NAVIGATING THE WAVES OF CHANGE AND RIPPLES OF CHALLENGES IN THE WATER SUPPLY CHAIN SECTOR

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ARTICLE INFO

Article details
Presented at the 34th annual conference of the Southern African Institute for Industrial Engineering, held from 14 to 16 October 2024 in Vanderbijlpark, South Africa

Available online 29 Nov 2024

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DOI
http://dx.doi.org//10.7166/35-3-3079

ABSTRACT

The Fourth Industrial Revolution (4IR) has ushered in a transformative era for industries worldwide, including the water sector. This paper investigates the difficulties that are encountered and the changes that are required in water sector supply chain management amid the 4IR. A comprehensive analysis of scholarly articles, research papers, and industry reports provides insights into the evolving dynamics of water supply chains. The review identifies challenges such as data integration complexities, cybersecurity vulnerabilities, budget constraints, regulatory intricacies, skills gaps, environmental sustainability concerns, infrastructure compatibility issues, data privacy dilemmas, resource limitations, socio-political factors, and geographical disparities. These are critically examined within their contextual frameworks, highlighting their significance for the water sector. This paper is valuable for researchers, policymakers, water utility professionals, and stakeholders seeking a comprehensive understanding of water sector supply chain management's intricate challenges and transformative changes during the 4IR. This paper could also assist in illuminating water-related problems and solutions.

OPSOMMING

Die Vierde Industriële Revolusie (4IR) het 'n transformerende era vir nywerhede wêreldwyd ingelui, insluitend die watersektor. Hierdie artikel delf in die uitdagings wat teëgekom word en die veranderinge wat nodig is in watersektor voorsieningskettingbestuur te midde van die 4IR. 'n Omvattende ontleding van vakkundige artikels, navorsingsartikels en bedryfsverslae bied insig in die ontwikkelende dinamika van watervoorsieningskettings. Die oorsig identifiseer uitdagings soos data integrasie kompleksiteit, kwesbaarheid met betrekking tot kuberveiligheid, begrotingsbeperkings, regulatoriese verwikkeldheid, vaardigheidsgapings, omgewingsvolhoubaarheidskwessies, infrastruktuurversoenbaarheidskwessies, data-privaatheidsdilemmas, hulpbronbeperkinge, sosio-politieke faktore en geografiese ongelykhede. Dit word krities ondersoek binne hul kontekstuele raamwerke, wat hul betekenis vir die watersektor beklemtoon. Hierdie artikel behoort waardevol te wees vir navorsers, beleidmakers, professionele mense in waternutsdienste en belanghebbendes wat 'n omvattende begrip soek van watersektorvoorsieningskettingbestuur se ingewikkelde uitdagings en transformerende veranderinge tydens die 4IR. Hierdie artikel kan ook help om waterverwante probleme en oplossings te belig.

1. INTRODUCTION

The Fourth Industrial Revolution (4IR) merges technologies such as artificial intelligence (AI), the Internet of Things (IoT), data analytics, smart metering, blockchain, and digital twins with urban systems, thus transforming water utility supply chains. This revolution optimises resource allocation, real-time monitoring, and sustainability in water management while presenting challenges in technology integration, data security, and infrastructure adaptability. This study investigates the dynamic synergy between 4IR and the water supply chain's difficulties and transformative potential. To understand properly the changes and challenges of this sector, a basic overview of the water supply chain network is depicted in Figure 1. This shows the four water utility system phases: water resources, treatment plants, reservoirs, and demand zones [1].

Water utility systems face significant stress, especially during droughts or erratic weather [2], [3]. By 2030, 66% of the world's population will live in cities [4], intensifying these issues. Climate change adds unpredictability to the water supply, necessitating modern solutions. 4IR technologies offer promise in addressing these problems and revolutionising water supply systems.

A global survey reveals water management as a key concern [5]. AI-driven predictive analytics, IoT sensors, blockchain, and digital twins are becoming essential in modern water supply chains, improving efficiency, reducing wastage, and enhancing resilience in the cities of, for example, Latin America [6] and Indonesia [7].

