



Optimization of water distribution networks: a digital approach

This dissertation is submitted in fulfilment of the requirements for the Master of Engineering Degree in the Department of Chemical Engineering in the Faculty of Engineering and the Built Environment at the Durban University of Technology.

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Abstract

Water stands as the fundamental cornerstone of life, and with the human population growing exponentially, the critical importance of sustainable water management becomes increasingly evident. Water not only serves as the essential working fluid for major chemical processes, including thermal energy generation, but it is also integral to manufacturing and domestic use. Despite its significance, water is a scarce commodity, and the planet continues to lose this precious resource due to theft, pipe bursts, and leakages in water distribution networks (WDNs). The consequences of water loss extend beyond the impact on physical resources, as it is intricately linked to financial challenges. Thus, water loss has the potential to result in substantial financial setbacks for companies, organizations, and government entities, underscoring the interdependence of water management and fiscal sustainability. In response to these challenges, digital technologies have been harnessed to optimize WDNs. A major constraint lies in deciphering the applicable digital technologies due to the multidisciplinary nature of the research area encompassing WDNs and digital technologies; therefore, this study adopts a systematic literature review (SLR) combined with digital tools, to comprehensively extract all aspects of a WDN, ranging from sensors to enterprise resource planning (ERP), including equipment and systems. This literature forms the foundational basis for constructing a framework aimed at creating a content repository for digital WDN sustainability.

To further develop the framework, this study reviews international best practices in digital WDN. This is adopted in developing a digital WDN framework based on the literature and classifying a database structure from sensor to ERP for a generic WDN. Furthermore, the study explores tools and systems for optimization as well as updating the theoretical structure with Johannesburg WDN data and provides a comprehensive evaluation for enabling digital WDN in South Africa. The digital WDN framework comprises three distinct components: security, a central management database (CMDB), and best practice architecture. The architecture involves five layers, including the physical layer, communication layer, data storage and analysis layer, benefit layer, and application layer. Utilizing systematic literature review and bibliometric keyword analysis, the study determines the equipment, systems, and their uses, leading to the development of a generic WDN. Validation of the framework using the generic WDN emphasizes the equipment and systems used in each of the five layers. Furthermore, the framework is validated using Johannesburg Water's WDN, leading to the development of a CMDB. The CMDB underscores the possibility of storing physical layer and communication layer configuration items (CIs) and highlights asset management, CI relations, change management, and historian capabilities. Maintaining an accurate and updated CMDB necessitates employing asset discovery solutions, while CMDB relationship mapping plays a crucial role in assessing the ripple effects of CI changes within a complex system. Finally, the measurement of the digital maturity of Johannesburg Water's WDN using the *Administração e Gestão de Sistemas de Salubridade* (AGS) maturity index reveals a maturity index of 62%. The index emphasizes strong capabilities in GIS integration and data collection through the SCADA system. Despite advancements in planning systems, such as domestic flow metering, there remains an opportunity to enhance asset management capabilities for continuous improvement in WDN operations.

Declaration

I, Regionald Mongwe, student number: 22290269 hereby declare that:

- I. This dissertation, submitted for a master's in engineering degree at the Durban University of Technology Postgraduate School of Engineering, represents my work.
- II. The research reported in this thesis, unless otherwise specified, represents my original work.
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Dedication

This work is dedicated to Regionald Mongwe, for persisting even during the moments when it felt nearly impossible to carry on with this thesis.

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List of Abbreviations

4IR	Fourth Industrial Revolution
AGS	Administração e Gestão de Sistemas de Salubridade
AI	Artificial Intelligence
CI	Configuration Item
CMDB	Configuration Management Database
CPS	Cyber-Physical Systems
DMA	District Metered Area
DWTP	Drinking Water Treatment Plant
ERP	Enterprise Resource Planning
FAVAD	Fixed and Varied Areas Discharge
GA	Genetic Algorithm
GIS	Geographic Information System
ICS	Industrial Control System
IoT	Internet of Things
IWA	International Water Association
LPWAN	Low Power Wide Area Network
MNF	Minimum Night Flow
MTU	Master Terminal Unit
NRW	Non-Revenue Water
OT	Operational Technology
OPC	Open Platform Communications
PAT	Pump as Turbine
PLC	Programmable Logic Controller
PRV	Pressure Reduction Valve

RF	Radio Frequency
RTU	Remote Terminal Unit
SA	South Africa
SCADA	Supervisory Control and Data Acquisition
SIV	System Volume Input
SLR	Systematic Literature Review
SQL	Structured Query Language
UDS	Urban Drainage System
UWC	Urban Water Cycle
VI	Visual Inspection
WDN	Water Distribution Network
WWTW	Wastewater Treatment Works

Research Outputs

LOCAL AND INTERNATIONAL CONFERENCES

Mongwe, R., Rathilal, S., Telukdarie, A., 2023, Optimization of Water distribution networks, a digital approach , Book of Abstracts, *American Society for Engineering Management 2023 International Annual Conference and 44th Annual Meeting*, United State of America, October 24-27, 2023.

PEER REVIEWED JOURNAL ARTICLES

Mongwe, R., Rathilal, S., Telukdarie, A., 2023, Optimization of Water distribution networks, a digital approach ,Journal of Water Research (*under peer review*).

Chapter 1– INTRODUCTION

1.1 Research Background

Water remains the essential foundation of life. As human population growth follows an exponential trajectory, the risk of threats to sustainable water management increases (Babunski *et al.* 2018). Water is the working fluid of major chemical processes such as thermal energy generation and is also utilized for manufacturing and domestic use. While water is a scarce commodity, the planet continues to lose this scarce resource due to theft, pipe bursts, and leakages in water distribution networks (WDNs). Water losses not only impact physical resources but are also closely tied to financial repercussions. Substantial water loss can lead to significant financial losses for companies, organizations, and government entities, highlighting the interconnectedness of water management and fiscal sustainability (Indah and Karpriana 2021).

Johannesburg Water, a City of Johannesburg municipal entity, plays a vital role in supplying 1.6 billion liters of potable water daily. This water is sourced from Rand Water, a South African water utility that supplies potable water to the province of Gauteng as well as some parts of South Africa. Rand Water distributes its water through a WDN that spans 12,288 kilometers, featuring 127 reservoirs, water towers, and 37 water pump stations. In parallel, Johannesburg Water manages an intricate wastewater system, encompassing 11,710 kilometers of wastewater networks and 38 sewerage pump stations. The utility treats a substantial 926 million liters per day (ML/day) of sewerage at its six-wastewater treatment works (WWTW). Among these facilities, there is a noteworthy biogas-to-energy plant that converts methane gas into valuable energy, contributing to sustainability and resource optimization (Sioga 2020).

In 2019, Johannesburg Water lost about 38 % of its bulk water supply due to damaged infrastructure. The number of water pipe bursts experienced per 100 km/year of pipe length was 221.16, while the corresponding sewer pipe blockages experienced per 100 km recorded were 286.08. The trend for infrastructure failure rates on water pipes increased on average when compared to the previous year. This was mainly due to the aging pipe infrastructure. To mitigate pipe failure and associated water losses, the implementation of an improved pressure management system had a positive impact (Sioga 2020). Additionally, several techniques were implemented to deal with the management of leakages.

Leak detection methods are classified in terms of external and internal monitoring methods. An internal method involves monitoring and measuring the physical state of water, like its level, pressure, temperature, and turbidity (Uwizeye 2021). The external monitoring system is mainly focused on the environmental condition of a pipe (Mondejar *et al.* 2021). Pipelines in a WDN, are designed and engineered to accommodate full-load operations, considering steady-state flow conditions as the baseline. Operational parameters within the network can vary widely, spanning from the maximum allowable operating pressure to a depressurized state corresponding to a no-flow situation. Daily WDN operations involve a variety of transient events, including the starting and stopping of pump operations, changing control valve settings, and changing supply rates. Given this dynamic operational landscape, it is essential for internal leak detection systems to

function effectively across a broad spectrum of process conditions, including some that may exhibit characteristics resembling leak patterns (Seyoum *et al.* 2017).

In the case of Johannesburg Water, the WDN is facing the challenge of aging infrastructure. Further complicating the situation, the city continues to operate the network above the allowable operating pressure threshold of 7 bar. Operating at higher pressures significantly increases the likelihood of leakages, leading to potential water losses and infrastructure deterioration. Furthermore, the network lacks a pressure-regulating mechanism (Sioga 2020).

Another notable absence in the WDN is the lack of leak detection technology. It is essential to recognize that numerous underlying challenges, such as aging infrastructure and operational inefficiencies, contribute to the challenge to address the complex issue of leak detection. Therefore, developing a robust framework to address and virtualize these interconnected problems is crucial for effectively managing and improving the water distribution system in Johannesburg.

Efficient WDNs can play a pivotal role in helping the city reduce water losses. This reduction in water losses has several significant benefits, with examples such as:

- **Cost Savings:** As water losses decrease, the city can realize substantial savings in pumping and water treatment costs due to the reduced need for pumping and treating water to meet the demands of the population (Kiewiet 2019).
- **Increased Revenue:** Reduced water losses translate into increased revenue for the city. The water that was previously lost can now be sold to customers, contributing to a boost in the city's finances (Kiewiet 2019).
- **Environmental Benefits:** The positive impact extends to the environment. Water losses have both environmental and economic consequences. Water that is lost has undergone energy-intensive processes, including pumping and treatment, which contribute to greenhouse gas emissions (GHGs). In cases where desalination is involved, the GHG emissions are even higher. For instance, in the case of Johannesburg, water treatment involves coal energy, which has a significant GHG impact. By reducing water losses, the city can minimize its carbon footprint and mitigate environmental harm (Kiewiet 2019).

In essence, an effective WDN not only conserves precious water resources but also brings about financial savings, environmental benefits, and increased economic value. This underscores the importance of proactively managing and optimizing water distribution systems to address both the financial and environmental dimensions of water sustainability.

1.2. Smart urban water

The global population residing in urban areas is projected to surge up to 70% of the total population, reaching approximately 9.7 billion people by 2050 (World Health Organization 2019). This rapid urbanization poses significant challenges for urban infrastructure, urban planning, management, and the provision of essential services like water and wastewater services. Coupled

with the challenges of urbanization, population growth, and increased urban density, climate change and resource limitations complicate the complexity of managing urban environments (Koop and van Leeuwen 2017). Climate change can lead to more extreme weather events, alter precipitation patterns, and affect water availability and quality. Resource constraints, including water scarcity and energy limitations, further stress urban water utilities. The water utilities are facing high demand for water. In order to mitigate the challenges encountered by water utilities, water corporations are increasingly embracing the concepts of water digitalization, often referred to as Water 4.0, as well as integrated water management systems (Alabi, Telukdarie and Van Rensburg 2019).

Water 4.0 represents a groundbreaking digital transformation within the water sector, with the overarching goal of revolutionizing various facets of the water industry to enhance its efficiency (Alabi, Telukdarie and Van Rensburg 2019). This transformation involves the integration of smart water management technologies and advanced digital management systems, coupled with faster response times, to bring about significant improvements in water reliability and a substantial reduction in water losses (Gupta and Kulat 2018).

Globally, the water industry is actively driving the transition into a new era of water management. This transition places a strong emphasis on automation, the Internet of Things (IoT), and the deployment of more sophisticated data management and analysis software (Alabi, Telukdarie and Van Rensburg 2019). These technological advancements empower water end-users and plant operators with valuable and actionable information. This shift toward data-driven decision-making and real-time monitoring is poised to usher in a more efficient, sustainable, and responsive approach to managing water resources and distribution systems. This ensures that water remains a reliable and accessible resource for urban populations worldwide (Daigger *et al.* 2019).

1.3 Water as a digital business

Clean water is a valuable proposition for water utilities. Water undergoes different processes before it is sold to consumers. These processes are dependent on each other, and ensure that a value proposition that customers care about is produced (Madeira and Gartner 2018). In addition to the primary processes carried out by water companies, which pertain to creating or transforming products into services, there are also support processes that assist (directly or indirectly) the primary processes. This support process includes, but is not limited to, human resource management, financial resource management, procurement, equipment and fleet management, and IT systems management. IT has assumed a greater role in water management as a result of its increasing advancement (Akimov and Simshauser 2020).

1.4 Research Problem

The City of Johannesburg loses 38% of clean water due to leakages in the WDN (Sioga 2020), resulting in financial losses and the loss of water as a scarce commodity. The leakages are caused by a variety of factors, including pressure management, the age of the network, maintenance management, and skills. The onset of the fourth industrial revolution (4IR) provides

significant tools and systems to facilitate optimization of an aged water network. 4IR also delivers tools for pressure management and asset management, thus presenting an overall opportunity for water networks such as Johannesburg Water to reduce water loss. Therefore, there is a need to unpack which digital tools can be deployed for optimization of WDNs, advancing water as a digital business, which is the identified research gap (Sioga 2020). Additionally, there is a need to unpack how to deploy these digital tools for WDN optimization accordingly. Based on this knowledge, this research study seeks to address the research gap by achieving the following:

- Review international best practices on digital WDN and develop a digital WDN framework based on the review;
- Classify a database structure in support of the proposed sensor to ERP framework for a generic WDN;
- Explore tools and systems for optimization of WDN;
- Test and validate the theoretical structure for digital WDN with a case study; and
- .

1.5 Research aim and objectives

The aim of this study is to build a framework for the digitalization of WDNs. Based on international best practices, incorporating sensor to enterprise in design can serve as a best practice for entities in South Africa (SA). The development of a framework and an associated database serves as a tool to support the development of digital water systems that can be used in the City of Johannesburg and other cities or towns with similar problems to achieve the following:

- Create a single repository structure (sensor to ERP) for all data associated with WDNs;
- The development of a case study through incorporating lead organization data into this database and validating the database capacity;
- Determine the digital maturity of the WDN; and
- Develop and test system capacity to digitally mature into a fully capacitated digital water network.

