* 2024). However, the adoption of digital technologies also introduces vulnerabilities, such as cyberattacks that can disrupt operations, compromise data, and pose health risks (Hassanzadeh *et al.* 2020). Despite increasing concern, many water utilities still lack collective situational awareness regarding cyber threats. Therefore, it is crucial for water utilities to understand the consequences of cybersecurity breaches (Bosco *et al.* 2022). This understanding can help water utilities better appreciate the potential impacts of cyber attacks on their operations. To mitigate these risks, security solutions must be integrated into infrastructure from the outset to ensure resilience and support the seamless implementation of digital technologies (German Water Partnership 2015).

A central enabler of digital transformation is high-quality data collection, which supports models, analyses, and decision-making whether automated or human-driven (Therrien *et al.* 2020). Frameworks such as the Internet of

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Things (IoT) provide systematic approaches to real-time data exchange and context-aware applications (Li *et al.* 2015). Key IoT features include device heterogeneity, scalability, interoperability, and embedded security, enabling the secure and efficient collection and management of large-scale data (Miorandi *et al.* 2012; Wang *et al.* 2021). These systems transform raw data into actionable insights, driving smarter and more resilient water management practices (Madakam *et al.* 2015; Chopra *et al.* 2019; Rejeb *et al.* 2022).

Despite the potential of digital solutions, many water utilities face challenges in systematically approaching digitalization (Rousso *et al.* 2024; Skantz 2024). Organizational divisions, lack of standardized data management practices, and limited interoperability hinder the connection between water production, distribution, and external datasets. This disconnect limits potential benefits such as improved water savings, management, and economic gains (GSMA 2017; Arnell *et al.* 2021). Moreover, fragmented pilot projects and a lack of strategic alignment often prevent full-scale adoption and integration of digital initiatives (Kiparsky *et al.* 2013). A systems-thinking perspective is required to address both technical and organizational aspects, fostering synergies that drive meaningful transformation.

This paper presents a strategic roadmap to address key barriers to digital transformation in UWSs, identified through a review of the literature and practical insights from projects developed in close collaboration with Vakin, a leading Swedish utility in digital transformation. The roadmap adopts a systems-thinking approach and structured practical guidance for utilities at various stages of their digitalization journey. The terms digitalization and digital transformation are used interchangeably in the paper to refer to the integration of digital technologies and processes in UWSs to enhance data-driven decision-making, operational efficiency, and sustainability. It involves not only technological advancements but also a strategic and organizational shift that is needs-driven to address challenges (Eggimann *et al.* 2017; Sarni *et al.* 2019; Arnell *et al.* 2021).

2. METHODOLOGY

2.1. Research design

The methodology (illustrated in Figure 1) used in this study for developing the roadmap was conducted in three steps: a literature review, case study analysis through workshops, and the synthesis of findings from both sources into a roadmap. This mixed approach ensured that the roadmap was both theoretically informed and practically grounded, bridging the gap between theory and practice. The literature review provided a foundation of theoretical frameworks, with generalizable insights into digital transformation. However, these frameworks often lack the specificity needed for real-world application. To address this, case study analysis through workshops was employed with one Swedish water utility to ground the roadmap in practical experiences, ensuring its relevance to stakeholders. By incorporating real-world insights, the study captured the situational context of digital transformation, such as organizational culture, resource constraints, and stakeholder dynamics. Additionally, workshops facilitated stakeholder engagement and co-creation, which are critical for building buy-in and ensuring the successful implementation of the digital transformation roadmap.

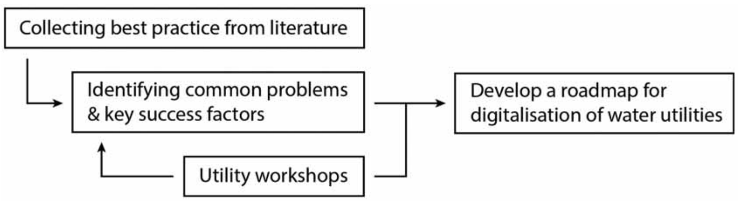

Figure 1 | Schematic of the research design used for the development of the roadmap.

2.1.1. Literature study

The literature review consisted of a reflection/lessons learned/experiences derived from previous projects and a thematic analysis to identify recurring patterns related to the digital transformation of UWSs from both a global perspective as well as the Swedish context. The literature review followed a structured and systematic approach described by Tranfield *et al.* (2003) to explore the digital transformation of UWSs. The process included defining the scope and objectives, focusing on understanding how organizational, cultural, and technical factors interplay to drive or hinder digital transformation. Specific goals included identifying key barriers and enablers, extracting

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lessons learned from previous implementations, and highlighting best practices and recommendations for successful digitalization in UWSs. A systematic search was conducted across multiple scientific databases, including Web of Science, Scopus, and Google Scholar, utilizing keywords and phrases such as 'digital transformation', 'digitalization', 'urban water systems', 'interoperability', 'organizational change', 'asset management', 'stakeholder engagement', 'frameworks for digitalization', and 'frameworks for digital transformation', both individually and in combination. The search targeted peer-reviewed journal articles, conference proceedings, reports, and grey literature published primarily from 2010 to 2025, emphasizing recent publications to ensure contemporary relevance.