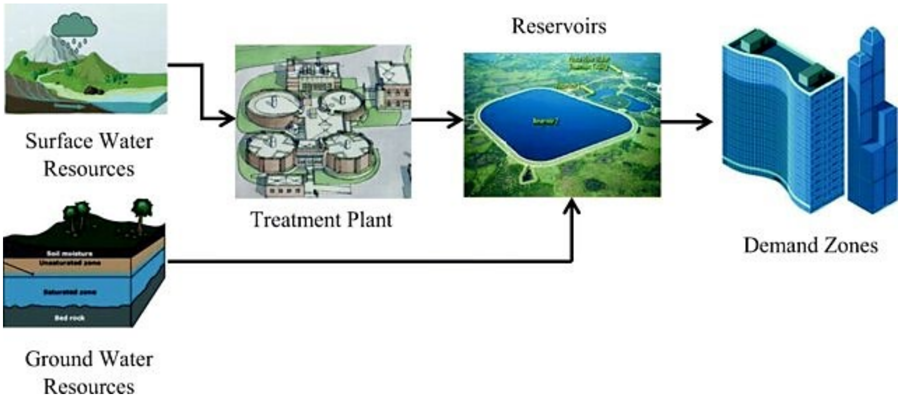

Figure 1: Water supply chain network [1]

This study illuminates the challenges and transformative potential of 4IR technologies in making water supply chains more efficient, reliable, and sustainable. The review emphasises the importance of understanding these technologies' relevance, trends, and interconnectedness to pave the way for resilient, resource-efficient, and sustainable water management in the digital age. This novel exploration underscores the integration of cutting-edge technologies as pivotal for the future of water utility supply chains, addresses the current gaps, and anticipates future needs in this critical sector.

While this paper provides a general overview of water sources and supply systems, it comprehensively analyses various regions and countries to understand the global applicability of 4IR technologies in water utility supply chains. By examining diverse case studies and examples from multiple regions, this review aims to offer a broad perspective on the challenges and opportunities in integrating 4IR technologies in different contexts.

Two research questions are investigated:

Research question 1: How could integrating 4IR technologies such as AI, IoT, data analytics, smart metering, blockchain, and digital twins change the efficiency, reliability, and sustainability of water utility supply chain systems?

Research question 2: What are the primary difficulties that water utility supply chain systems face as they adapt to the demands and disruptions introduced by the 4IR?

2. REVIEW METHOD

This section outlines the systematic literature review (SLR) methodology for data collection, analysis, and synthesis. The screening and selection process ensures that selected sources are relevant and high-quality and directly address the research questions. This involves systematically applying inclusion and exclusion criteria (Table 1) to the initial literature pool.

Table 1: General inclusion and exclusion criteria

Criteria	Inclusions	Exclusions
Databases	Scopus	IEE Xplore
	Google Scholar	Proquest
	Web of Science	Academic Search Premier
	Thesis/dissertation	Jstor
	* Grey literature	ResearchGate
Publication types	Articles	Editorials
	Reports	Magazines
	Conference proceedings	
	Books	
	Reviews	
Publication dates	After 2012	Before 2012
Language	Literature published in English	Literature in languages other than English
Location	Worldwide	None
Demographic	All	None
Industries	Primary	None
	Secondary	
	Tertiary	
	Quaternary	
Sectors	Water	
General	Covering both qualitative and quantitative analyses of challenges.	Studies that do not meet minimum quality criteria (e.g., poor methodology)
		Articles that lack relevance to the water utility industry

** Non-bibliometric databases used (grey literature) include:*

- Inter-American Development Bank
- Institute for Public Policy Research
- World Economic Forum
- Cooperative Research Centre for Water Sensitive Cities
- International Water Management Institute
- Asian Development Bank
- Public Utilities Board Singapore

Figure 2 depicts the literature selection and reduction process. This approach, along with authoritative bibliometric databases, assured the relevance and quality of the literature that was used, maintaining its rigour and credibility.

To make it manageable for screening and selection, several steps were taken:

- Duplicate removal: duplicate sources were removed.
- Title and abstract review: sources were reviewed on the basis of their title and abstract, and those that were irrelevant to the research questions were eliminated.
- Full-text assessment: the remaining sources underwent a full-text assessment, and were scrutinised for compliance with the inclusion and exclusion criteria.

Sources that did not meet these criteria were excluded.

The screening and selection process in this SLR was a critical stage in ensuring the inclusion of authoritative and relevant sources, using a systematic approach to identify and curate the literature from reputable bibliometric databases.