1.6 Research Questions

The research questions are:

RQ 1: What is the international best practice in digital WDN management and optimization?

RQ 2: What is an optimum database design for a repository of all data associated with a digital WDN?

RQ 3: Can a SA WDN entity develop and validate a digital WDN management system to determine digital maturity?

1.7 Research Justification

Currently, there are different conceptual, technical, and practical perspectives on digital water systems, such as smart meters and smart pumps. However, there is no systematic consensus between the perspectives. To implement a digital WDN system, governments, water entities, researchers, and other concerned stakeholders must reach consensus on the structure, data, and tools that are required to develop a digital WDN (Li 2020). Therefore, there is a need to compare different perspectives, identify the best practices in digital WDN and classify database structures for the system. By comparing different perspectives, identifying best practices, and classifying database structures for WDNs with the aim of facilitating consensus amongst the aforementioned stakeholders, this justifies the purpose of this research study.

1.8 Significance of the research

On a global scale, the digital WDN framework contributes to innovation and the establishment of best practices in the digitalization of WDNs. As water utilities face challenges in managing water resources efficiently, the research provides a valuable blueprint for integrating advanced technologies and methodologies. The optimization of network performance, reduction of water loss, and improvement of operational efficiency, as highlighted in the framework, offer potential resource- and cost-savings for water utilities worldwide.

In the context of Johannesburg Water, the research offers a unique opportunity to enhance operational efficiency within the specific challenges faced by the utility. By validating the framework with real-world data from Johannesburg's water distribution network, the utility gains tailored insights into optimizing the local system's performance. Implementation of the framework, coupled with the configuration management database (CMDB), can lead to improved resource management, streamlined asset maintenance, and a reduction in water losses. Additionally, the applicability of the framework to real-world data enables Johannesburg Water to make informed decisions regarding infrastructure planning and upgrades, ensuring effective resource allocation to address the evolving needs of the city.

The impact of the research extends beyond utility operations to the communities served by Johannesburg Water. Improved water distribution, reduced service interruptions, and enhanced water quality directly contribute to a better quality of life for residents. Moreover, the research aligns with smart city initiatives, supporting Johannesburg's efforts to create a technologically advanced and sustainable urban environment.

Chapter 2 – LITERATURE REVIEW

2.1 Introduction

Water is a fundamental resource, serving countless activities within a city. Consistent and reliable delivery of water, along with effective management of wastewater, plays a crucial role in ensuring the health, operational efficiency, and advancement of urban areas (Nikolopoulos *et al.* 2018). The infrastructure of the urban water cycle (UWC) comprises elements such as the water distribution network (WDN), urban drainage system (UDS), drinking water treatment plant (DWTP), diverse water sources, and the end-users of water (Peña-Guzmán *et al.* 2019). The cyclical process of water supply and management plays an essential role in ensuring a consistent and reliable water supply within cities (Peña-Guzmán *et al.* 2019). However, it is crucial to recognize that the increasing threats to environmental and water resource security stem from the complexities of urbanization and climate change (Koop and van Leeuwen 2017). Tackling these challenges necessitates the establishment of resilient and effective management systems within the UWC.

Effective management of UWC systems is critical for overcoming these challenges and sustaining the continuous circulation of water within the urban environment (Sun, Puig and Cembrano 2020). By implementing reliable and efficient water management practices, cities can enhance resilience in the face of urbanization pressures and the uncertainties posed by climate change. Implementing this proactive strategy is vital to ensuring the availability and quality of water resources, ultimately safeguarding the well-being and prosperity of urban populations.

It is a common practice for different water authorities to operate the WDN and urban drainage system (UDS) separately, each aligned with its own set of organizational objectives (Christodoulou *et al.* 2017). Furthermore, both of these systems comprise numerous subsystems that often operate independently of each other. However, it is WDN that frequently encounters substantial challenges. The WDN encompasses a multitude of components, including pipelines, pumps, valves, reservoirs, storage tanks, and an array of sensors such as flow meters and pressure meters. Alarming, global statistics indicate that the world loses approximately 35% of clean water due to leakages within the WDN (Liemberger and Wyatt 2019). This loss not only leads to financial ramifications but also contributes to the depletion of precious resources. The significant water losses observed underscore the urgent necessity to optimize the WDN. By doing so, these losses can be minimized, ensuring a more efficient use of this valuable resource while simultaneously mitigating financial setbacks and alleviating the strain on our limited water supplies.

Various factors contribute to leakages, including inadequate pressure management, the aging of the network, insufficient maintenance oversight, and a lack of necessary skills (Szpak 2020). The onset of 4IR provided significant tools and systems to facilitate the optimization of an aged water network. 4IR also delivers tools for pressure management, water quality monitoring, and asset management (Dall'Omo 2017).

As previously highlighted, leakages within WDNs cause a global loss of 35% of clean water. It is noteworthy that, although this statistic indicates a substantial portion of water loss, smaller and medium-sized leaks within distribution networks frequently escape detection or receive less emphasis (Seyoum *et al.* 2017). These smaller leaks, although individually less dramatic than larger leakages or pipe bursts, can collectively contribute to substantial water losses over time. Further, they may also contribute to the aging and deterioration of the infrastructure, potentially leading to more significant and costly issues in the future.

The leaks can also go undetected below the ground, and some leakages are not reported on time or not reported at all by the communities (Moni 2020). When considering water loss from individual small and medium-sized leaks may make the repair seem inconsequential; however, the cumulative effect of sustained water loss over time amounts to a significant overall depletion. The rate of water loss fluctuates based on the leak type, severity, and pipe pressure. For instance, a leakage from toilet cisterns can lead to an approximate loss of 10 liters per day. (Vaverka *et al.* 2021). A leakage from a dripping tap can result in losses between 3 and 7 liters per day; and a leakage from visible leaks can result in a loss of more than 340 liters per day (Alarefi and Walker 2017). There are several techniques to deal with the management of leakages. Four primary components constitute the management of leakages (Aboelnga *et al.* 2018) namely,

- Quantifying water loss,
- Leakage monitoring,
- Network pressure and asset management, and
- Leak detection, location, and repair.

Having all four components of leakage management can help quantify water losses, monitor pressure in the distribution, measure the amount of water lost, detect leaks, and repair them. However, these endeavors come with substantial costs. Water utilities primarily concentrate on leak management through the detection and localization of leaks within the water distribution network (WDN). Leak detection involves proactive measures to identify the precise location of a leak (Seyoum *et al.* 2017).

2.1.1 Water loss quantification

Quantifying the annual volume of water lost from the network is the initial step in optimizing the WDN and reducing water losses. Achieving this objective involves employing diverse methods. In 2019, Liemberger and Wyatt (2019) determined the global water loss volume by utilizing the International Water Association Table 1.1 as extracted. The study underscored that the global non-revenue water (NRW), encompassing water lost from the water distribution network (WDN), including unpaid water like stolen water, amounted to 346 million cubic meters, equivalent to 126 billion cubic meters annually, with an estimated financial value of USD 39 billion per year. To ascertain the non-revenue water volume, the study calculated an average domestic water consumption for each country based on the available data. Additionally, a provisional volume of 30% was incorporated to account for non-domestic water usage (Liemberger and Wyatt 2019). The system volume input (SIV) was estimated, based on total consumption and a percentage of

NRW from previous studies, and finally, NRW was calculated. This method measures the volume of water lost and determines if there are leaks in the District Metered Area (DMA). However, it does not address the problem of pressure in the WDN; it also does not locate the leakages in the WDN.

Another method that is commonly used to quantify water losses in a WDN is the International Water Association's (IWA) water balance. This approach is applied to determine the water losses in a WDN or DMA. To calculate the volume of water losses, all input and output volumes are determined up to customer metering. It is crucial to accurately measure both the system input volume and authorized consumption, which includes both paid and unpaid water (such as water provided for free to facilities like parks) (Mastaller and Klingel 2017). The authorized consumption is measured using a digital meter. This procedure goes hand in hand with flow rate monitoring in the meters.

Table 2.1: The International Water Association (IWA) water balance (Alegre et al. 2016).

System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption (including water exported)	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorized Consumption	Unbilled Metered Consumption	Non- Revenue Water (NRW)
			Unbilled Unmetered Consumption	
	Water Losses	Apparent * Losses	Unauthorised Consumption	
			Metering Inaccuracies	
		Real * Losses	Leakage on Transmission and/or Distribution Mains	
			Leakage and Overflows at Utility's Storage Tanks	
Leakage on Service Connections up to the measurement point				

Minimum night flow is another water loss-quantitative method that is commonly used. The data collection for a minimum night flow should occur in a time interval where there is a minimum consumption of water. In many WDNs, this is usually at night, hence the name minimum flow. The best time to collect minimum night flow data is between midnight and 4:00 (Maggs 2020). The

NMF includes the estimated unavoidable background losses (small leaks in WDN) and nighttime domestic water usage, mainly from toilets and non-domestic use. To determine the volume of leakage in a DMA, the estimated values of unavoidable background losses, domestic and non-domestic, are subtracted from SIV. For advanced uses, the NMF can be used to calculate the trigger value for intervention. The trigger value for intervention marks the threshold at which action should be taken, prompting the initiation of an active leakage detection survey within that specific DMA. The NMF is comparable in the small areas (e.g., DMA) where the water usage events can be seen. In large WDNs without DMAs, this method is not comparable because the water usage at night cannot be accurately determined.

2.1.2 Network pressure and asset management

Pressure is a variable directly influencing failures or leaks in the WDN, capable of worsening an existing leakage. It is for this reason that monitoring the pressure is important. Sustaining pressure stability in a WDN involves assessing pressure fluctuations and implementing pressure management tools to guarantee consistent operating conditions. Such a tool can be a pressure reduction valve. Özdemir et al. (2021) examined the impact of pressure on water losses and minimum flow (MNF). To ascertain the number of leakages considering pressure changes, the Fixed and Varied Area Discharge (FAVAD) approach was utilized. In a hydraulic model, the minimum flow rate and potential leakages within the water distribution network (WDN) were initially established under the network operating conditions in a specific study region. Subsequently, a pressure reduction valve was employed to decrease pressure, and the resulting leaks and MNF were determined. Upon reducing the pressure from 9.10 bar to 3.2 bar in the region, the minimum flow rate (MNF) decreased from 6.95 l/s to 3.29 l/s. This shows that a pressure management system can reduce water losses; in this case 28.624 m³ was saved annually.

Pressure stands as a pivotal variable directly impacting the incidence of failures and leaks within WDNs (Güngör, Yazar and Firat 2017). Fluctuations in pressure can impact the behavior of existing leaks, making pressure monitoring an essential component of effective network management. Ensuring pressure stability in a water distribution network (WDN) requires identifying pressure fluctuations and deploying pressure management tools for consistent operating conditions. A commonly employed tool for this purpose is a pressure reduction valve.

A study conducted by (Özdemir *et al.* 2021) investigates the impact of pressure on both water losses and minimum flow (MNF). The study utilized the fixed and varied areas discharge (FAVAD) approach to calculate the number of leakages based on pressure changes. In the initial phase, the study determined the minimum flow rate and potential leakages within the WDN under its operating conditions. Subsequently, pressure reduction was implemented in a specific study region using a pressure reduction valve, and the resulting impact on leaks and MNF was assessed.

The study's results indicated a notable decrease in MNF when the pressure was reduced from 9.10 bar to 3.2 bar in the specified region. This reduction in pressure was associated with a

decrease in the MNF rate from 6.95 liters per second to 3.29 liters per second. This compelling evidence underscores the effectiveness of a pressure management system in reducing water losses. In the case study conducted by (Özdemir *et al.* 2021), the implementation of pressure management resulted in an annual water savings of approximately 28.624 cubic meters.

These findings emphasize the importance of actively monitoring and managing pressure within WDNs as a valuable strategy for curbing water losses and optimizing water distribution systems.

A) **Pressure turbine**

Another way to control pressure in a WDN is by using a pump as a turbine (PAT). In this approach, pressure reduction valves (PRV) are replaced by a special pump (PAT) that can also act as a turbine to produce energy. Reducing both water leakage and energy losses in a WDN is necessary to increase efficiency and reduce the energy impact (Fecarotta and McNabola 2017). By placing the PATs in an appropriate location in the WDN, pressure control and energy production can be achieved. A genetic algorithm (GA) can be used to determine the optimal position of PATs in a system. The use of a GA to position the PATs has been proven effective in Andishe WDN in Tabriz Province, Iran, where pressure control and leak reduction were achieved, and 7,284 kW of electricity were produced per day (Jafari *et al.* 2015). However, the use of PAT has its own limits. It cannot be used in WDNs that do not have high water pressures.

2.1.3 Monitoring flow rate, water quality and pressure

Supervisory Control and Data Acquisition (SCADA) systems find extensive use in overseeing and regulating water flow within WDNs. (Bruno *et al.* 2021). These systems are integral for overseeing and controlling various structures and components in the network, including water tanks, dams, pipelines, water pumps, and water elevation stations (Val Ledesma, Wisniewski and Kallesøe 2021). SCADA systems operate through computer and network connections, facilitating remote management and automation of these critical infrastructure elements. SCADA systems gather data from an array of sensors strategically distributed throughout the WDN. These sensors measure parameters such as water flow, pressure, temperature, and water quality. The collected data is transmitted to a central controller, where it is processed, analyzed, and managed. Operators can remotely monitor and control various aspects of the network's operation through the SCADA interface. In certain scenarios where wired communication is impractical or cost-prohibitive, SCADA systems may utilize wireless communication technologies. Wireless connections enable data transfer in areas where running physical wires may not be feasible (Bruno *et al.* 2021).