Inclusion criteria prioritized studies explicitly addressing digital transformation processes in urban water utilities, emphasizing practical case studies, theoretical frameworks, or strategic roadmaps. A two-step screening process was implemented: an initial screening of titles and abstracts to assess relevance, followed by full-text reviews to confirm alignment with the study's objectives. Bias reduction strategies included sequential reviews conducted independently by at least two researchers during abstract screening and full-text reviews. Efforts were made to incorporate diverse perspectives from various geographical contexts and publication types. Additionally, findings were cross-validated through triangulation across multiple independent studies to mitigate biases arising from limited sources or perspectives.

The thematic analysis was conducted to identify recurring patterns and group findings into broader themes closely aligned with the methodology described in Naeem *et al.* (2023). The methodology included literature familiarization, keyword identification, coding insights into thematic categories, and developing themes aligned with research objectives. Cross-cutting themes and interdependencies were identified to provide a holistic understanding. The findings were synthesized into a coherent narrative, with key arguments and insights documented in a summary table (Table 1) to facilitate cross-comparison. Contrasting perspectives and gaps in the literature were highlighted to ensure a balanced overview, and the insights were contextualized for UWSs, particularly within the Swedish context.

Table 1 | Literature overview thematic themes, relevant studies, and key findings and/or arguments on digital transformation are outlined

Theme	Study	Key findings and arguments
Organizational and cultural change	Hamilton *et al.* (2021)	• Implementing technical solutions and digitalization requires staff training and cultural change • A smart water utility aims to centrally collect data • This requires technological and organizational development • Development should begin with an assessment, a roadmap, a development plan, and a long-term plan • Case studies often highlight successes but omit the necessary development or decision-making • A challenge for water utilities is not having a proper business model for integrating smart water information technologies (SWIT) • Institutional challenges can also hinder the effective use of SWIT.to move forward in leveraging the full benefits of SWIT in a cost-effective manner'
	Ng *et al.* (2020)	• Employee inclusion is critical for optimizing the functionality and use of digitalization efforts • Digitalization of water management is an organizational development requiring symbiotic human resources • The primary goal is to create organizational value, including improved work environment, services, and efficiency • A systems approach is key to the project's success • A framework guides the design and implementation of new projects, aligned with a long-term strategy
	Myeong *et al.* (2021)	• A critical component of achieving digital transformation is a culture of innovation • This approach can help ensure the transformation survives leadership changes

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Table 1 | Continued

Theme	Study	Key findings and arguments
	Wahlström *et al.* (2020)	• Long-term vision, prototyping, testing, iteration, and fostering an innovative culture are important aspects needed for digital transformation
	Ramböll (2020)	• End-user involvement is essential • Structured project management is critical • Competence and continuity are needed in the transition: • Cultivating a positive organizational culture
	Bondesson *et al.* (2022)	• Individual development projects need to be part of a long-term strategy • follow-up development needs to focus on organizational development • collaboration and solving common problems across divisions is a prerequisite • formulating clear and specific use cases is a success factor
	The expert group on digital investments (2018)	• An agile development process should be adopted • An innovative culture should be fostered • Investments in digitalization should be future-oriented
Data and systems interoperability	Carrico *et al.* (2020)	• Data and systems interoperability is crucial for realizing the benefits of digitalization • Commercial software and services are often not well-suited to the specific needs of water utilities
	Arnell *et al.* (2021)	• Digital transformation requires both technical and organizational change • Lack of systems interoperability and cybersecurity concerns are hindering the digital transformation of water utilities
	Victorian Government (2020)	• The five steps of successfully adopting the strategy are outlined as organising, developing an implementation roadmap, back- and forecasting, prototype/trying on a project, evaluating, and adapting
	Bondesson *et al.* (2022)	• Using Fiware as a standard for the platform has been valuable • Pilots take time, and the development of processes and establishment of dialogue need to be viewed as results and managed post-project
	Philip (2007)	• Digital transformation requires strategic alignment between business and IS, effective communication and planning, strong leadership support, and proactive implementation with review
	Carriço & Ferreira (2023)	• Digital transformation requires more than technology; it needs cultural and organizational change • Successful transformation relies on high-quality, data and a strategic approach to data management • Utilities must adopt a data-driven philosophy
	Okwori *et al.* (2024)	• Data integration as a core digital transformation activity • Actionable information is the goal of digital transformation: • Digital transformation is fundamentally about leveraging data
	Rousso *et al.* (2024)	• Digital transformation is a continuous process that requires specific actions across several interconnected steps
Stakeholder engagement and roadmap development	Victorian Government (2020)	• Outlines five steps to successfully adopt digital asset strategies with stakeholder involvement
	GSMA (2017)	• Defining objectives and resources, understanding problems, and engaging stakeholders is a key first step • Route mapping (strategy and scope, pilot, establish, scale, evolve) creates a flexible and iterative process which is essential for a sustainable investment
	van der Zouwen *et al.* (2015)	• Mapping stakeholders is a main guideline • Visioning and communication are necessary guidelines • Defining objectives with different time horizons is important