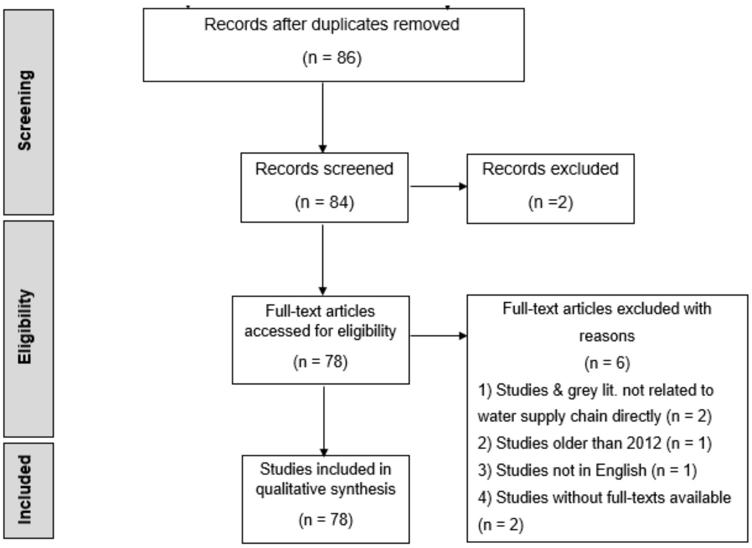

Figure 2: Literature selection and reduction process

The data extraction and summary process in this SLR was meticulously designed to gather information systematically from each included research study, paper, or article and to present it in a structured manner. This section delineates the steps taken to extract the relevant data, create an author matrix, and assess the quality of the extracted data.

After the generated articles were screened, the full-text studies were added to Atlas.ti, a software research tool. Each article was comprehensively read, and codes were added to relevant key concepts. In addition, details such as the author's name, publication year, research methods, key findings, and specific insights related to the research questions were identified. An author matrix organised and summarised each author's key findings and contributions. This matrix was valuable for comparing and contrasting the insights from different sources, offering a concise literature overview.

To ensure the quality of the extracted data, the following criteria and processes were applied:

- Relevance to research questions: data extraction focused on information directly relevant to the research questions, with any irrelevant or extraneous information omitted.
- Peer-reviewed sources: emphasis was placed on data extracted from peer-reviewed sources, which generally undergo rigorous quality control processes.
- Citation analysis: the quality of the extracted data was assessed by considering the impact and citation frequency of the source, with highly cited sources being given priority.

- Bias and objectivity: the data extraction involved evaluating whether the information was presented objectively and free from undue bias.
- Quality assessment criteria: each included study went through a ranking of its quality, based on specific criteria such as the relevance of the data, the diversity of the changes or challenges covered, the supported claims, and alignment with the research questions.

The structured data extraction process, coupled with quality verification measures, ensured that the extracted data was of a high quality and was directly relevant to the research questions, thus upholding the rigour and credibility of the review. Once the data quality selection, screening, extraction, and assessment were complete, the information was analysed further.

The synthesis of the data was achieved through a narrative approach. This allowed for weaving conceptualised data into a coherent and logically structured narrative. The narrative served as a platform to discuss the evolution of ideas and how different authors' contributions collectively advanced the understanding of the research questions. It provided a logical flow that enhanced the readability and coherence of the review.

Using Atlas.ti after the full-texts had been read and coded, the codes were added to a data extraction library consisting of the categories shown in Table 2.

Table 2: Data extraction library (using Atlas.ti)

<table>
<tr><th colspan="2">Phases</th></tr>
<tr><td colspan="2">Surface water
Reservoir (groundwater)
Water treatment
Distribution/demand zones</td></tr>
<tr><th>Themes</th><th>Categories</th></tr>
<tr><td>Changes in water supply chain (with 4IR technologies)</td><td>Water supply chain
AI
IoT
Smart metering
Blockchain
Digital twins
Efficiency
Reliability
Sustainability</td></tr>
<tr><td>Challenges faced in water supply chain (with 4IR)</td><td>Water supply chain
Cybersecurity
Data privacy
Socio-political
Socio-economic
Complexity
Regulations
Skills gap
Geographical</td></tr>
</table>

The SLR used a structured approach to categorise key concepts, themes, research methodologies, and significant findings into relevant groups that were aligned with the primary research questions. This ensured that the data was organised effectively to meet the review's objectives. Subsequently, a comparative analysis was conducted to identify common themes, trends, and variations across the different works, facilitating a nuanced exploration of the ideas' evolution and the field's diverse perspectives. Overall, this methodological approach enabled the review to provide comprehensive insights into the research questions by synthesising and analysing the literature coherently and systematically.