However, the adoption of wireless communication in SCADA systems introduces a significant challenge, such as cybersecurity risks (Franco *et al.* 2019). The use of wireless communication exposes SCADA systems to potential cyber threats, necessitating robust security measures to safeguard the integrity and functionality of the system. It is important to emphasize that while SCADA systems are a vital component of modern water management, they alone do not solve water leakages or quantify them. Instead, SCADA systems serve as a critical tool for utilities,

enabling them to detect and respond promptly to issues within the WDN. They provide real-time insights into network performance, allowing for more efficient operation and proactive problem-solving to mitigate water losses and enhance system reliability.

2.1.4 Leak detection, location and repair

As of the present day, some water utilities continue to rely on manual techniques for locating leakages within their WDNs. In the organizational structure of Johannesburg Water, the Physical Loss Section is an integral component of the Technical Services Division, situated under the jurisdiction of the Operations Department (Nthutang and Telukdarie 2018). This section comprises 49 employees stationed at various regional offices of Johannesburg Water.

The primary goal of the Physical Loss Section is to mitigate and diminish water losses within the WDN. To attain this objective, the section utilizes various interventions, encompassing active leakage control, pressure management, and water zone management. Active leakage control is a targeted strategy employed to detect and rectify all existing leaks within the network. This process often involves the use of ground microphones (Nthutang and Telukdarie 2018).

These manual techniques and interventions are crucial for water utilities like Johannesburg Water to proactively address water losses, optimize network performance, and conserve this valuable resource. While technology such as SCADA systems can aid in monitoring and detecting issues, hands-on approaches like active leakage control remain essential for pinpointing and addressing leaks effectively within the WDN.

Visual Inspection (VI)

Visual Inspection (VI) stands as the conventional method for identifying water leaks within a WDN. The process involves walking along a pipeline to identify wet spots caused by leaks (Ayadi *et al.* 2019). Additionally, to inspect prospective leaks, experienced personnel must be present. The supervisory approach underwent further development (Wu *et al.* 2018), transitioning to the utilization of satellites, drones, and videos. These technologies capture the environment and deliver real-time, three-dimensional (3D) images to the end-user. Visual inspections have the capability to identify bursts and various other types of pipeline issues (Wu *et al.* 2018). In the past decade, utilities have been introducing new technologies to supplement or add on the tech tools that are already in practice, such as the technologies mentioned by Wu *et al.* (2018) to digitalize the WDN.

2.2 Digital water distribution system: Applicable Technologies and benefits

The projected increase in the global population living in urban areas to 70% of 9.7 billion by 2050 underscores the ongoing trend of urbanization. The trend is marked by an increasing population shift from rural to urban areas, driven by the pursuit of better opportunities and enhanced living conditions. As urbanization continues to shape the world's demographics, it presents several significant challenges (World Health Organization 2019). Apart from the challenges posed by swift

urbanization, population expansion, climate change, and resource limitations, these issues give rise to significant problems in urban infrastructure, urban planning and management, as well as water and wastewater services. (Koop and van Leeuwen 2017). Currently, the world loses 35% of its clean water due to leakages in the WDN (Liemberger and Wyatt 2019). This results in financial losses and a loss of scarce commodities. Various factors contribute to leakages, encompassing pressure management, the age of the network, maintenance oversight, and the proficiency of skills (Szpak 2020). In response to the challenges confronted by water utilities, numerous water corporations are steering towards the digitalization of water systems and the adoption of integrated water management. Alabi et al. (2019) characterizes Water 4.0 as the “digital transformation of the water sector, with the objective of disrupting various facets of the water industry to enhance its efficiency”. The argument presented by Gupta and Kulta (2018) highlights the transformative potential of smart water management technologies and digital management systems in WDNs. Their assertion that these technologies, when combined with faster response times, can lead to a significant improvement in water reliability and substantial reductions in losses underscores the importance of adopting modern approaches to managing water resources. The global water industry's shift towards a new era of water management is driven by several factors, including the need for greater efficiency, sustainability, and improved service delivery.

Before the realization of 4IR and digitalization, WDNs' operational technology systems, for example, SCADA, were isolated from IT systems and other systems within an enterprise. The advent of the Fourth Industrial Revolution (4IR) introduces technologies like big data analytics (BDA), blockchain, simulation and modeling semantics, cloud computing, automation, Cyber-Physical Systems (CPS), Industrial Internet of Things (IIoT), and robotics (Ghobakhloo 2020). To digitalize the WDN and take advantage of some of these incoming technologies, operational technology systems such as SCADA should unveil the data to other systems (e.g., IT systems) within and/or external to the enterprises. This endeavor aims to bridge the gap between SCADA and IT networks of entities, facilitating real-time data acquisition and seamless information transfer to the management level, thereby improving data-driven decision-making (Shilenge and Telukdarie 2021). Currently, in WDN many operational processes, such as checking for leakages, monitoring water quality, and reading meters, are handled manually. In an era characterized by a diminishing yet more educated workforce, the implementation of digital solutions is anticipated to streamline manpower needs and optimize work processes through the automation of mundane tasks (Bhadra 2019). Anticipated benefits of a digital WDN include:

- **Provide customers with real-time water consumption information to help customers make informed decisions:** The implementation of a digital WDN will facilitate real-time feedback on water and energy usage for customers, utilizing technologies such as automated meter readings and smart water-saving devices. This empowers customers to make informed decisions regarding water conservation in their homes and workplaces. Additionally, automated meter readings contribute to more accurate demand forecasts, optimizing pumping schedules, water reservoir turnover, and assessing the required quantities for water pumping and treatment. (Liu and Mukheibir 2018; Curry *et al.* 2019).

- **Monitoring the condition of assets in real-time for preventive maintenance:** Leveraging advanced sensing technologies allows for the creation of risk-based models for pipeline replacement projects. Through this approach, water utilities can enhance the planning and scheduling of pipe replacements and rehabilitations, ensuring that the appropriate pipes are replaced at the optimal time (Li, Yang and Sitzenfrei 2020).
- **Monitoring water pressure and water quality in real-time to improve planning and network operations:** Water utilities can continuously monitor hydraulic and water quality conditions across their networks through real-time sensor and meter data. The prompt detection of leaks and early identification of pipe stress help mitigate the risk of pipe bursts, minimizing water loss by pinpointing the location of leaks. Monitoring water quality in distribution pipelines is critical for ensuring the safety and reliability of a water supply system. In the event of issues, automated valves can respond by closing off valves in affected areas to prevent flooding, mitigate further damage, reduce water loss, or prevent the spread of contaminated water. Additionally, real-time sensor data not only aids in the calibration of hydraulic models but also offers an alternative to the traditional calibration process, which is costly, time-consuming, and laborious (Creaco *et al.* 2019).

Overall, water 4.0, or digital WDN, is driven by several technologies. The incorporation of cyber-physical systems (CPSs) and digital twins will contribute significantly to the overall management and operations. Blockchain will have a major impact on the water utility business model (Giudicianni *et al.* 2020). In the following subtopics, further information is provided in references to some of the 4IR technologies that are relevant to water 4.0, or digital WDN.

2.2.1 Robotics

Manufacturing and in hazardous environments that are deadly and risky for humans, for example, search and rescue and military operations are increasingly deploying robots with sensing capabilities and artificial intelligence. Robots can perform some of the tasks much faster, more consistently and more accurately than humans (Delmerico *et al.* 2019). The increase in the use of robots results in job losses and reduced wages across various economic sectors (Acemoglu and Restrepo 2020). However, the benefits of using robotics are proving to be rewarding in terms of improving human lives.

Practical application examples

Within the water sector, autonomous underwater and surface-water vehicles serve a crucial function in the modeling of water quality. These robots are equipped with pH sensors, temperature sensors, and turbidity sensors, enabling them to offer comprehensive spatial coverage of water quality across extensive areas, even at significant depths, and in real-time (Amaran and Mohan 2021). Another area of application for robots is the structural condition of underground assets. This is because the underground assets are difficult to inspect. Inspecting underground assets typically involves non-destructive methods utilizing a CCTV camera or, alternatively, destructive approaches that require removing a short section of pipe for inspection. However, these methods

come with significant costs, potential service interruptions, and the inspection coverage is limited, addressing only a small percentage of the network. Robots offers assessments of underground assets, offering valuable data to support asset management planning (Savić 2022).

2.2.2 Digital Twin

Digital twins are progressively gaining utility as decision-support tools for the management of operational water systems within the water sector. These digital twins function as dynamic digital representations of real-world systems, continually updated with data to simulate their past, present, and future behavior (Redelinghuys, Basson and Kruger 2020). In a practical application, a digital twin was implemented for a water supply system catering to 1.6 million residents in Valencia, Spain, showcasing how it could simulate diverse network operating scenarios. The emergence of digital twins opens up a new avenue for an immersive and engaging modeling experience that includes serious gaming and encounters with augmented, virtual, or mixed augmented and virtual reality. This has the potential to captivate a diverse range of stakeholders (Conejos Fuertes *et al.* 2020). Through the integration of these technologies, various stakeholders, including operational personnel, planners, end-users, and regulators, gain the capacity to gain insights into the intricate dynamics of water systems, conduct safe experiments within the digital twin environment, appreciate diverse perspectives, and formulate strategies aimed at discovering more sustainable solutions (Conejos Fuertes *et al.* 2020).

2.2.3 Blockchain

The concept of blockchains involves envisioning a decentralized database where records are segmented into blocks, creating a linked chain. The information within each block constitutes only a partial representation of the complete dataset. As a result, the partitioning of the records into blocks ensures a secure and safe exchange of information between multiple stakeholders (Niranjanamurthy, Nithya and Jagannatha 2019). This advancement marks a substantial stride in mitigating data security concerns linked to the emerging domain of digital water business (Pappas *et al.* 2018). The information blocks can be viewed as nodes in the network and their interactions as links. The integration of blockchain technologies into intricate networks introduces new paradigms regarding database synchronization and control. Additionally, it opens avenues for utilizing machine learning models to optimize database management and representation (Jamil *et al.* 2020).

2.2.4 Cyber-Physical Systems and the Internet of Things

Smart water grids, or digital WDNs, are directly related to CPSs (Tsakalides *et al.* 2018). Digital WDN is related to CPSs because, like CPS, it has sets of sensors, smart monitors, and actuators that are embedded throughout the infrastructure. A CPS is able to communicate effectively using the IoT and make optimal decisions both hierarchical and distributed through the IoT. In addition to SCADA and near-real-time water system management, the benefits of Cyber-Physical Systems (CPS) encompass, but are not restricted to, providing an online perspective of the hydraulic state within a Water Distribution Network (WDN), enhancing safety and security, detecting water

contamination, and optimizing overall system performance (Wolf and Serpanos 2017; Barrère et al. 2020; Vrachimis et al. 2020).

2.2.5 Big data

The big data revolution is universally acknowledged as one of the most pivotal technologies capable of enhancing productivity and efficiency in water operations (Wu et al. 2016). Adamala (2017) described big data as

Data characterized by high volume, velocity, and variety necessitates the application of novel technologies and techniques for its capture, storage, and analysis. This type of data is employed to improve decision-making, offer insights and discoveries, as well as support and optimize various processes.

In addition to social media platforms and internet data, big data can be gathered from, but not limited to, GPS data, manufacturing data (e.g., machinery data), mobile data, water data, business data (i.e., customer information and inventory data), daily transactional data (e.g., business data), public data (e.g., data from NGOs and universities), government-generated data sets (i.e., government agencies), industrial data and sensor-based data (Smirnov et al. 2021). Data can be analyzed by big data technology to find hidden patterns and trends. Global integration of big data technology into the water sector not only stands to benefit the entire industry but also offers numerous advantages to consumers. It provides the sector with a competitive edge and enhances the ability to serve customers effectively (Alabi et al. 2019).

A) Practical application examples

Global regions are plagued by water quality issues and climate resilience issues. Using big data, assets can be managed, and decision-making insights can be gained about pipe leakage. Since inaccurate data has adverse consequences, reliable data generated from reliable sensors is needed. Big data, behavioral science, and cloud-based platforms can be used to reduce utility energy consumption (Sahal et al. 2020).

2.3 Digital Water distribution network best practices

According to Quayzin (2021), best practices refer to the most efficient and effective methods for performing tasks, according to what has worked in the past. Given that best practices are constrained by limitations such as bounded rationality, limited validity, and a finite duration until new practices emerge, and acknowledging that they can serve as barriers to innovation, there is a need to actively challenge them through innovative approaches (Quayzin 2011). Utilizing best practices in operations brings about benefits such as cost savings, standardization, and process improvement.

Digital WDN best practices are digital systems that are proven to have worked on the WDN and have been practiced at least once worldwide, or the digital system approach has been peer

reviewed. Digital WDN is defined as the cluster of technologies for information creation and processing that are enabled by software, hardware, communication technologies, and other related services (Gartner, 2018). With the ushering in of 4IR, various digital WDN systems and tools are being introduced. These systems have different architectures, and they have different objects in the WDN. To standardize the application of these systems worldwide, a framework is needed, and to create a framework for such systems, a detailed review to understand their functionality and architecture should be conducted. Below, some of the best practices of a digital WDN are reviewed:

2.3.1 Machine learning for event management

United Utilities, a water company based in the United Kingdom, has made a significant investment in enhancing its event management system. They have adopted advanced event detection tools to offer nearly instantaneous alerts for various events, including water leakages, pipe bursts, irregular pressure or flow patterns, and sensor malfunctions. This system for identifying anomalies leverages a combination of self-learning artificial intelligence (AI), machine learning (ML) techniques, and statistical data analysis tools to autonomously analyze data from pressure and flow sensors. Typically, this sensor data is gathered at 15-minute intervals from various district-metered areas. It is important to note that anomaly detection methods can also be used to detect water quality anomalies (Qian *et al.* 2020). The traditional method for identifying water quality anomalies within WDN involves the random collection of potable water samples at predetermined intervals, which are then subjected to manual laboratory analyses (Qian *et al.* 2020). Some of the ML anomaly detection techniques that have been applied in the WDN include K-nearest neighbors (KNN), artificial neural networks (ANN), linear discriminant analyses, logistic regressions, support vector machines, recurrent neural networks, random forests, decision trees, extra tree classifiers, long short-term memory, passive aggressive classifiers, and the Ridge classifier (Sebestyen, Hangan and Czako 2021).