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Table 1 | Continued

Theme	Study	Key findings and arguments
		• Creating resilience regarding flexibility and/or robustness is needed • Prioritization and specific adaptation are required • Evaluation and iteration are essential
	Hein *et al.* (2012)	• Digital transformation requires four stages: scoping, forecasting, backcasting, and roadmap transfer
	Fernandez-Anez *et al.* (2018)	• linking governance, stakeholders, and implementation • A stepwise integration process is needed for successful implementation
Technological and business model Alignment	de Vitry *et al.* (2019)	• Recommends four guiding principles:' (i) invest in technology that can reduce risk, (ii) look to other sectors for inspiration, (iii) be transparent about successes as well as failures
	Díaz (2020)	• Lack of a systems approach and robust business models are major hindrances to digital transformation
	Bettin (2023)	• Collaboration between various stakeholders is essential for the success of digital transformation projects
	Daniel *et al.* (2023)	• A gap exists between the motivation for digital transformation and the actual adoption of technology. This gap can be attributed to factors such as the economy, internal processes, company structure, and leadership qualities
Planning, evaluation, and iteration	Nottarp-Heim *et al.* (2015)	• Planning and forecasting are an important part of guiding operations and management to the future's water utility management. Uncertainties need flexibility and adaptive systems

2.1.2. Case study analysis via workshops

The workshops were performed with Vakin one of the larger and more digitally mature water utilities in Sweden. A set of two workshops were conducted with Vakin in November and December of 2021. The structured workshop approach allowed for an in-depth exploration of Vakin's practices, combining reflection on past efforts with forward-looking strategies. This participatory process also helped align the roadmap with Vakin's operational realities and strategic goals, and more representative of the Swedish context increasing its relevance and applicability. The workshops followed the methodology by Svensson & Swenningsson (2015) which emphasizes structured, participatory engagement. The methodology systematically integrates creativity into a clear meeting structure, their method promotes collaborative problem-solving and the exploration of complex challenges. This structured yet flexible methodology is highly relevant for conducting participatory workshops. Examples include activities such as brainwriting, association cards, and idea development templates. Workshop 1 focused on reflecting on Vakin's digital transformation journey, analysing their alignment with findings from the literature, and identifying instances that diverged, including successes, challenges, and gaps. This process provided an opportunity to learn from their experiences, gaining a deeper understanding of their unique approach and how they addressed specific obstacles. Workshop 2 built on these insights by exploring future plans, strategies, and anticipated difficulties, with an emphasis on aligning their goals with the proposed roadmap. Discussions included how Vakin could leverage lessons from their past efforts to navigate complexities and overcome barriers more effectively in their ongoing transformation. The workshops included around seven participants, four from Vakin: the maintenance manager, chief executive officer (CEO), production manager, and Chief Information Officer (CIO). These roles represent a balanced structure, combining office-based decision-making personnel (CEO and CIO) with those directly involved in field operations and practical implementation (maintenance and production managers). Additionally, three participants from RISE, comprising researchers and subject matter experts, joined to facilitate the workshops and contribute expertise. This participant composition ensured a balanced representation of different organizational perspectives, capturing insights across strategic, tactical, and operational levels, thereby achieving a representative and inclusive participant group.

These workshops provided practical insights that directly informed the design and refinement of the roadmap.

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3. RESULTS

3.1. Literature review

The literature synthesis and thematic analysis are presented in Table 1. Findings highlight the critical interplay between organizational, cultural, and technical factors such as interoperability and alignment between technological and business models in driving digital transformation in UWSs. This interplay, as emphasized by studies like Hamilton *et al.* (2021) and Bondesson *et al.* (2022), can have either a positive or negative impact depending on how it is managed. When these dimensions are aligned and managed strategically, fostering collaboration and innovation, they effectively drive digital transformation. For example, Ng *et al.* (2020) and the Victorian Government (2020) stress that iterative approaches and cross-functional collaboration are essential for success. However, misalignments such as cultural resistance, lack of leadership, or fragmented initiatives can hinder progress. Addressing these challenges proactively and strategically is essential to ensure that the interplay between organizational, technical, and cultural dimensions supports, rather than obstructs, transformation efforts. A structured mechanism such as a roadmap or stakeholder engagement model is necessary to navigate these complexities and maximize potential benefits.

Further deductions from the literature also emphasize the importance of flexible, iterative roadmaps informed by stakeholder needs and long-term visions, as outlined in GSMA (2017) and Wahlström *et al.* (2020). These roadmaps must be supported by adaptive systems to address uncertainties and evolving demands. Key barriers include risk-averse organizational cultures (Albury 2005), poor scalability of pilot projects (Díaz 2020), and misaligned user needs (Myeong *et al.* 2021). At the same time, critical enablers include leadership buy-in, clear strategies, and user-centred design, as highlighted by Moussa *et al.* (2018) and Philip (2007). Lessons from past failures underscore the importance of aligning digital projects with organizational goals, fostering innovation, and prioritizing operational needs during design and implementation. These insights provide a criterion for what needs to be included in a roadmap for the digital transformation of UWSs which includes leveraging digital tools, improving operational efficiency, enhancing resource management, and making informed decisions that align with their strategic objectives.

3.1.1. Digital transformation in practice: previous experiences and lessons

Digitalization will need investments in both technological and organizational development. Doing all of it simultaneously will be associated with large expenses. Hence, prioritization is necessary. In particular, this is true for digital applications to avoid digitalization being driven for its own sake. Formulating and deciding on a strategy for digital development is a key success factor for the sustainable implementation of digital technologies and applications. This is true for companies of all sizes and especially in environments of high uncertainty and rapid development since a strategy can enable guidance in development, controlled flexibility, and streamlined decentralized decision-making (Philip 2007; Titus *et al.* 2011; Reid *et al.* 2014; Elbanna *et al.* 2016). Also, new organisational functions need to be arranged and suitable competencies hired (Arnell *et al.* 2021).