3. FINDINGS

The initial part of this section sheds light on the challenges that water utility supply chain systems face as they adapt to the disruptions introduced by the 4IR. It explores common themes and variations in the literature, mapping the interrelationships and dependencies between the different challenges and providing insights into the complex landscape of 4IR's impact.

The latter section focuses on the changes driven by integrating 4IR technologies. It examines the efficiencies, reliability enhancements, and sustainability improvements by AI, the IoT, data analytics, smart metering, blockchain, and digital twins. The narrative synthesises diverse insights from various authors, elucidating the transformative potential of these technologies.

The literature results are reviewed regarding the various water supply chain network phases, namely water resources, treatment plants, reservoirs, and demand zones, as seen in Figure 1.

3.1. Surface water resources

Surface water in the utility supply chain is sourced from above-ground sources such as runoff, stormwater drains, rivers, lakes, reservoirs, and ponds. Intake structures such as dams or pumping stations capture the surface water. This initial stage is the least investigated in the water utility cycle.

Using Atlas.ti to analyse the changes (Figure 3) and challenges (Figure 4), it was evident that digital twins are rarely implemented in surface water management. However, significant work is being done in AI, the IoT, blockchain, and smart metering, with 37, 43, 18, and seven common codes respectively. Real-time monitoring and control of stormwater networks increase efficiency and reliability. The Pipedream toolkit from Bartos and Kerkez [8] updates stormwater statistics using sensor data, while smart water grids (SWGs) integrate the IoT and AI for catchment water management [9], [10]. A study in Indonesia showed that a mobile application improved water reliability and system efficiency [7]

Drones equipped with the IoT and AI could monitor water quality, flow rates, and weather conditions in real time, aiding effective water management [11]. High-performance embedded systems (HPES) would further enhance this process [12]. Blockchain could improve trust and accountability in water management in municipalities [13].

However, challenges such as skill gaps and stringent regulations hinder the implementation of these technologies in surface water management. The European Union's water framework directive (WFD) pressures European governments to protect and sustain water resources [14], [15]. There is a lack of awareness and education about 4IR technology, with only 24 common codes identified for the challenges. Studies highlight a skills gap and labour shortage in the EU and UK water sectors [16], [17], and a digital literacy gap in the USA [18]. Regulatory gaps are also noted, with 16 common codes identified. The complexity of systems remains high, and cybersecurity and data privacy issues are prevalent globally [19].

		1. Surface Water 15 1654	Totals
AI (Artificial Intelligence)	295	37	37
Blockchain	187	18	18
Data Analytics	4		0
Digital Twin	200		0
Efficiency	604	63	63
Internet of Things (IoT)	1167	43	43
Reliability	147	13	13
Smart metering	220	7	7
Water sustainability	7		0
Totals		181	181

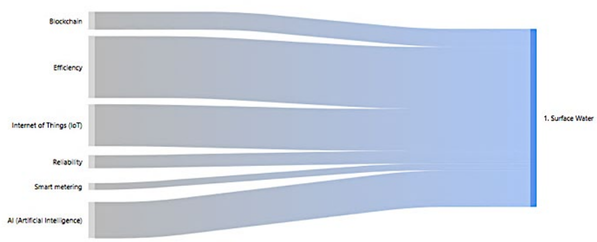

Figure 3: Sankey of surface water changes

	1. Surface Water 15 1654	Totals
Cyber security 104	1	1
Geographic and institutional aspects 2		0
Regulation and compliance 63	16	16
Skill gap 166	4	4
Socio-political indicators 24	2	2
Socioeconomic aspects 18	1	1
System complexity 4		0
Totals	24	24

Figure 4: Sankey of surface water challenges

3.2. Reservoir (groundwater)

Reservoirs are the second stage in the water utility supply chain, strategically built to store large volumes of water. This stored water can be released as needed, stabilising the water supply, especially during dry seasons or droughts.