United Utilities has adopted an ANN as part of its anomaly's detection approach. A typical United Utilities WDN consists of multiple District Metered Areas (DMAs) (Romano *et al.* 2020). DMAs play a crucial role in enhancing the efficiency of WDN operations, as they facilitate the identification and isolation of problematic segments within the network. This targeted approach allows for more efficient repairs and minimizes disruptions for consumers. Further, DMAs contribute to the equitable allocation of water resources by accurately measuring consumption in specific regions, aiding in billing processes and resource management (Monks *et al.* 2019). DMAs are indispensable tools for water utilities, contributing to improved water efficiency, reduced operational expenses, and the continuous provision of clean water to communities (Romano *et al.* 2020).

The WDN uses pressure and flow sensors for data acquisition. The data from pressure and flow sensors installed across DMAs is acquired and stored with the help of the SCADA system; thereafter, the artificial neural network (ANN) uses the collected data to forecast the near-future operating values of the WDN (Romano *et al.* 2020). The forecasted values undergo analysis and are compared with new observations to identify significant deviations. Statistical process control

techniques are employed to analyze deviations in pressure and flow from the forecasted and observed signals. The evidence gathered is then input into the Bayesian network to assess the likelihood of event(s) occurrence. This process generates an estimate of the likelihood of an event occurring, which feeds into detection alarm mechanisms. The machine learning aspect of the system utilizes historical events to enhance the detection of future events (Romano 2020).

Romano (2020) provides insights on the capabilities of the system. On May 31, 2016, a 450-mm-diameter main pipe in the city of Formby in United Kingdom experienced a failure. The event management system identified the burst more than three hours before the residents of Formby could report any disruption on their end. The early detection of the burst enabled a swift deployment of responses. Another failure was identified by the system when the pressure-reducing valve failed to open. Early detection of this issue helped prevent a likely burst. Figure 2.1 shows the output of the event from the moment the failure occurred (the first high pressure peak from 8 September 2019 graphs) to the final stage of intervention.

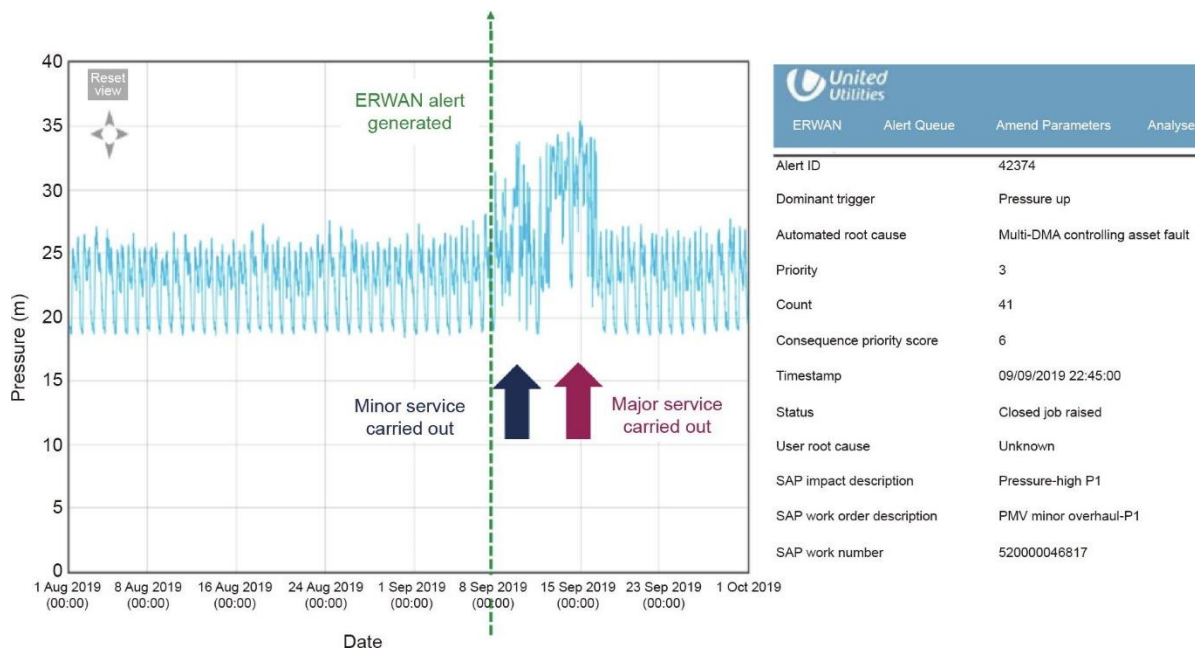


Figure 2.1: System alert indicating a sudden pressure increase, likely due to a faulty pressure-reducing valve (Romano 2020).

The Event Recognition in the Water Network (ERWAN) is used to visualize the event. The pressure increased from 8 September to 25 September and went back to normal between 15 September and 25 September 2019.

2.3.2 Software to optimize Water distribution network.

Software tools have been adopted by water utilities throughout the world. These tools serve different purposes, including hydraulic modeling and simulation. Examples of such software include Aquas, WaterCAD, EPANET, Synergi Water, and HydraulCAD, among others (Awe, Okolie and Fayomi 2019). The advent of the 4IR has led to the adoption of a new set of software tools with the ability to optimize WDN. An example of such software is the Water Wise System (WS2), a three-time winner of the H₂O challenge (World Summit Awards 2022). The Water Wise System is a software solution that empowers water utilities to read, store, and process substantial amounts of data from both the network and associated systems, unveiling fresh insights into operational knowledge (Figueiredo, Esteves and Cabrita 2021).

The W2S integrates real-time analytical and predictive components, incorporating geo-referenced data from both the network and external sources. This integration enhances the capability for real-time monitoring, control, and management of water supply networks (wakaru 2021). Serving as an event management system, the W2S is agnostic to specific equipment manufacturers or communication protocols. Consequently, it offers a comprehensive view of the entire ecosystem within the operational framework of a water network management organization (Figueiredo, Esteves and Cabrita 2021).

Figueiredo et al. (2021) emphasized that W2S represents a cutting-edge digital water solution, establishing a smart water network designed to reduce costs and boost operational efficiency through remote monitoring and control using sensors, devices, and automation. This solution converges analytical and predictive models, incorporating machine learning (ML) and deep learning (DL), presenting a value proposition that focuses on the integral real-time management of the water cycle. W2S leverages machine learning techniques to transform data into knowledge, identifying anomalies and providing a holistic view of the water network. This approach facilitates proactive measures to prevent and address issues such as service interruptions, losses, fraud, asset conditions and failures, communication glitches, supply and demand balancing, pressure and flow management, as well as water quality concerns (Figueiredo et al. 2021).

In the study, the emphasis was placed on W2S being a state-of-the-art digital water solution that establishes a smart water network. This network is crafted to diminish operational costs and elevate efficiency by facilitating remote monitoring and control through sensors, devices, and automation. The system achieves this by integrating analytical and predictive models supported by both ML and DL techniques (wakaru 2021). The fundamental value proposition of W2S centers on the real-time and holistic management of the complete water cycle, harnessing data to cultivate knowledge through the application of machine learning methods.

The W2S system provides a comprehensive view of the water network, proving crucial in proactively addressing and preventing issues such as service disruptions, losses, fraudulent activities, asset conditions and failures, communication glitches, supply and demand balance, pressure and flow optimization, as well as water quality concerns (Figueiredo, Esteves and Cabrita 2021).

In line with the previous point, a DL architecture enables Water Wise Systems to collect and describe data automatically and characteristically. Figure 2.2 shows the architecture of the W2S, in which various levels of representation of data are not linear. Each level can be trained independently to attain a higher abstraction level of the processed data. The output of one level serves as the input to the next level (Figueiredo, Esteves and Cabrita 2021).

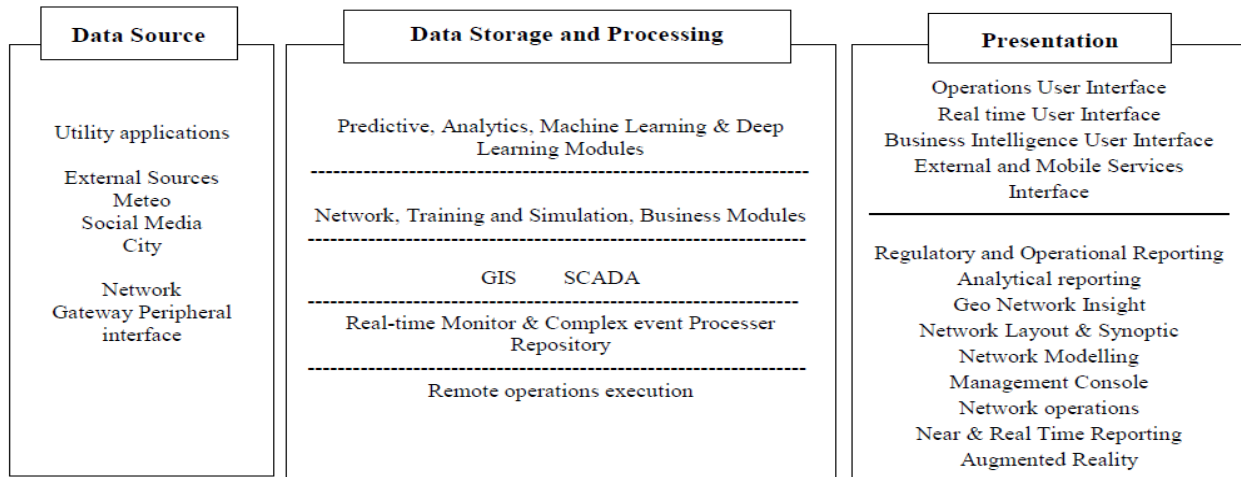


Figure 2.2: Water wise logical architecture (Figueiredo et al.2021)

The research and development (R&D) efforts behind the W2S, achieved a notable milestone with the creation of a novel hardware sensor designed for integration at critical junctures within the WDN (wakaru 2021). This innovative sensor, known as a hydrogenator, is equipped with an energy control system. Its primary purpose is to provide continuous and secure energy independence to the existing District Metered Areas (DMAs). This breakthrough has facilitated the installation of additional sensors that rely on energy or batteries, which were previously deemed cost-prohibitive or logistically challenging to implement. Consequently, this advancement has enabled DMA entry points to be outfitted with a greater number of remote network-manageable sensors for in-depth analysis, thus ushering in a transformative shift from DMAs to Intelligent Operation Zones (IOZs) (Figueiredo, Esteves and Cabrita 2021). Figure 2.3. highlights some noteworthy highlights of W2S in this context.

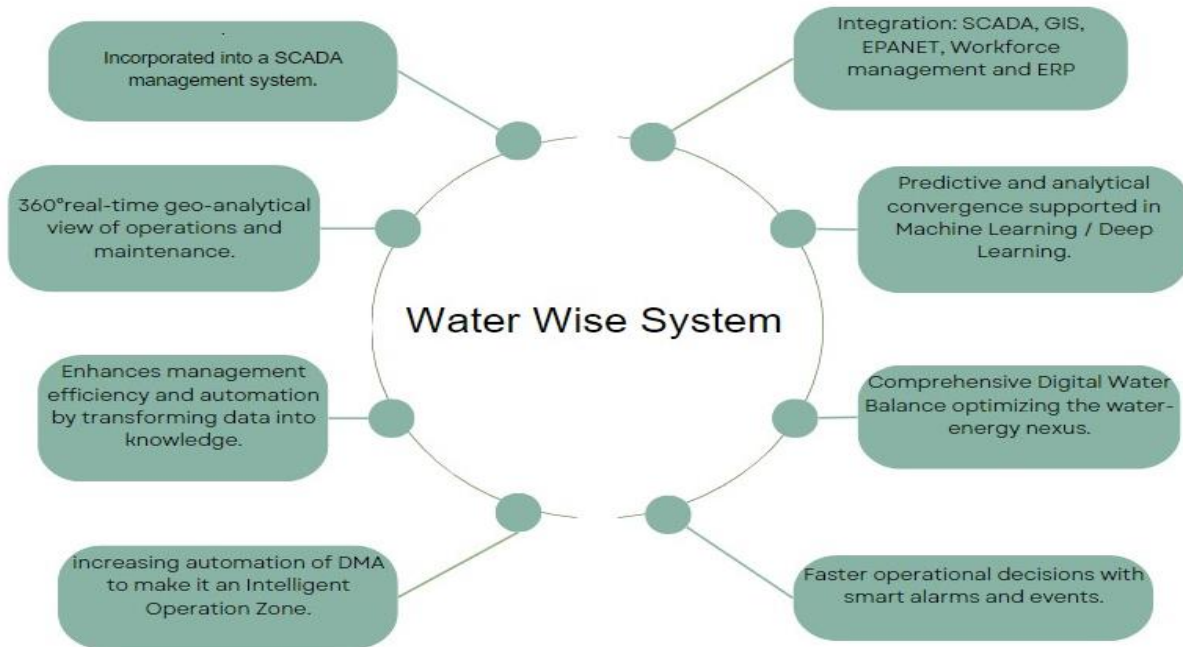


Figure 2.3: Water wise system capabilities (wakaru 2021).

Through intelligent data analysis, water authorities can discern various types of consumers, end-users, or businesses while also pinpointing irregularities in water consumption (Andrić *et al.* 2022). Such anomalies could signify issues like leaks or other disruptions in the water supply system. Consequently, the Water Wise System (W2S) serves a dual purpose: functioning both as a smart meter and as an event detection system within a single WDN (wakaru 2021).