A common reason in the literature studies reviewed is the lack of broader implementation of digital solutions in the water sector in the existing culture, with public sector utilities often focused on mitigating risks rather than fostering innovation (Albury 2005). Furthermore, the need to overcome systems integration and interoperability issues, particularly in dealing with legacy systems remains a significant challenge in many utilities worldwide (IWA 2022; Okwori *et al.* 2024). Furthermore, full-scale implementation is not invested in if real incentives cannot be identified and quantified (Senge 2006; Díaz, 2020; Jönsson, 2021; Myeong *et al.* 2021). However, the benefits will not be seen unless tested, which creates a Gordian knot (Moussa *et al.* 2018). Therefore, it would be beneficial to formalize this leadership acceptance process in strategy and steering documents to formalise the mission, and responsibilities, and create stability in the deployment.

Digital transformation also requires robust data management, including standardized formats, ownership rights, and modular platforms to enable interoperability and scalability. While concerns about standards and 'lock-in' effects persist (Bondesson *et al.* 2022; Popp Larsen *et al.* 2022), organizations must begin internal processes and developments to avoid delays. Lessons from innovation and smart city projects such as Manyika *et al.* (2015), emphasize the importance of fostering an innovative culture, basing goals on clear needs, and adopting iterative, agile approaches (Albury 2005; Moussa *et al.* 2018; Ramböll 2020; Wahlström *et al.* 2020; Bondesson *et al.* 2022).

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3.1.2. Digital transformation of UWSs in Swedish context

In Sweden, digital transformation in UWSs is considered in its early stages, characterized by incremental integration of digital technologies rather than sweeping, disruptive change. The sector's established stability, regulatory frameworks, and focus on risk-averse practices have largely shaped its cautious approach to adopting new digital tools (Bennich 2024a). Digital technologies mainly serve as add-ons to existing systems. The focus remains on 'rematerialization' integrating digital properties into physical assets rather than achieving fundamental transformation. The institutional environment in which Swedish water utilities operate is highly regulated and emphasizes safety and reliability. While this ensures consistent service, it also tends to favour stability over innovation, slowing the pace of digital adoption. Many utilities also lack the foundational digital infrastructure needed for advanced data-driven solutions, facing issues with data integration, standardization, and cybersecurity.

The sector is largely dependent on collaboration with external actors, including technology suppliers and consultants, due to limited internal expertise and resources. Collaboration among utilities is also crucial, with larger entities often leading the way and sharing best practices with smaller ones. Two competing narratives frame digital transformation in this context: the 'stretch and transform' narrative, which envisions major systemic changes, and the 'fit and conform' narrative, which sees digitalization as a gradual enhancement of existing practices. To effectively navigate digital transformation, a balanced context-aware approach that considers the unique characteristics of the urban water sector in Sweden is essential (Bennich 2024b). As the sector evolves, keeping sight of the long-term impacts while adapting to new insights will be key to successfully navigating this transformation.

3.2. Workshop insights informing the roadmap

Workshop 1: The goal of the first workshop was to identify barriers in the digitalization process in Vakin and propose solutions for implementing open platforms and advancing digital transformation. The identified barriers in the digitalization process and proposed solutions are presented in Table 2.

Workshop 2: A key practical barrier or requirement for the digital transformation of UWSs identified in the first workshop was a flexible and open data platform, enabling seamless data integration, interoperability, and adaptability. This was deemed essential for supporting diverse use cases and aligning digital systems with Vakin's strategic and operational goals. The second workshop focused on advancing the utility's digitalization efforts by exploring the implementation of digital applications and IoT technologies. The workshop aimed to identify and prioritize potential applications and technologies that could leverage Vakin's system-wide data platform. The output from the workshop was a priority matrix/importance-feasibility matrix (Figure 2).

The workshops conducted with Vakin highlighted both practical challenges and successful strategies in their digital transformation journey, providing valuable insights that validated and complemented findings from the literature. Key obstacles identified during the workshops such as the lack of a unified digital culture, fragmented digitalization efforts, and limitations in integrating systems aligned with themes in the literature. However, Vakin's experiences also emphasized nuanced challenges, such as the difficulty of maintaining flexibility in system architecture and ensuring data quality across platforms.

Practical strategies discussed in the workshops validated theoretical recommendations, particularly the importance of iterative planning, organizational learning, and aligning digitalization initiatives with business needs. For instance, Vakin's focus on gradual milestones, stakeholder collaboration, and leveraging existing systems ('best-of-breed' approach) demonstrated effective ways to address the scalability and integration barriers identified in the literature. Additionally, their development of a dedicated data platform, driven by operational needs described through the priority matrix (Figure 2), highlighted the critical role of tailored solutions for long-term digital success. These insights reinforced the need for a flexible and context-aware roadmap, as suggested in the literature, while also providing practical examples of how utilities can navigate complexities in digital transformation.

The workshops conducted with Vakin provided practical insights that directly informed the design and refinement of the roadmap. Table 3 summarizes how specific findings from the workshops contributed to the development of each step in the roadmap, ensuring its applicability and grounding in real-world utility operations.