Globally, reservoirs have seen more positive advancements (Figure 5) than challenges (Figure 6), with 542 codes for changes and only 34 for challenges. Despite limited investigation, significant developments in emerging technologies are evident. The IoT is the most used technology in this phase, with 209 codes. Integrating sensors and predictive models allows for smart data parameter capturing [20]. In Denmark, 4IR technology is used for groundwater capture zone delineations [21]. AI combined with the IoT facilitates infrastructure planning for reservoirs, as supported by studies from Australia and Thailand [22], [23].

Blockchain and digital twins add complexity and advancements to water storage. When combined with AI and the IoT, digital twins can monitor reservoir levels and predict water quality based on weather patterns [9]. Smart metering, however, has not been reported on in the literature.

Challenges at this stage primarily involve a gap in the skilled workforce [17]. Owing to a lack of educational proficiency, the potential and vulnerabilities of these technologies have not been fully assessed, although cybersecurity threats persist. Major infrastructure and regulatory requirements pose additional challenges, especially in third-world and non-urban areas [2]. Groundwater depletion and climate change also negatively impact the reservoir phase.

	2. Reservoir (Groundwater) 22 2647	Totals
AI (Artificial Intelligence) 295	82	82
Blockchain 187	44	44
Data Analytics 4		0
Digital Twin 200	48	48
Efficiency 604	118	118
Internet of Things (IoT) 1167	209	209
Reliability 147	22	22
Smart metering 220	17	17
Water sustainability 7	2	2
Totals	542	542

Figure 5: Sankey of reservoir changes

	2. Reservoir (Groundwater) 22 2647	Totals
Cyber security 104	8	8
Geographic and institutional aspects 2	1	1
Regulation and compliance 63	6	6
Skill gap 166	16	16
Socio-political indicators 24	2	2
Socioeconomic aspects 18	1	1
System complexity 4		0
Totals	34	34

Figure 6: Sankey of reservoir challenges

3.3. Water treatment

Water treatment is a crucial process in the water utility supply chain, ensuring water is safe and clean for various uses by removing impurities and contaminants. Integrating digital technologies in water quality monitoring and treatment has significantly enhanced the industry's efficiency and reliability [24].

The IoT stands out as the most popular technology in water treatment, with 264 out of 580 total codes (Figure 7). IoT-based frameworks improve water distribution systems' reliability and efficiency, enabling real-time monitoring of water quality and flow rate [25]. These technologies allow utility companies to respond quickly to changes and to optimise networks [26], [27]. For example, Hong, Kim and Hwang [28] established a monitoring system for water filters in apartment buildings using Arduino and IoT technology, highlighting its global and local applicability. Similarly, Lakshmikantha [29] analysed IoT-based smart water quality monitoring systems. Blockchain technology introduces the concept of a peer-to-peer water trading system, enhancing water resource management and promoting efficiency [20], [30].

IoT frameworks have revolutionised water treatment, enhancing monitoring, control, and optimisation [13]. This integration enables real-time data analysis, improving water quality and cost-efficiency [31].

Digital models for decision support in smart water grids (SWGs) in the Netherlands show promise. Digital-twins-based fault detection frameworks, such as the combined anomaly detection framework (CADF) designed by Wilson [32], outperform alternative methods in wastewater treatment plant fault detection. The UK faces challenges with workforce training and knowledge gaps in emerging technologies, with 45 out of 77 codes indicating the skills gap as the leading issue (Figure 8). Training programmes are necessary to bridge this gap [33]. Cybersecurity is a concern, highlighted by the cyberattack on a water treatment plant in Oldsmar, Florida [34]. South Africa's cybersecurity policy and legislative framework efforts aim to protect critical water infrastructure [35]. Water quality index (WQI) models are valuable for assessing water quality, but regulatory gaps can hinder their integration, as demonstrated by the Flint, Michigan case study [36]. Socio-political and socio-economic factors influence sustainability in water utilities. Policies supporting sustainable practices are essential to overcoming these challenges [37].