The data utilized in this system is typically sourced from smart meters equipped to transmit meter readings (De Craemer and Deconinck 2010) and information through a dedicated radio protocol tailored for the monitoring system's requirements. Subsequently, this monitoring system collects and transmits the data from these smart meters to a cloud-based platform. Within the cloud platform, the data streams undergo processing, and subsequently, the platform delivers almost real-time information to end-users through the Water Wise System. Figure 2.4 presents the architectural framework for this entire process.

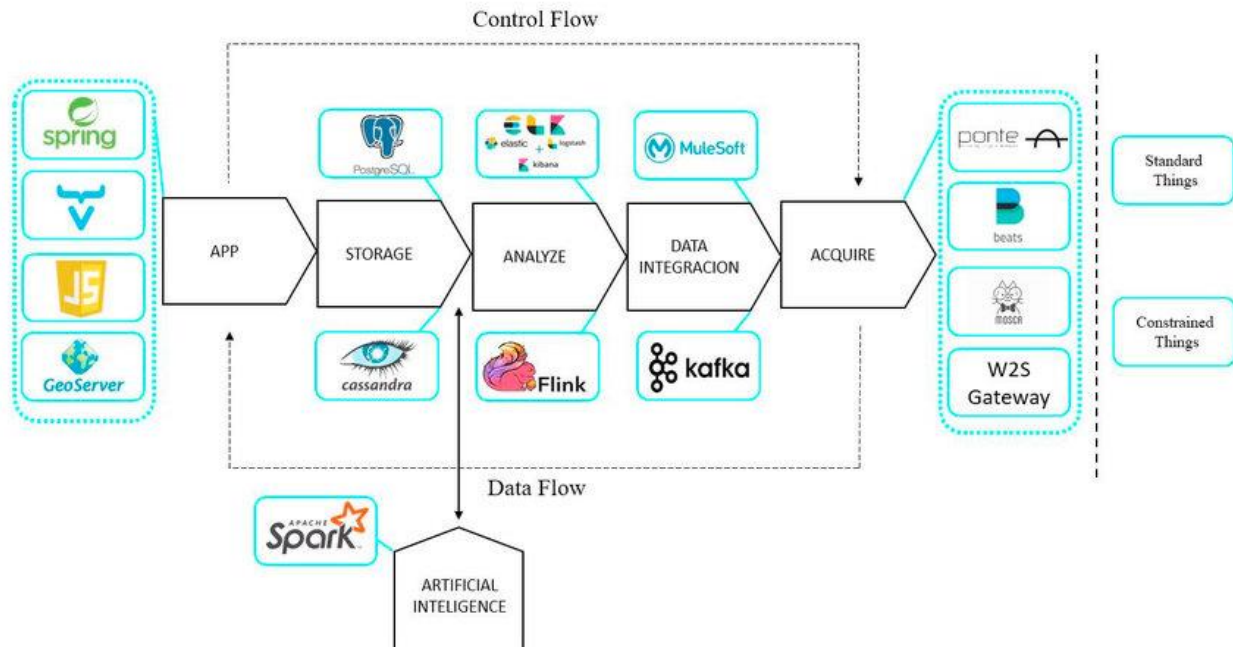


Figure 2.4: Water wise system architecture (Figueiredo et al. 2021)

The depicted architecture, as shown in Figure 2.4, encompasses multiple layers, commencing with data acquisition and ending in the end-user application. The technologies employed are open source and enjoy widespread industry adoption, rendering them reliable for the water utility sector. To gain a comprehensive understanding of the architecture (Figueiredo, Esteves and Cabrita 2021), it is essential to provide descriptions for the individual layers:

- **Acquire:** This layer is responsible for the collection of water sensor data, which encompasses both standard and constrained sensors. It then transmits this data to the subsequent layer. The communication technologies utilized in this process within the Internet of Things (IoT) framework include Eclipse Ponte, serving as a versatile IoT/Machine-to-Machine broker; Beats, providing a secure file transfer mechanism; MOSCA, functioning as a data encryption mechanism; and custom gateways specifically designed for water utility applications in cases where other technologies are deemed unsuitable.
- **Data integration:** The primary objective at this level is to integrate sensor data alongside third-party sources, such as weather information. The key requirement is to establish a continuous data stream to effectively process the substantial volume of data, including that transmitted by the water sensors. The Kafka technology stack oversees the data streaming aspect, while the Mulesoft Enterprise Service Bus (community edition) facilitates communication with external entities.
- **Analyze:** Data analysis plays a crucial role in identifying critical events for water network management. Utilizing Apache Flink, a sophisticated and complex event-processing

technology, facilitates real-time event detection. Additionally, the ELK stack (Elastic Logstash and Kibana) is employed to efficiently search through extensive data logs.

- **Storage:** This level integrates two database systems: PostgreSQL, which supports the application, and Cassandra, serving as a big data repository responsible for storing all the incoming data.
- **Artificial intelligence:** To leverage the full scope of data stored at the storage level, multiple machine learning models are trained to offer valuable insights for improving water network management. To facilitate ML and DL processes, the Apache Spark stack has been adopted as the supporting technology.
- **App:** Through the integration of diverse technologies on both the front end and the back end, it becomes possible to develop an application that presents data from water sensors and empowers end users to oversee water assets. This data can be visualized in various formats, including a synoptic view, geographical representation, and analytics display. The frameworks suggested for constructing this layer include Spring, Vaadin, multiple JavaScript options, and GeoServer.

In summary, the W2S consists of six interconnected layers, each collaborating to deliver value to water utility operations.

2.3.3 Smart water grid management using LPWAN IoT technology.

LPWAN stands for "Low Power Wide Area Network," and it is a wireless communication network type specifically designed to connect devices over long ranges while consuming minimal power (Rubio-Aparicio *et al.* 2019). LPWAN technology is particularly well-suited for applications demanding low data rates, such as the IoT. In IoT scenarios, where sensors and devices need to transmit small amounts of data over considerable distances for extended periods without frequent battery replacements, LPWAN proves highly efficient (Chaudhari, Zennaro and Borkar 2020).

Several LPWAN technologies exist, encompassing Long Range Wide Area Network (LoRaWAN), Sigfox, Narrowband IoT (NB-IoT), and LTE for Machines (LTE-M) (Ikpehai *et al.* 2018). These LPWAN technologies cater to different use cases and have varying network architectures and business models. The choice of which LPWAN technology to use depends on the specific requirements and constraints of the application in question (Ikpehai *et al.* 2018).

A LoRaWAN was implemented in Mori village, located in the south-eastern delta of Andhra Pradesh, India, as part of a study conducted by Saravana and Iyer (2017). The authors assert that Mori village, like many other villages in India, grapples with issues related to the contamination of clean water by sewage, inadequate water treatment, irregular water supply, and ineffective management of flow control gates. To tackle some of these challenges, a low-power, long-range system was implemented, enabling intercommunication and real-time data generation (Leonardi *et al.* 2019; Saravana and Iyer 2017). This system has the capability to autonomously alert the relevant authorities, eliminating the need to rely on community members for complaints. Consequently, this reduces response times, potentially minimizing water losses in cases of leaks

or pipe bursts. The system comprises five key components: sensors, a LoRa module, a LoRa gateway, an Ericsson cloud, and a web page.

A) The sensors component

The sensor component plays a crucial role in data generation, and it is equipped with seven standard sensors connected to an Arduino microcontroller (Saravanan, Anusuya et al. 2018). This is a fundamental element in most IoT technologies. The advantage of using multiple sensors lies in their ability to provide diverse insights into water quality and water flow (Saravanan et al. 2018). The sensors include:

- **The Oxidation Reduction Potential sensor** generates water quality data based on the Standard Hydrogen Electrode (Yamin *et al.* 2020).
- **The pH sensor** Measuring the acidity or alkalinity of water involves assessing the concentration of hydrogen ions in the water (Cambra *et al.* 2018).
- **The salinity sensor** quantifies the water's saltiness level using electrical conductivity. Pure water exhibits high resistance to electrical conductivity (Kholimatussadiyah and Prijo 2018).
- **The level sensor** measures data concerning the water level in a tank or pipe. This sensor employs ultrasonic frequency technology to gauge heights (Ahmed, Zhou and Mathur 2018). Notably, it does not require direct contact with the water to measure the height (Shrenika *et al.* 2017).
- **The turbidity sensor** provides data on the turbidity of water within tanks or pipes. This sensor measures the amount of light scattered due to suspended solids, with less scattered light indicating lower turbidity (Trevathan, Read and Schmidtke 2020).
- **The temperature sensor** measures the temperature of the water, with a higher diode voltage indicating higher temperatures (Mazza and Raymo 2019).
- **The flow sensor**, the seventh integrated sensor connected to the Arduino microcontroller, assesses the water flow rate by counting pulses from its output (Tahir 2021).

These sensors, when used together, contribute to a holistic understanding of water quality and flow, rendering them invaluable in various applications. The sensors generate data that is passed to the upstream components.

B) The LoRa module

The LoRa module consists of two primary subcomponents: an Arduino microcontroller and a LoRa radio frequency (RF) module. The Arduino microcontroller physically connects to the sensor array and is capable of retrieving data from all seven attached sensors. The extracted data is real-time data acquisition, enabling the seamless transmission of data to the LoRa gateway through wireless communication (Saravanan, Das and Iyer 2017). This setup plays a critical role in ensuring the efficient collection and delivery of data from the sensors for further processing and analysis.

C) LoRa gateway

The LoRa gateway serves as a pivotal component in this setup, as it receives real-time data from the LoRa RF module via cables. The LoRa gateway is subsequently connected to a network server through a standard IP connection, allowing it to relay data to the cloud (Saravanan, Das and Iyer 2017). The LoRa module is configured to work in tandem with the LoRa gateway, with the gateway receiving data in the form of packets.

The LoRa gateway is equipped with a microcontroller that serves several essential functions. It can store data, monitor the connection status between the LoRa modules and the gateway, and issue instructions to the LoRa module as needed. This microcontroller ensures the efficient management of the data flow and connectivity within the system.

In addition to its core functions, the LoRa gateway is also connected to a GSM 3G dongle. This dongle plays a critical role in transmitting data to the Ericsson cloud, making it a crucial part of the data processing and transfer pipeline (Saravanan, Das and Iyer 2017).

D) Ericsson cloud

As per Saravan (2017), the Ericsson cloud serves as the repository for data transmitted from the LoRa gateway via the IP connection, where predictive modeling is executed on this data. Distinct data channels are established for information received from the gateway, distinguished by the LoRa module's device ID, which corresponds to specific locations. Besides its role in water quality monitoring and alert triggering, the analytical processing of this data is incorporated into the web page (Saravana and Iyer 2017). Alerts are dispatched to relevant authorities through SMS and email, as illustrated in Figure 2.5. The system diligently monitors sensor readings until the sensor values normalize and, in cases of anomalies, alerts higher-level authorities. By leveraging the centralized data records, the prediction model is employed for automated water quality monitoring and control.

In contrast, Manimegalai's study in 2020, titled "An IoT-based smart water quality monitoring system using the cloud," employed Firebase Cloud instead of Ericsson Cloud. Similar to the Ericsson-based approach, data was collected from the field using sensors and subsequently analyzed in the cloud.

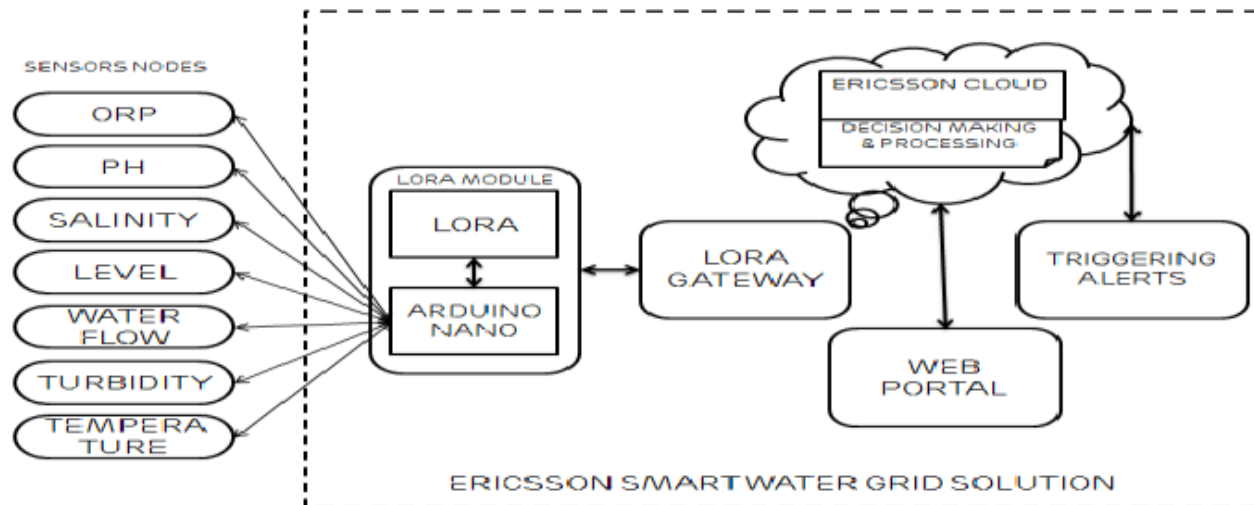


Figure 2.5: LPWAN architecture (Saravana and Iyer, 2017)

E) Web Pages

The web page is linked to the Ericsson cloud to fetch real-time data from the LoRa gateway, and it is accessible to the public. It includes a water quality gauge that visually represents water quality on a scale from 0 to 100. Utilizing the Google Maps API, the web page displays each sensor's value based on the location of the corresponding LoRa module (Saravana and Iyer 2017).