3.3. A proposed roadmap for digital transformation in UWSs

Building on insights from the literature review and the case study workshops, a practical roadmap has been developed to guide the digital transformation journey of water utilities. The proposed roadmap described in Figures 3 and 4 advocates for a strategic, phased approach, moving from basic digital maturity to holistic integration. By

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Table 2 | List of key obstacles to becoming a 'digitalized' organization and suggested solutions

Barriers	Potential solutions identified
Lack of a cohesive 'digital culture' within organizations.	1.1 Find the motivation to improve the digital state of the organization for different functions and tiers, e.g. the leadership, individuals, and the organization as a whole 1.2 Educate employees and create a learning organization 1.3 Include digitalization activities in resource plans and employment descriptions
Pilot projects and investments are not properly aligned with leadership or operational aspects	2.1 Create prerequisites for development by broad inclusion in the organization and approval from the leadership 2.2 Create non-person-specific ownership for the activities' effect realization 2.3 Predefine organizational needs for, and benefits of, the tested application, technology, or solution
Digitalization efforts and day-to-day O&M are separated, and processes to work or implement digital solutions are not integrated into the regular work	3.1 Create an understanding of general needs and prerequisites 3.2 Ensure that any development is based on business needs and done in collaboration between IT and process owners
Factors outside the organization hinder digitalization, such as municipal infrastructure	4.1 Create principles for technical and organizational requirements, including standards for data in the organization, and responsibilities
Organizations are afraid to move in the wrong direction and sometimes wait for others to take the first step	5.1 Create a long-term strategy for the organization 5.2 Create flexibility and openness in the systems and platforms implemented
Lack of control over data	6.1 Take control over collected data by creating clear processes and structures for data management including data stewardship processes 6.2 Include data stewardship in data management processes, including information classification based on risk, sensitivity, and availability for secure data use
Difficulty with procurement	7.1 Framework outlining technical requirements

systematically motivating organizational stakeholders, mapping the current state, assessing and visioning future needs, and building a well-defined strategy, utilities can construct a stable foundation for digitalization. Concurrent investment in robust data platforms and iterative application development ensures that the transformation is both technically sound and operationally relevant. Ultimately, this framework may be used to support utilities in navigating the complexities of digital change, maximizing the long-term benefits of their digital transformation journey.

3.3.1. From pilots to integration

As illustrated in Figure 3, the trajectory of digital transformation may typically begin with basic digital maturity characterized by isolated pilot projects and rudimentary data management practices. Early initiatives often focus on improving operational efficiency through local applications (e.g., SCADA systems, manual data analysis) that deliver immediate cost savings or process optimizations. However, these gains can remain limited if the organization lacks a coherent long-term vision and supporting 'soft' digital infrastructure such as standardized data formats, robust data governance, and interoperable systems. Over time, as the utility learns from these initial efforts, it can advance towards a more integrated and holistic approach. This transition entails moving beyond scattered applications towards a scalable, flexible, and innovation-oriented environment. Achieving this stage typically requires addressing organizational barriers and cultural inertia, developing a unified strategic direction, and investing in the necessary technical enablers particularly data platforms that facilitate interoperability and knowledge-sharing.

3.3.2. Description of the roadmap structure

The roadmap's strategic process (Figure 4) comprises four foundational steps designed to guide water utilities through the digital transformation of their UWSs. A detailed guide to each step is available in the Supplementary

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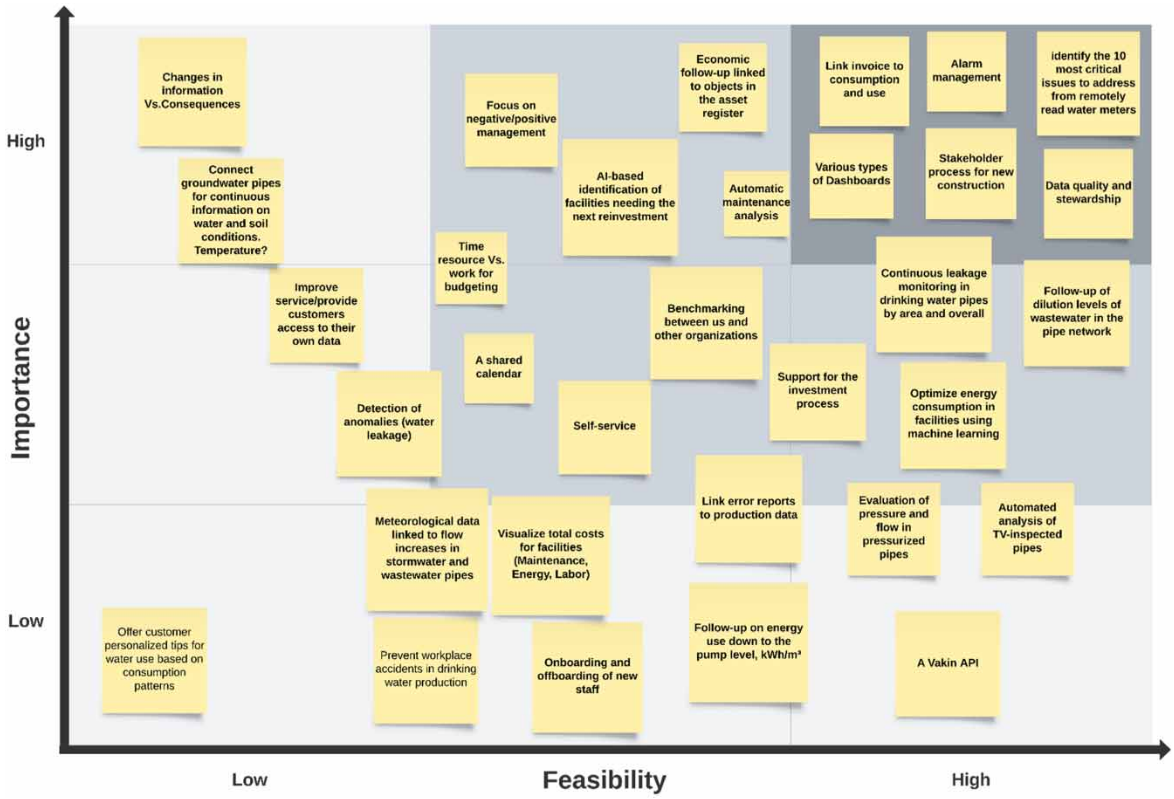