		3. Water Treatment 31 3190	Totals
AI (Artificial Intelligence)	295	85	85
Blockchain	187	27	27
Data Analytics	4	1	1
Digital Twin	200	30	30
Efficiency	604	126	126
Internet of Things (IoT)	1167	264	264
Reliability	147	26	26
Smart metering	220	19	19
Water sustainability	7	2	2
Totals		580	580

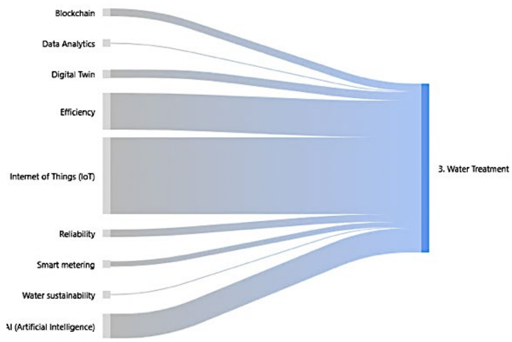

Figure 7: Sankey for changes in water treatment

		3. Water Treatment 31 3190	Totals
Cyber security	104	12	12
Geographic and institutional aspects	2		0
Regulation and compliance	63	12	12
Skill gap	166	45	45
Socio-political indicators	24	4	4
Socioeconomic aspects	18	2	2
System complexity	4	2	2
Totals		77	77

Figure 8: Sankey for challenges in water treatment

3.4. Distribution/demand zones

In a water utility supply network, ‘demand zones’ and ‘distribution zones’ manage the flow and distribution of potable water to consumers. Implementing 4IR technologies in this phase is important for efficiency, reliability, and sustainability. AI and the IoT are particularly beneficial for real-time leak detection, infrastructure management, and smart metering, as indicated by 919 codes in the reviewed literature (Figure 9).

AI and the IoT enable precise leak detection and proactive infrastructure repairs, conserving resources [38], [39]. The Swedish water industry emphasises robust digital infrastructure for modern water management [40]. Blockchain technology further enhances water management efficiency and sustainability [41], [42]. Apps such as ‘Control your water’ in Spain and similar tools in Pakistan improve water system efficiency and access [43], [44]. Smart water grids boost distribution efficiency and resource security [45].

Challenges include a skills gap in emerging technologies, accounting for 101 out of 246 coded phrases (Figure 10). Chinese cities need aligned socioeconomic, legal, and regulatory reforms [46]. Cyberattacks are a significant concern owing to smart meter vulnerabilities, posing data privacy risks [19]. The United Kingdom’s smart meter implementation programme faced system complexity and socio-political issues [47]. Funding limitations and institutional structures also hinder smart water grid implementation [48], [49]. Globally, integrated IoT systems optimise water consumption and resource allocation [10].

The artificial intelligence hierarchy of needs (AIHN) framework ensures system reliability and operational optimisation through real-time leak detection [3]. AI algorithms also optimise water distribution network design [50]. Digital twins and the digitalised water management model (DWMM) enhance energy efficiency and water distribution management [5], [51]. Smart metering, which is crucial in this phase, offers efficiency and security [52]). IoT-based smart metering and data analytics improve water management [38].

		4. Distribution (53, 6439)	Totals
AI (Artificial Intelligence)	295	91	91
Blockchain	187	98	98
Data Analytics	4	3	3
Digital Twin	200	122	122
Efficiency	604	297	297
Internet of Things (IoT)	1167	651	651
Reliability	147	86	86
Smart metering	220	177	177
Water sustainability	7	3	3
Totals		1528	1528

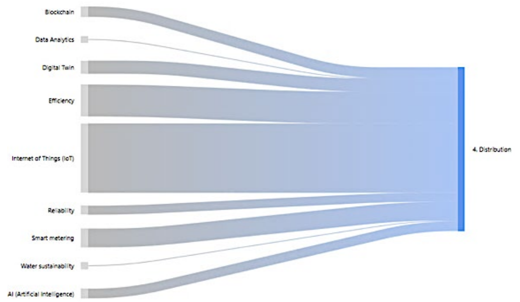

Figure 9: Sankey of changes in distribution phase

		4. Distribution (53, 6439)	Totals
Cyber security	104	83	83
Geographic and institutional aspects	2	1	1
Regulation and compliance	63	29	29
Skill gap	166	101	101
Socio-political indicators	24	16	16
Socioeconomic aspects	18	14	14
System complexity	4	2	2
Totals		246	246

Figure 10: Sankey of challenges in distribution phase

4. DISCUSSION

The integration of 4IR technologies is revolutionising water supply chain management, presenting challenges and opportunities. Through a systematic literature review, this study has explored the primary challenges faced by water utility supply chain systems in adapting to 4IR, and examined how these technologies are enhancing reliability, efficiency, and sustainability. The review has revealed common challenges such as cybersecurity vulnerabilities, system complexity, regulatory issues, and skill gaps in the workforce. However, integrating 4IR technologies offers real-time monitoring, predictive maintenance, resource conservation, and reduced environmental impact, thus promoting sustainability in water supply systems.