2.3.4 Detection and localization of leakages

The primary objective of water utilities globally is minimizing non-revenue water (Farok 2017). Nonetheless, the utilities encounter formidable challenges arising from the size, complexity, and predominantly subterranean nature of their systems. This subterranean infrastructure makes it difficult to pinpoint the precise locations of water losses or leakages. Several leak detection methods are available, with the majority concentrating on the identification of leaks in the primary pipelines (Zaman *et al.* 2020).

Water utilities prioritize the reduction of water losses by detecting and pinpointing leaks in the WDNs, primarily due to the costliness of water monitoring and pressure management activities (Darsana and Varija 2018). Consequently, the development of sensor devices has predominantly focused on professionally monitoring large-diameter pipes, primarily employing acoustic principles, like listening devices (Darsana and Varija 2018). Recent advancements in these devices aim to address issues such as user bias uncertainty by incorporating multiparameter measurements, including flow, pressure, noise, and even vibration. Moreover, modern technologies have introduced wireless solutions that include video cameras, microphones, acoustic sensors, and smart balls for active inspection in large-diameter pipes (Latif *et al.* 2022).

An example of a listening device is an acoustic leak detection method applicable to all types of pipes. This method comprises hardware, such as a hydrophone sensor, and software advances. The hydrophone sensor listens to the sounds and sends the signal to the software for interpretation (Seyoum *et al.* 2017). The software operates in a manner similar to the well-known Shazam mobile application, which is used to identify song titles and artists from short audio clips in noisy environments. It includes a mechanism designed to analyze and recognize audio data captured by sound sensors. Among the techniques employed for recognizing patterns in audio signals (time series), audio fingerprinting is one. However, for the software to effectively identify audio signals associated with leaks, it must be pre-trained using audio samples of leak sounds (Seyoum *et al.* 2017). This approach is capable of identifying and pinpointing the location of a leak, providing real-time information on its precise whereabouts based on the sensor's location; however, this method cannot detect pipe bursts because bursts make a different sound. Further, the approach is expensive because a lot of hydrophones need to be installed in WDN.

Accelerometers are sensitive and flexible sensors that measure acceleration. The small size of the accelerometers allows this sensor to be deployed without destruction and with ease. The sensors are convenient to use for effective event detection in water pipes. The acceleration values of leak-induced pipe vibrations on the surface are higher than those from other vibration sources (Tariq *et al.* 2022). As a result of this principle, accelerometers can measure the constant difference between acceleration values over time, thus enabling them to distinguish between leakage and leak-free situations (Marmarokopos *et al.* 2018).

2.3.5 Smart water metering and billing

The term "smart metering" has gained widespread recognition in technical literature and within utility sectors to describe systems that facilitate the remote reading of electricity, gas, and water meters. This capability enables real-time consumption monitoring (Luciani *et al.* 2019). Although water utilities have not fully embraced these systems, their popularity is increasing due to the associated advantages they offer, including streamlined water consumption billing and the detection of water losses at both the district and individual user levels (Ramos *et al.* 2019). In general, these systems employ smart meters equipped with integrated communication units, allowing consumption data to be accessed remotely. The manufacturers of the water meters typically use costly architectures for collecting data from these smart meters employed by water utilities.

Traditionally, water utilities have approached the management of water distribution as a nuanced endeavor, demanding a careful equilibrium between humanitarian concerns and economic efficiency (Salamé *et al.* 2021). This equilibrium, at times, resulted in disproportionately high costs in water management and intricate cost-sharing arrangements among various consumer categories (Adams, Zulu and Ouellette-Kray 2020). Billing for water consumption has consistently served as the predominant revenue source for water utilities (Pierce *et al.* 2021). Consumption metering and billing play a pivotal role in financing capital expenditures for new installations, daily operations, maintenance, and other essential activities. Over the past decade, utilities have endeavored to leverage communication and IT infrastructure for customer relations and billing

management (CRBM) (Monks *et al.* 2019). However, traditional water meters are not seamlessly integrated into CRBMs, impeding their capacity to provide real-time consumption data and unlock additional advantages. In the following discussion, we will delve into the structure of one of the proposed smart meters.

Smart Metering Architecture

Detailed information on the Smart-Meter system architecture proposed by Suresh, Muthukumar and Chandapillai (2017) for water distribution operations and CRBM can be found below. The proposed smart meter system comprises a hardware component known as the Electronic Interface Module (EIM) that attaches to the basic water meter (Suresh, Muthukumar and Chandapillai 2017). A schematic of the smart-meter architecture is shown in Figure 2.6.

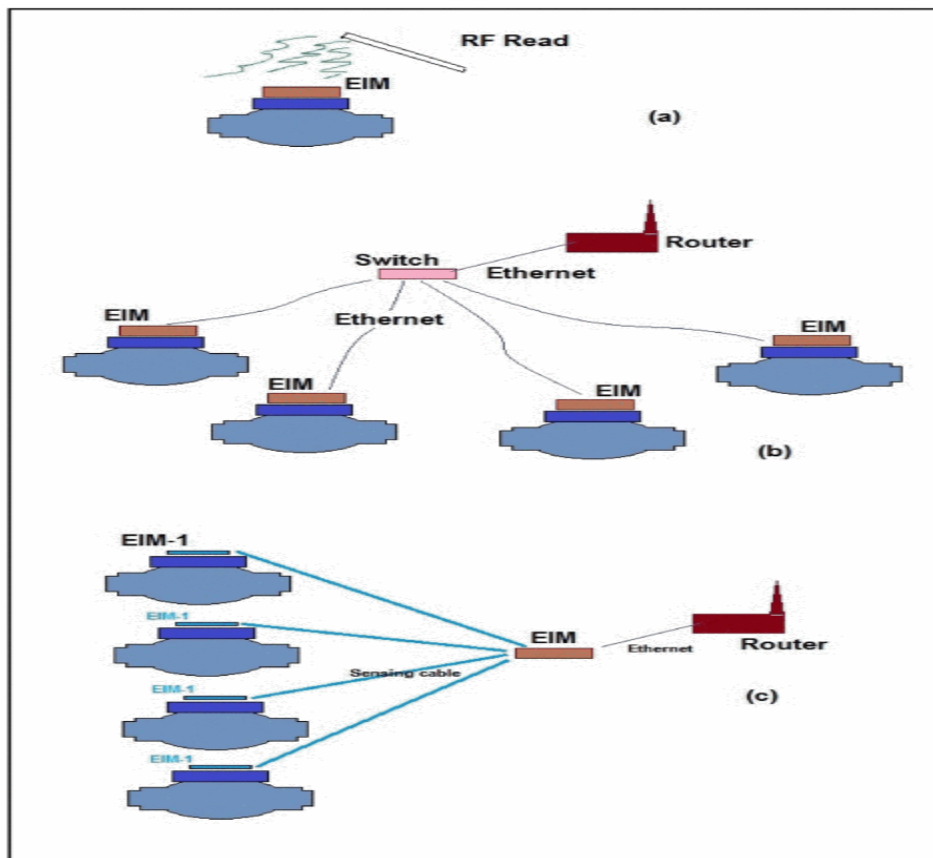


Figure 2.6: Smart metering architecture (Suresh *et al.* 2017)

Meters establish connections with smartphones through EIM (over Wi-Fi or Bluetooth). Users can utilize the smartphone Metering App to send queries for polling meter readings, which include

date-time stamps, tamper flags, and meter IDs. It's important to note that EIMs with smartphone communication features, such as Wi-Fi or Bluetooth, will require periodic charging of their batteries. Opting for batteries with high power ratings may increase both the initial and maintenance costs. This system is typically recommended for bulk water meters used in large-scale consumption monitoring or for monitoring flow in distribution branch pipelines (Chaudhari, Zennaro and Borkar 2020).

Smartphone App for Metering and Diagnostics

The Android SDK and Java were utilized in the development of the smart meter reading and diagnostics application. This multifaceted application empowers users to configure and tag water meters with consumer ID and address details in the Customer Relations and Billing Management (CRBM) system. Through the application, users can execute meter diagnostics, checking date-time information, obtaining the unique meter ID, reviewing tamper-flag statuses, saving live consumption records, retrieving periodic logs (hourly data), and accessing other relevant information from the EIM. Further, users can update meter consumption records to the CRBM system after secure login access, view consumption records from previous billing cycles, and analyze monthly consumption trends for registered meters based on CRBM records. This functionality allows consumers to assess losses, curb over-consumption, and plan for water conservation (Suresh et al. 2017).

2.4 Current Challenges faced by digital WDN.

In the management and science of water, enormous amounts of data are produced that come with challenges related to the 4Vs of big data: volume, velocity, veracity and variety (Stanley and Gunn 2018). Within the water industry, big data technologies offer significant benefits for enhancing decision-making and forecasting favorable outcomes. These technologies are particularly effective in synergy with the latest generation of sensors, which are characterized by their improved accuracy, smaller form factor, and cost-effectiveness (Stanley and Gunn 2018). These sensors can transmit data in real-time and seamlessly integrate with various other industry-specific devices. Despite the substantial volume of data collected from diverse sources and technical resources within the water industry, water utilities tend to underutilize these data sources for enhancing water quality. This underutilization represents one of the key challenges faced by the water industry when it comes to harnessing the potential of big data (Sun and Scanlon 2019).

In the realm of the water sector, the Internet of Things (IoT) is gaining substantial popularity for the monitoring and control of water supply, as mentioned earlier (Laghari *et al.* 2021). Nevertheless, the water industry confronts challenges associated with water monitoring and control. Solutions for water monitoring and control based on the Internet of Things (IoT) provide the industry with the capability to collect data from numerous IoT-connected devices. This data can be processed and subsequently transmitted to various applications or other IoT-connected devices. However, the utilization of IoT introduces security concerns (Perwej *et al.* 2019). Security and privacy issues emerge with the deployment of infrastructure IoT networks, given the potential access that hackers may have to customer IoT networks, such as those involving smart water

meters. To avert hacker attacks and network vulnerabilities, an IoT network tailored for the water sector must be meticulously designed and implemented with robust security and privacy safeguards in place (Greguras 2018).

Within the digital WDN project, one of the most demanding endeavors is the creation and deployment of a bidirectional and wireless fixed network (Velayudhan *et al.* 2022). This network is essential for enabling real-time telemetry and remote-control services. The challenges lie in navigating dense urban environments, dealing with robust structural materials, and addressing the limitations of radio frequency (RF) technologies, which collectively complicate network design and implementation (Antzoulatos *et al.* 2020).

In order to establish a wireless communication network, a combination of multiple telecommunication protocols is often employed, encompassing both legacy technologies like wM-Bus and GSM as well as low-power wide area network (LPWAN) technologies such as LoRa and NB-IoT. Different gateway types are utilized in this setup, including commercial outdoor LoRaWAN gateways, wM-Bus-to-LoRa bridges, and LoRa repeaters (the last two are integrated into Multi-Protocol Gateways, or MPG). This diverse combination of technologies and gateways is essential to achieving optimal connectivity conditions and minimizing data packet loss. When determining the installation points for these gateways, it is crucial to take into account both connectivity requirements and budgetary constraints (Antzoulatos *et al.* 2020).

In summary, a comprehensive literature review on the best practices within the digital WDN was conducted, which are transforming various facets of the water industry worldwide and enhancing its efficiency. Previously, we outlined some of the substantial advantages associated with the Digital Era of Water 4.0. In addition to the economic benefits arising from enhanced water and energy management, these advantages encompass increased water security, heightened public consciousness regarding the environment and the water cycle, improved service quality, elevated user satisfaction, knowledge transfer, and an enhanced corporate image.

The review of the best international practices in digital WDN and the associated benefits makes it abundantly clear that there is a compelling need for the water industry to embrace a digital water management system that is both decentralized and data driven. To achieve successful water digitalization, it is crucial to address the business aspect of this transformation (Alabi, Telukdarie and Van Rensburg 2019). Water networks are recognized as intricate and complex systems, demanding meticulous planning before comprehensive digitalization or decentralization can be implemented effectively. In the following discussion, we will delve into the business dimension of the water industry.

2.5 Digital Water as a Business

Water utilities, in pursuit of their enduring mission, encounter substantial challenges on multiple fronts. These challenges encompass the need to maintain reliable and uninterrupted water services, safeguard public health, and protect the environment (Berglund *et al.* 2022). This environmental protection includes mitigating pollution caused by human activities and various

industries. Further, ensuring the sector's sustainability necessitates achieving full cost recovery and improving operational efficiency and effectiveness. Often, to secure the sustainability of a water company, management must strive for improved outcomes and the reduction of inefficiency-related costs. These conditions can be quite challenging to grasp and address within the current socioeconomic landscape. Like any other organization, water companies rely on a series of organizational processes to plan, produce, deliver, and sustain their products and services. These processes yield the outcomes that the organization delivers to its clients (Madeira and Gartner 2018).

A process is essentially a collection of activities that, when taken individually, are inadequate to attain the intended outcome. Value is created by effectively integrating these activities in a systematic manner with a clear purpose. The activities within a process are not random or arbitrary; they are interconnected and organized (Trivedi, Trivedi and Goswami 2018). In order to yield a meaningful result for customers, all these activities must be in alignment and collaborate toward a common objective.

Processes serve two essential roles in an organization's strategy: (1) they determine the value proposition that an organization will offer to its customers, and (2) they work to minimize costs, boost productivity, and expedite delivery times (Temido and Sousa 2010). Figure 2.7 (Temido and Sousa 2010) outlines the primary processes within the value chain of a water company, which form the essential core for the management and are critical for fulfilling the company's mission. This illustration is designed to depict the principal business processes within the value chain and how they interact with each other.