Figure 2 | Prioritization of digitalization needs for UWSs: balancing importance and feasibility of initiatives to support Vakin's goals, including data integration, IoT implementation, and enhanced decision support.

Table 3 | Summary of how insights from workshops with Vakin informed the development of the roadmap steps, highlighting practical contributions to each phase of the framework

Key insights	Impact on roadmap
Leadership buy-in was identified as critical; the lack of cohesive 'digital culture' as a barrier	• Engage leadership early • Define clear mandates • Align strategy with organizational goals
Fragmented systems, unclear data ownership, and lack of integration were identified as key challenges	• Map existing systems • Document data flows • Define user roles • Identify integration gaps
Future needs, dependencies, and gaps in current practices explored (e.g., IoT requirements, data stewardship)	• Define vision • Conduct GAP analysis • Address organizational needs (flexibility, interoperability, data control)
A priority matrix was developed to balance the importance and feasibility of initiatives	• Focus on IoT applications • Prioritize data platform implementation • Create a structured strategy with clear timelines and milestones
The need for flexible, open data platforms emphasized	• Enable system-wide integration • Ensure interoperability • Implement scalable and adaptable platform architecture
Requirements for modular hardware/software solutions identified	• Establish lifecycle management protocols • Create iterative testing frameworks • Address procurement, installation, and maintenance challenges

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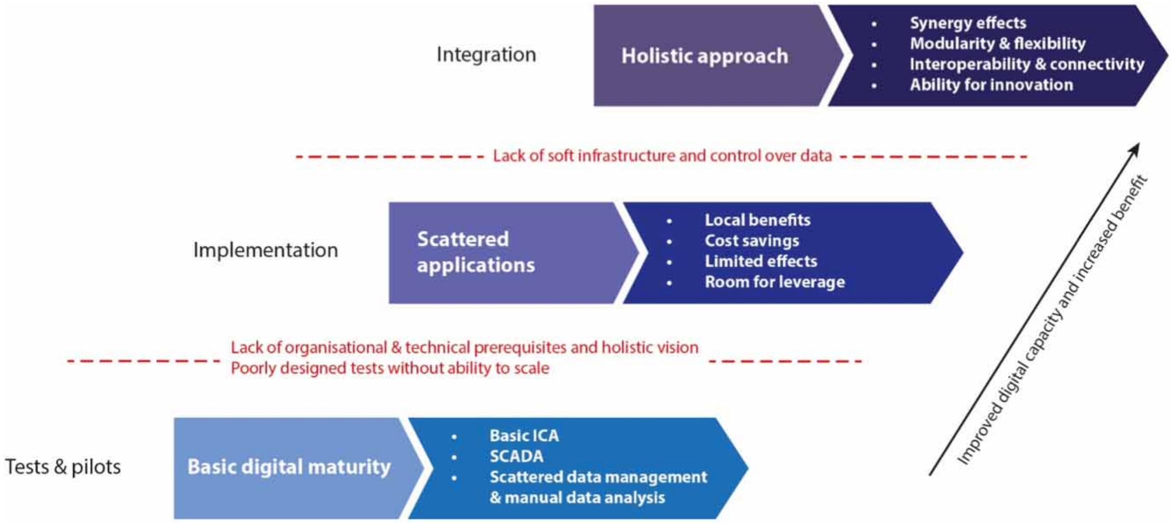

Figure 3 | Conceptual model of the stages of digitalization and innovative maturity in any organization and highlighting barriers to progression.

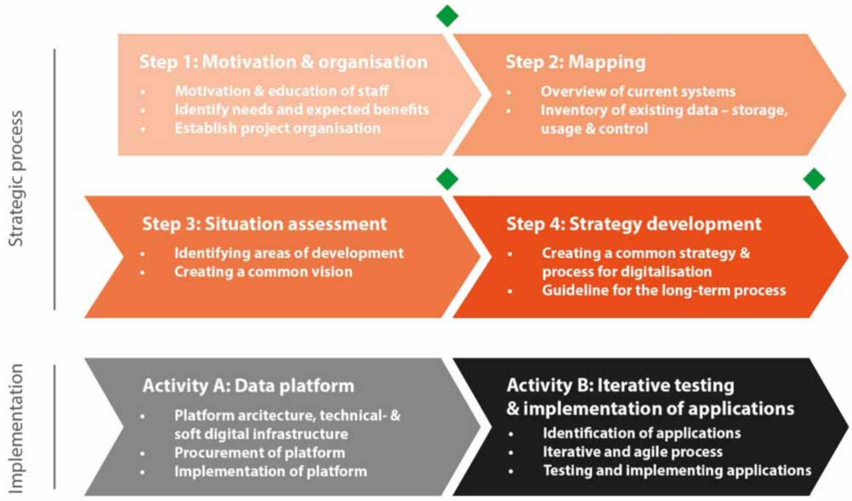

Figure 4 | A strategic, four-step process for digital transformation in urban water utilities.