In summary, as shown in Figure 11, IoT and AI are closely linked to improvements in efficiency and reliability, but there is an unclear relationship between sustainability and changes. Figure 12 shows that cybersecurity is significantly affiliated with the IoT, while efficiency is linked to socio-economic factors and skill gaps. This answers research question 1.

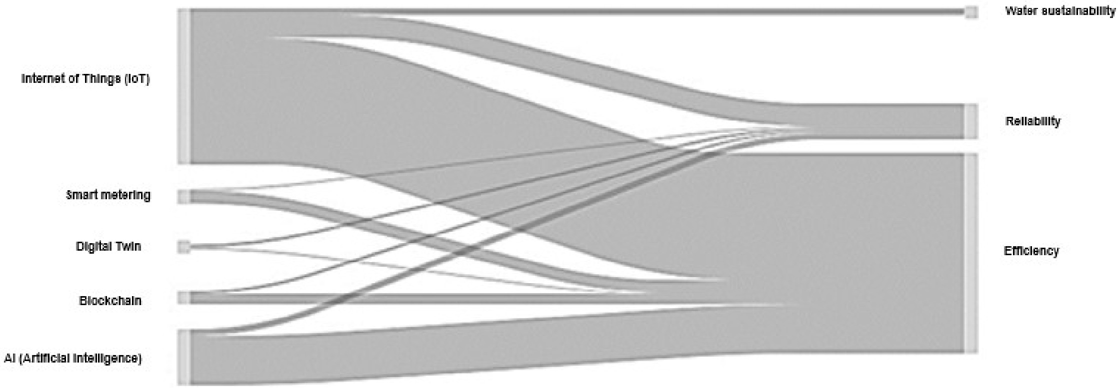

Figure 11: Sankey of changes and challenges

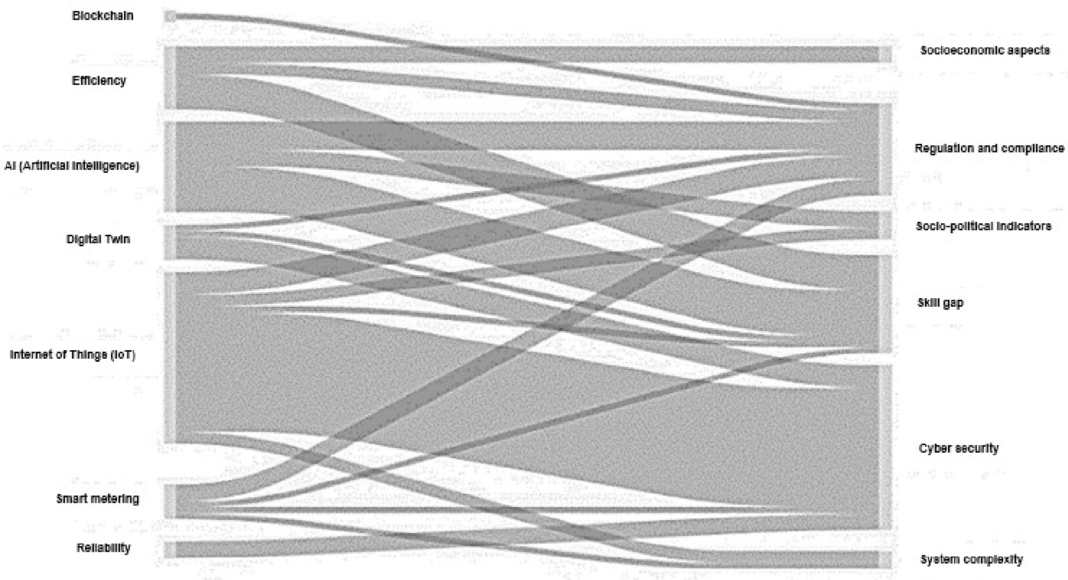

Figure 12: Sankey of changes

The water supply chain management challenges during the 4IR are multi-faceted and interlinked, necessitating a holistic approach to address them. 4IR technologies offer unprecedented potential to enhance water utility supply chain systems' reliability, efficiency, and sustainability. Adopting AI, the IoT, data analytics, smart metering, blockchain, and digital twins would be instrumental in mitigating the challenges while unlocking opportunities for transformative change.