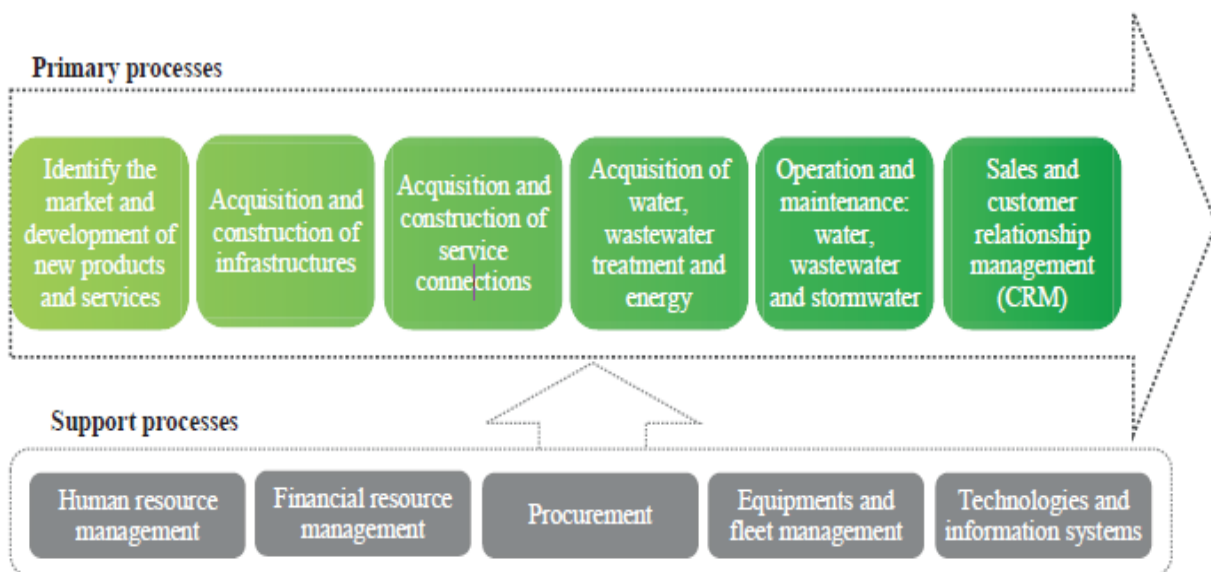


Figure 2.7: Value chain of a water company – primary processes and support processes (Temido and Sousa 2010)

In addition to the core processes carried out by water companies, which are directly associated with creating or transforming products into services, there are also support processes that assist the primary processes either directly or indirectly (Temido and Sousa 2010). The key support processes include human resource management, financial resource management, procurement, equipment and fleet management, and IT systems management. With the continuous advancements in technology, IT has assumed an increasingly significant role in overall management (Akimov and Simshauser 2020).

Information plays an important role in the management of water companies, particularly due to their widespread infrastructure, encompassing water sources, treatment facilities, transmission pipelines, tanks, and distribution networks. These companies rely on technologies to provide timely and relevant information to technicians and decision-makers involved in various organizational processes (Saad and Gamatié 2020). This, in turn, enhances effectiveness and efficiency. Water distribution companies have identified several critical technologies and IT systems, including customer relationship management (CRM), enterprise resource planning (ERP), document workflow system, fleet management system, geographical information system, hydraulic modelling system, supervisory control and data acquisition, and supply chain management (Alabi, Telukdarie and Van Rensburg 2019). To achieve full digitalization and establish a digital business, it is essential to integrate these IT systems.

2.5.1 Digital business

Zaki (2019) defines digital business as “

the process of applying digital technology to reinvent business models and transform a company’s products and customer experiences—innovating products that create new value and connecting people with things, insights and experiences”.

Through digital business, a company can better engage its customers by developing:

- innovative ways to interact with their customers, employees, and partners;
- business models that are disruptive;
- products, experiences, and services that are innovative; and
- go-to-market approaches.

Consequently, the business can foster new growth, achieve meaningful differentiation, and generate real economic value (Zaki 2019).

2.5.2 Digitalization in Water Industry

Digitalization encompasses the comprehensive integration of diverse digital technologies into a system, aiming to significantly impact all facets of business operations (Legner et al., 2017). This integration involves the incorporation of an increasing number of digital technologies and innovations into business processes (Ivančić, Vukšić, and Spremić, 2019). In the context of the water sector, digital water innovation is identified as a crucial aspect of overall innovation, addressing the evolving needs of the industry (Godfred Amankwaa and Richard Heeks et al., 2021).

The force behind the digitalization of the water industry lies in the widespread adoption of interconnected digital devices and applications across water networks, infrastructure, and management (Mondejar et al., 2021). This transition is marked by the growing digitalization and interconnection of various integrated business processes within the water industry (Alabi, Telukdarie, and Van Rensburg, 2019). As digital technologies continue to advance, the water sector is presented with new opportunities for innovation and improved operational efficiency.

2.5.3 Integrated Business Model/architecture

In the context of Water 4.0, the objective of integrated business models or architectures is to cultivate internal business cultures that promote ongoing enhancement and innovation (Köbnick, Velu and McFarlane 2020). Doleski (2015) characterized an integrated business model (IBM) as "a process that ensures all critical success factors are comprehensively considered, with well-defined and structured components". Moreover, a successful business model should encompass the entire organization and its interactions with the external environment. In a complex sector like the water industry, an integrated business model is indispensable for crafting processes and, ultimately, goods and services that can stand up to market scrutiny (Doleski and Doleski 2015). The smart water management system, often referred to as Water 4.0, facilitates a more unified infrastructure and the streamlining of water-related processes. In the realm of digital solutions, the water industry's vertical and horizontal value chains are expected to be integrated and managed as part of the smart water revolution.

2.5.4 Horizontal and Vertical Water Integrated Business Approach

Embracing water digitalization not only revolutionizes the water industry but also fosters the adoption of transformative business models, encouraging horizontal collaboration across water value chains (Alabi, Telukdarie, and Van Rensburg, 2019). This transformation is facilitated by the integrated utilization of data and analytics. In the Water 4.0 vertical and horizontal integration process, there is a dynamic interplay between implemented systems that rely on highly specialized software and user interfaces integrated with digital networks, resulting in the emergence of new functionalities (Doleski, 2015).

A) Horizontal Integration

In the water industry, integrated horizontal business models seamlessly blend various information technology (IT) systems, spanning diverse water infrastructure networks and contributing to comprehensive business process planning. This integration involves communication, energy, and resource exchange, creating an end-to-end value chain within a digitally water-integrated business. The systems encompassed by horizontal integration include customer relationship management, supply chain management, vendor management, and more, aligning with the principles of Water 4.0 (Zhang, Luo, and Yu, 2020).

B) Vertical Integration

Vertical integration in water digitalization involves the integration of various IT systems at different organizational levels, including sensors, enterprise resource planning, business intelligence, and more. This approach, implemented within the Water 4.0 framework, provides a unified perspective of all processes. It incorporates a dashboard capable of monitoring and controlling water demand and supply across multiple networks, exemplifying the comprehensive nature of vertical integration (Zhang, Luo, and Yu, 2020).

The integrated business model for Water 4.0, as proposed by Alabi et al. (2019), draws inspiration from Industry 4.0 paradigms and comprises three core elements: technologies, the business stack of systems, and the business strategy. Figure 2.8 visually represents the interactions between these components, showcasing the synergies that drive the transformative potential of Water 4.0.

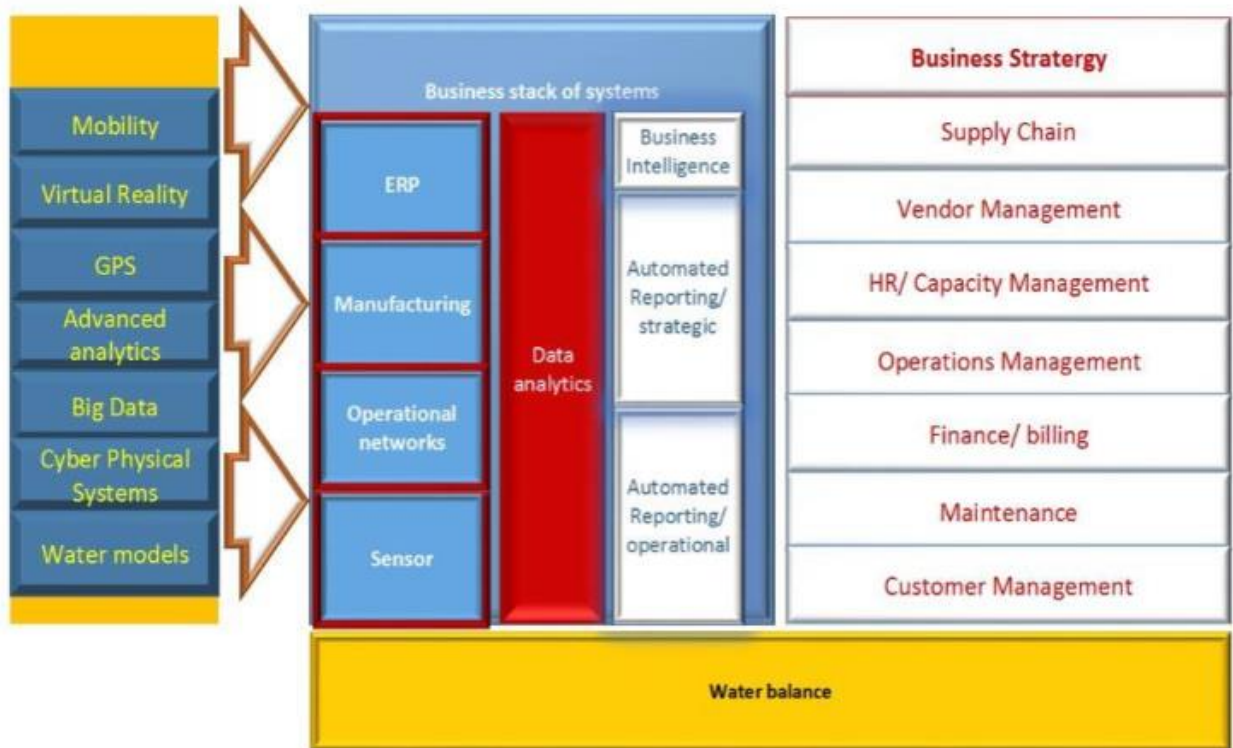


Figure 2.8: Proposed water 4.0 revolution integrated business model

C) The Technologies Component

In the integrated business model of Water 4.0, the technology component incorporates the advancements associated with the industry 4.0 revolution. The selection of these technologies has been influenced by an extensive review of recent studies on Industry 4.0, ensuring the adoption of cutting-edge tools and methodologies. The primary goal is to establish seamless connections between water companies and the technologies integrated into the Business Stack of Systems component. Among these technologies, data analytics tools play a pivotal role in processing and interpreting data, facilitating informed decision-making for both internal (staff) and external (client) purposes (Alabi, Telukdarie and Van Rensburg 2019). Notably, water organizations often opt for a selective approach, choosing specific technologies that best align with their unique environment and system requirements. This tailored adoption ensures a strategic and effective integration of technology resources.

D) The Business Stack of System Component

This section is instrumental in enabling real-time management of business systems within the water industry. By employing best practices in data science, it integrates the systems and data generated by active systems to derive meaningful insights that support decision-making in the

water industry. As depicted in Figure 2. 8, the "Business Stack of Systems" component places a strong emphasis on data analytics, underscoring the central role of data in the business processes of the industry 4.0 revolution (Alabi, Telukdarie et al. 2019). The advantages of each system within the business stack have been previously discussed in relation to their applicability in the water industry.

E) Business Strategy Management Component

An essential element of the organizational system is business strategy management. In order to attain the long-term objectives of Water 4.0, a well-defined business strategy is important. Business strategy and management encompass the process of devising, executing, and assessing cross-functional decisions aimed at enabling those in authority to achieve their goals and realize their desired outcomes. Decisions regarding water business activities are fundamentally rooted in the overarching strategy (Alabi, Telukdarie and Van Rensburg 2019). An in-depth exploration of the benefits of business strategy within the integrated business model for the water 4.0 revolution is discussed below.

- **SCM** is a digital supply chain management, often referred to as Supply Chain 4.0, leverages 4IR innovations like the IoT, robotics, and more to enhance the water industry's ability to conduct their daily operations with greater speed, efficiency, and precision.
- **Vendor Management**, a digital-based system that functions as a mechanism for the water industry to manage and optimize its relationships with external suppliers for both project and business process purposes.
- **HR and Capacity Management System** aids the water industry in sourcing the right talent, including graduates with a solid understanding of Industry 4.0. The digital HR system plays a crucial role in training new staff and providing a platform for retaining the talent that has been sourced.
- **Operations Management** is a digitized management system that is designed to control the processes of water network operations, enabling the efficient transformation of both materials and information into goods and services. Its goal is to maximize profits for the organization.
- **Finance/billing Management** Encompassing the organization's control, planning, evaluation, and monitoring of financial resources, this process enables the company to achieve its overarching goals. Crucially, Industry 4.0 technologies such as cloud computing, big data and analytics, and blockchain technology play a significant role in this financial management framework.
- **Maintenance Management:** New maintenance techniques, including intelligent maintenance and predictive maintenance systems, are valuable for enhancing the water network system's performance. Incorporating a range of sensors, sensor technologies can be smoothly integrated into the computerized maintenance management system (CMMS). This integration facilitates the storage and analysis of data gathered from these sensors. Subsequently, predictive algorithms can be formulated to tackle issues identified through the analysis of sensor data.

- **CRM:** This system aids in managing the organization's relationships and communications with both existing customers and potential customers. 4IR technologies like cloud computing and the IoT facilitate interaction between the organization and its current customers, as well as with potential customers.

As previously highlighted, a WDN is a vast and complex infrastructure encompassing various assets, such as sensors, pumps, storage tanks, and software. A fully integrated digital water business should possess the capability to monitor all of its assets comprehensively and gain a clear understanding of how these assets interact both within departments and across different departments. CMDBs are recognized as effective tools for managing the assets of large systems.