Material. Before these steps can begin, the organization must first create an enabling environment, i.e. securing budget allocations, ensuring personnel resources, and granting the responsible team a sufficient mandate to drive the initiative and integrate it into routine operations. Once this initial readiness is established, Steps 2 through 4 focus on developing a clear understanding of the problems, needs, prerequisites, and opportunities associated with IoT implementation. Each step builds upon the outcomes of the previous one, and a range of business analytics methods descriptive, diagnostic, predictive, and prescriptive can be employed throughout this process. In addition, two targeted activities, A – Data platform deployment and B – iterative testing and implementation of applications, help to ensure that the resulting digital infrastructure effectively meets operational and strategic objectives.

This framework is tailored specifically to the operational, regulatory, and organizational characteristics of the urban water sector. Unlike more generic digital transformation roadmaps, it recognizes the uniquely risk-averse culture and strict public health and safety standards that water utilities must uphold. By incorporating structured steps to understand and address sector-specific constraints such as legacy infrastructure, and data interoperability issues the framework guides utilities towards more practical and context-sensitive solutions. It emphasizes

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iterative development, stakeholder engagement, and resource allocation in ways that align with the long-term service commitments and reliability demands inherent in water provision.

4. DISCUSSION

4.1. Comparison with existing roadmaps/frameworks and contributions

Existing roadmaps/frameworks for the digital transformation of UWSs are presented in Table 4. These frameworks highlight various perspectives on digital transformation, including process-based approaches, technology-focused perspectives, and case studies of specific implementations. The proposed roadmap aligns closely with existing digital transformation frameworks for UWSs, yet it distinguishes itself through its tailored approach and structured implementation guidance. The common thread among the existing roadmaps/frameworks and this study includes advocating for a systems-thinking perspective, i.e. improved understanding of the interconnectedness and dependencies between various elements, the increasingly important role of data and data management, and the emphasis on a phased interactive progression towards digital maturity (Wan Rosely & Voulvoulis 2023).

The specific contributions of the proposed roadmap not covered by existing roadmaps/frameworks include its explicit focus on the operational, regulatory, and organizational nuances of the urban water sector.

Table 4 | Summary of the digitalization or digital transformation processes discussed in existing frameworks

Source	Digitalization process	Key elements
Daniel *et al.* (2023)	A five-step continuous improvement process for the digital transformation of water utilities: (1) Identification of priority areas, (2) Acquisition of devices for high-frequency data collection and communication, (3) Development of models to support decision-making, (4) Transforming data into valuable information for water management, and (5) Data-informed proactive asset management and water pricing.	Mapping water utility status, capacity, and needs. - Improvements in sensor hardware - Integration of big, multi-sourced data and cybersecurity - Increased generality of smart data applications - Data-informed proactive asset management and water pricing
Ciliberti *et al.* (2021)	Emphasizes a six-pillar model for digital transformation: (1) People, (2) Processes, (3) Technology, (4) Customers, (5) Partners, and (6) Planet, highlighting the importance of integrating business processes.	Understanding and incorporating consumer needs. - Aligning, optimizing, and redefining organizational processes - Addressing the evolving ecosystem of customers, partners, and the planet
IWA (2022)	Five main phases: (1) Data acquisition and analysis, (2) Data warehouse implementation, (3) Business intelligence dashboard development, (4) Development of a mobile application for field activities, and (5) Integration with SCADA systems.	- Integration and organization of operational and business-related data into a common data lake - Establishment of a control room with real-time dashboards integrated with operational tools - Development of a mobile application for field activities and integration with SCADA systems
Adedeji *et al.* (2022)	A strategic digital transformation for the water industry, outlining a five-phase 'digital water adoption curve' to guide utilities: (1) Immature, (2) Exploring, (3) Experimenting, (4) Advancing, and (5) Transformational. It highlights the importance of setting the ambition at the CEO and Board level and pursuing pilot projects to explore digital implementation.	Remote sensing and digital twin technologies for connectivity between a utility and its water supply - Customer service and analytics tools to bridge the gap between a utility and its customers - Transformative digital solutions (e.g., process optimization, digital customer engagement, predictive maintenance)
Bettin (2023)	A five-step continuous improvement process for the digital transformation of water utilities: (1) Identification of priority areas, (2) Acquisition of devices for high-frequency data collection and communication, (3) Development of models to support decision-making, (4) Transforming data into valuable information for water management, 5) Data-informed proactive asset management and water pricing.	Mapping water utility status, capacity, and needs

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Unlike existing frameworks that primarily focus on broad principles or technical components, the proposed roadmap in this study offers a four-step process with clear, actionable steps (detailed in the Supplementary Material). For instance, the priority matrix developed with Vakin (Figure 2) exemplifies how feasibility and importance can guide strategic decisions, addressing gaps in scalability and integration often overlooked in other frameworks. These unique elements ensure practical relevance and adaptability across diverse utility contexts. This specificity enables utilities to translate high-level concepts into tangible actions, reducing uncertainty and supporting structured decision-making. The roadmap also confronts the risk-averse culture commonly found in Swedish water utilities and acknowledges the strict public health and safety requirements they face, an aspect not always central to existing frameworks.