The primary challenges are cybersecurity vulnerabilities, data complexity, socio-political, socio-economic, geographic, regulatory, and compliance hurdles, and workforce skill gaps (research question 2). These challenges must be addressed comprehensively to ensure the reliability and resilience of water supply systems.

To address water issues and identify the gaps that 4IR could fill, the SLR highlighted several key points. Chuks and Telukdarie [5] discuss how Industry 4.0 tools could revolutionise water management by improving efficiency and reducing wastage. Jenny *et al.* [12] demonstrate the potential of AI in smart water management systems, addressing predictive maintenance and real-time monitoring challenges. Xin, Lang and Mishra [15] evaluate the sustainable implementation of Supply Chain 4.0, emphasising the circular economy's role in addressing resource conservation and system optimization. David *et al.* [45] integrate 4IR technologies into the water-energy-food nexus, highlighting the need for enhanced cybersecurity, regulatory compliance, and workforce training to ensure sustainable security. These studies have revealed significant gaps in current water management practices that 4IR technologies could address, such as inefficiencies, data management issues, and infrastructure limitations.

Integrating 4IR technologies brings about changes through enhanced reliability, optimised efficiency, and improved sustainability. These technologies offer real-time monitoring, predictive maintenance, resource allocation, and environmental responsibility.

4.1. Strengths and limitations of the study

The SLR's strengths lie in its comprehensive approach, drawing from diverse data sources such as academic articles, reports, and grey literature, ensuring a well-rounded understanding. A rigorous systematic methodology and interdisciplinary perspectives were employed, resulting in consistent findings about the challenges and changes in the water supply chain during the 4IR. However, its limitations include the potential exclusion of valuable insights, variability in the quality of grey literature sources, and the possibility of recent developments not being fully captured. In addition, the findings may not be universally applicable owing to the impact of regional contexts on the water supply chain dynamics.

4.2. Generalisability and managerial implications

The review's findings hold implications for academics, practitioners, and policymakers, emphasising the need for interdisciplinary research and strategic decision-making. Academics could explore regional variations in 4IR's impact on water supply systems, while practitioners could prioritise cybersecurity and infrastructure upgrades. Policymakers are urged to craft regulations that foster innovation and sustainability in water management. These insights offer valuable guidance for navigating the complexities of 4IR's influence on water supply chain management, facilitating the development of resilient and efficient systems.

5. CONCLUSION

The 4IR is reshaping the water supply chain management sector, introducing challenges and opportunities. This SLR has illuminated how integrating 4IR technologies such as AI, the IoT, data analytics, smart metering, blockchain, and digital twins affects water utility supply chain systems' reliability, efficiency, and sustainability. Digital technologies, particularly AI and the IoT, enhance leak detection and infrastructure optimisation, but raise issues such as cybersecurity vulnerabilities and workforce training needs. Despite these challenges, digital solutions have immense potential for improving water quality, supply chain management, and global access to water services. However, further investigation into the sustainability and reliability aspects of these technologies is necessary. This review has provided insights for navigating 4IR's impact on water supply chain management, offering a blueprint for building a resilient, efficient, and sustainable water future.

6. FUTURE RESEARCH RECOMMENDATIONS

Future research should focus on longitudinal studies that track the evolution of water supply chain systems alongside cross-city comparisons to understand regional variations. In addition, sustainability assessments, cost-benefit analyses of 4IR technology adoption, and user perception studies would be crucial. Further investigations into regulatory frameworks, public-private partnerships, resilience enhancement, and ethical considerations would also be warranted. These recommendations provide a roadmap for addressing knowledge gaps and advancing resilient, efficient, and sustainable water supply systems in the digital age.

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