4.2. Implications for practice

The transition to fully digital systems in UWSs is complex but achievable. By focusing on modular design, interoperability, cybersecurity, and organizational culture, water utilities can build resilient, scalable systems tailored to their unique needs. A well-defined and adaptable roadmap, supported by robust knowledge-sharing initiatives, is essential for navigating the challenges of digital transformation and achieving sustainable, data-driven operations. Some important points to consider in practice include:

4.2.1. Challenges in large-scale implementation of digital systems

Large-scale implementation of fully automated data collection and analysis systems in UWSs faces significant challenges, largely due to a lack of documented cases. Most available examples focus on pilot projects or short-term implementations, with limited information on large-scale strategies, decision-making processes, or hindsight evaluations (GSMA 2017; Díaz 2020). This creates a pilot-project bias, where the positive outcomes observed in controlled trials or limited implementations often fail to translate effectively at scale. As a result, critical complexities and blind spots in the digital transformation process are underrepresented. Organizations are left without detailed insights into the strategic and operational challenges required to scale pilot successes into comprehensive, system-wide implementations.

4.2.2. Data integration – flexibility, modularity, and systems interoperability

Surveys and interviews with Swedish water utilities documented in studies such as Arnell *et al.* (2023), Okwori *et al.* (2024), and Skantz (2024) including studies outside Sweden such as Halfawy (2008), Panetto *et al.* (2016) and Carriço & Ferreira (2021) consistently emphasise the critical role of data integration and systems interoperability in achieving successful digital transformation. These studies also highlighted the need for clear organizational structures regarding data management, access rights, and flows for data.

Practical experience highlights the importance of flexibility and modularity in system design, enabling systems to integrate seamlessly with existing infrastructure while remaining adaptable to future extensions (Manyika *et al.* 2015; Goncalves *et al.* 2020). Modular systems, composed of interconnected yet separated components, allow for incremental updates, enhance resilience, and support continuous system evolution without disruption. However, creating this linkage between systems could also create security implications regarding cyber security and a gateway to critical system components, such as SCADA systems. To ensure data security, all collected data needs to have an information owner and be security classified. This is part of the data stewardship process that needs to be clear and defined. International standards and national guidelines exist to advise the classification of information and data (International Organization for Standardization 2013; Dahlqvist *et al.* 2020).

However, this flexible approach and modular systems design require the organization to have clear and updated guidance on systems' architectures and responsibilities. This should be recorded and described in strategies and frameworks, having a clear owner updating them continuously. Otherwise, there is a risk of developments done in patches, poorly documented, and lost if the organization changes.

4.2.3. Organizational inclusion and digital culture

Successful digitalization projects require organizational inclusion and a digital culture that promotes innovation. Creating an understanding of development potential is crucial for engaging stakeholders and gathering input on needs and solutions. Digitalization efforts must be anchored and led both bottom-up and top-down to avoid solutions designed for a single function, and instead should adopt a systems approach focused on user needs and existing processes (Broring *et al.* 2017). To ensure interoperability and user simplification, it is important to establish modular systems, well-structured data management, and systems architecture. Business improvement

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strategies should emphasize a systems and needs-based approach rather than isolated development projects (Burnes & Jackson 2011; Abd El Aziz & Fady 2013). This proposed roadmap has been designed to address key obstacles to achieving a fully digital water utility by integrating identified success factors, however, it must be tailored to the specific needs, steering documents, and digital maturity levels of individual organizations. Pilot programmes are beneficial for utilities with low digital maturity to identify challenges and refine the framework, and more mature organizations should document their experiences to provide insights for others. Sharing solutions, procurement guides, and strategies across the sector will encourage collaboration and learning from each other's successes and failures.

4.3. Limitations and future research

The proposed roadmap was developed within the context of Swedish water utilities, reflecting specific legal, organizational, and operational frameworks. While the general steps are applicable internationally, regional adaptations must be carefully considered. Additionally, the lack of documented large-scale implementations limits insights into scalability and real-world complexities.

The significant variation in digital maturity among utilities highlights the need for tailored approaches, as a universal roadmap remains challenging. Further research should focus on piloting the roadmap in diverse contexts, gathering post-implementation experiences, and building a shared knowledge base.

5. CONCLUSION

The potential benefits of digital transformation include enhanced, operational efficiency, sustainability, and increased resilience of UWSs. However, digital transformation is complex and requires a strategic, phased approach that considers both technical and organizational factors. This study presented a practical roadmap for digital transformation, conceptualized through a combination of a literature review and hands-on case study workshops with a Swedish water utility.

The proposed roadmap builds on insights from a literature review and practical experience from a water utility, to propose a framework that can be adapted to utilities at varying levels of digital maturity. It moves beyond isolated pilot projects to advocate for a holistic, organization-wide approach, ensuring that digital initiatives align with strategic objectives and operational realities. The roadmap emphasizes a needs-driven approach that includes aspects related to systems interoperability, iterative development, and stakeholder engagement, providing utilities with actionable steps to navigate their digital transformation journey. While the roadmap is based on empirical findings situated in the Swedish context, its principles are broadly applicable to utilities in other regions facing similar challenges. The proposed roadmap includes four steps: motivation and organisation, mapping, situation assessment, and strategy development; followed by two activities: data platform and iterative testing and implementation of applications. Emphasising the importance of creating a supportive digital culture, aligning leadership priorities, and ensuring the inclusion of all organizational levels in the transformation process.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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