2.6 Configuration management database

Systems that oversee industrial plant operations through networks of devices are termed either industrial control systems (ICS) or operational technology networks (OT) (Paes *et al.* 2019). In these networks, assets or valuable items are often not documented with the necessary level of detail and scope to achieve a satisfactory level of control. Documentation of operational technology (OT) assets is typically insufficient compared to the documentation of assets that transmit and store information, or information technology assets. This discrepancy arises because many industrial control systems (ICS) were designed and implemented before the advent of digitalization and the internet of things (IoT) (Koskelo 2020).

Given the evolution and modernization of the industrial control system (ICS), it is evidently crucial to update its documentation of hardware and software components. Typically, maintenance and modernization projects are thoroughly planned. However, if the plans are based on outdated documentation, the project may be unsuccessful. To safely operate and modify the ICS, a CMDB must be up to date (Koskelo 2020; Shilenge and Telukdarie 2021). Organizations have been operating without an OT CMDB (Drogseth, Sturm and Twing 2015), and there are other asset management tools available that can be used to track OT assets. However, there are several reasons why an OT CMDB is beneficial:

- **Centralized view of OT assets:** An OT CMDB provides a centralized view of the organization's OT assets and their dependencies. This can help to ensure that maintenance and other activities are performed safely and efficiently and can help to avoid downtime or other issues caused by inaccurate or incomplete information (Del Sale, Virtanen and Sainio 2021).
- **Standardized documentation:** An OT CMDB can provide a standardized way of documenting OT assets, including their configuration, maintenance history, and other important details. This can help to ensure that information is consistent and up-to-date and can facilitate communication between different teams and departments (Shilenge and Telukdarie 2021).
- **Compliance requirements:** In some industries, such as healthcare or manufacturing, there may be regulatory requirements that mandate the use of an OT CMDB or similar

asset management tool. Having an OT CMDB can help ensure compliance with these requirements (John Vitalis, Pete Shelkin and PMP 2018).

- **Integration with other systems:** An OT CMDB can be integrated with other systems, such as maintenance management or security tools, to provide a more comprehensive view of the organization's OT infrastructure. This can help to improve overall efficiency and effectiveness.

SCADA asset reports can help achieve some of the benefits of an OT CMDB.

2.6.1 CMDB VS SCADA

SCADA systems can provide detailed information about the assets that they are monitoring, including their configuration, maintenance history, and other important details (Nugent and August 2016). However, there are some limitations to relying solely on SCADA asset reports for asset management:

- **Limited scope:** SCADA systems are designed to monitor and control specific processes or systems and may not provide a comprehensive view of the organization's OT infrastructure. For example, there may be assets that are not monitored by the SCADA system but are still important to the organization's operations (Garimella 2018).
- **Lack of standardization:** SCADA systems may use different terminology or data structures for asset information, which can make it difficult to integrate data from multiple SCADA systems or compare data across different assets (Tsochev, Yoshinov and Iliev 2019).
- **Maintenance and other activities:** While SCADA systems can provide information about asset performance, they may not be designed to track maintenance activities or other important details that are necessary for effective asset management (Tsochev, Yoshinov and Iliev 2019).

In summary, while SCADA asset reports can be a useful tool for asset management, they may not provide all of the benefits of an OT CMDB. It is important to evaluate the specific needs and requirements of the organization to determine whether an OT CMDB, SCADA asset reports, or a combination of both is the best approach.

Data traffic in an ICS system is limited to the inner network of factories or plants, which is isolated from the rest of the world (Macaulay and Singer 2011). Centralizing the control equipment into remote control stations requires data to be transmitted via tunneling through a public network, such as the internet, from one private network to another. In turn, this creates vulnerabilities and could expose ICS networks to cyberattacks. Consequently, hackers exploit the vulnerabilities of outdated operational technology (OT) elements to cause havoc in industrial systems (Lekbich *et al.* 2017). Asset owners and corporate security cannot ensure the security of industrial control system (ICS) networks without an effective asset management system and an up-to-date configuration management database (CMDB) (Koskelo 2020).

Maintaining a proper CMDB is crucial for the safe and secure operation, maintenance, and development of an Industrial Control System (ICS). Failure to comprehensively understand the ICS components can significantly delay response time to unforeseen events. This delay could potentially lead to financial, safety, or quality issues in the production process (Shilenge and Telukdarie 2021).

2.7 Digital maturity

Water utilities across the world are already making use of digital services, such as billing, customer relationship management, geographic cadastre, controller software, and data acquisition (Daniel *et al.* 2023). Several studies have shown that utilities' performance is improving with the implementation of these tools. Digital transformation in general refers to the application and utilization of modern technology for a company's business processes in order to achieve its goals and increase efficiency. Together with digital transformation, digital maturity is becoming increasingly popular (Aslanova and Kulichkina 2020). According to Dominguez (2017), digital maturity

is intricately linked to digital transformation, representing the ultimate stage that companies strive to attain. Organizations reaching this level of digital maturity often experience significant enhancements in operational efficiency and heightened customer satisfaction.

This means that digital maturity is a process that can be measured. A method to measure the maturity of water utilities is discussed below.

2.7.1 Digital Maturity Index

To establish uniformity in the digital attributes of water utilities and organize the need for enhancement at AGS, a digital maturity index was internally developed (Aslanova and Kulichkina 2020). AGS, a company under the ownership of Marubeni, extends its engineering services to water utilities across Europe, Latin America, and Asia. In addition to its service portfolio, AGS is actively engaged in the upkeep of numerous water and wastewater treatment facilities. The development of a digital maturity index serves as a strategic initiative to streamline and benchmark the technological advancements and operational efficiency within AGS, ensuring a cohesive approach to digital transformation across its diverse range of services and global operations. This internal framework allows AGS to systematically evaluate and propel improvements in its digital capabilities, aligning with the ever-evolving landscape of water utility management on a global scale.

AGS is also responsible for managing thirteen utilities in Brazil and Portugal under concession contracts and public-private partnerships (Cassidy *et al.* 2020). AGS assumes responsibility for the management of thirteen utilities in Brazil and Portugal through concession contracts and public-private partnerships, as highlighted by Cassidy *et al.* in 2020. To gauge digital maturity, AGS employs a qualitative assessment framework derived from the International Water

Association (IWA). The AGS maturity index, consisting of seven levels indicating varying degrees of complexity, serves as the benchmark for water utilities to assess their digital maturity. Within each level, sublevels are evaluated for both availability and usability, rated on a scale from 1 to 3. The digital maturity of a water utility is then determined by calculating the ratio of total points achieved to the maximum points possible across the seven levels. This approach ensures a comprehensive and standardized evaluation of digital capabilities. AGS has devised the maturity index to foster an unbiased self-evaluation, particularly focusing on system availability and usability grades (Feliciano et al. 2021). The AGS maturity index is illustrated in Appendix A as extracted.

Chapter 3—METHODOLOGY

3.1 Introduction

This chapter details the methodology used to develop a framework for the digitalization of WDNs. Further, the chapter details how the systematic review is used to determine the equipment and systems that are found in the WDN, from sensors to ERP. Furthermore, the methods of the development of CMDB that are used to structure data and validate the framework are detailed; the CMDB is built based on a real-world WDN. The initial section of this chapter highlights the research design and the diverse methodologies employed in this study. Subsequently, the chapter addresses the sampling techniques employed and the strategies for data collection and analysis. Lastly, the chapter summarizes the research approach and the data collection methods that were applied.

3.2 Research design

The primary objective of this study is to develop a framework for the digitalization of WDNs by drawing upon international best practices that integrate sensor-to-enterprise planning resources into the design. This framework is intended to serve as a best practice model for entities in South Africa (SA). It is constructed based on references from previous research best practices, and successful case studies, as well as information obtained from a water utility regarding its business requirements. The study employs a mixed-methods approach, encompassing both qualitative and quantitative research methods. The qualitative research method is deductive by nature (Umair et al. 2021). Such an approach is appropriate when collecting specific data and information. The quantitative method suits the CMDB portion of the research, where data or CIs are gathered. The development of the framework based on best practices aligns with the qualitative method. Further, the qualitative methods also cover the case study. A case study is an in-depth and detailed examination of a particular subject, typically a real-world situation or phenomenon (Rashid *et al.* 2019). Case studies are often utilized in research to gain insights into complex issues, explore relationships, and draw meaningful conclusions based on specific instances (Rashid *et al.* 2019). In this research, the case study seeks to validate the framework of digitalization in WDN by incorporating data from a real-world WDN. Overall, section 3.3 highlights the overview of the research approach in this study.

3.3 Overview of the research approach

The methodology for this study applies a combination of all the methods discussed in section 3.2.

The methodology is defined as follows:

Figure 3.1 illustrates the sequential steps of the adopted research methodology, with subsequent paragraphs providing further explanation for each step.

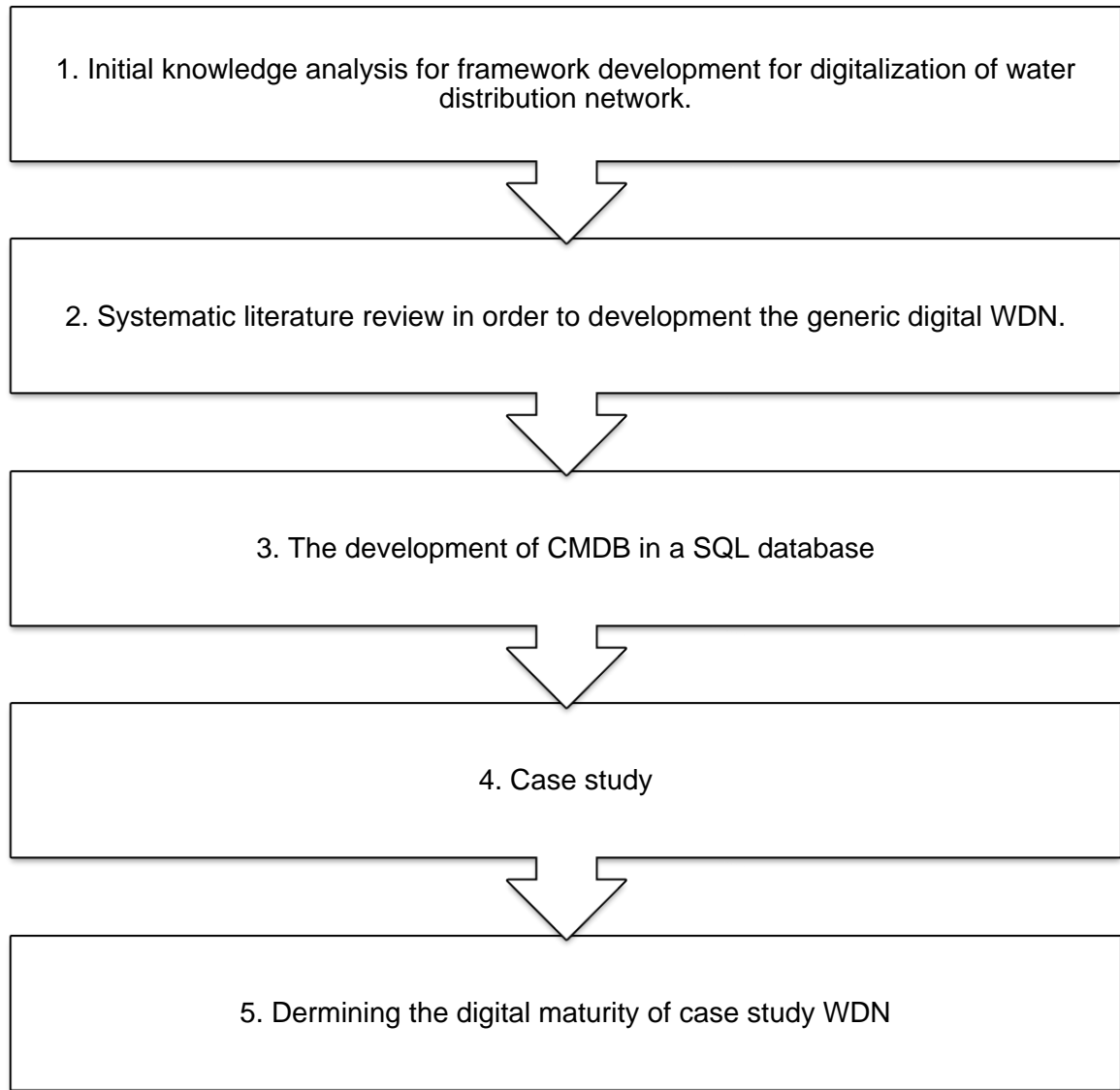


Figure 3. 1: Research methodology steps block diagram

3.4 Development of a framework for digitalization of water distribution network.

The digital WDN best practices literature highlighted that the Water 4.0 architecture is composed of multiple layers that work together synergistically to accomplish useful functions. It is possible to consider a WND as a set of components, each with specific properties and benefits. Different versions of Water 4.0 have been proposed in previous studies to meet their particular demands. Digital WDN and ICT were combined to define a new approach to water management that is different from traditional methods.

Digital WDN should inherently encompass elements like smart meters, smart valves, and smart pumps, as well as sensors and microcontrollers. These networks are intricately connected with communication protocols and embedded systems, all of which are integral components of the Internet of Things (IoT), serving as the foundation of digital WDN. Consequently, a digital WDN should be structured around three fundamental frameworks: hierarchy, technical system, and function (Ntuli and Abu-Mahfouz 2016).

In addition to the hierarchical framework and technical system, other variables are also essential for a comprehensive digital WDN. A critical aspect of digital WDN is the need for an easily understandable architecture. Research conducted by (Kartakis, Abraham and McCann 2015) categorized the architecture of digital WDN into the following layers:

- Physical layer (e.g., pipes),
- Sensing and control layer (e.g., flow sensors and remote control),
- Data collection and communication layer (e.g., data transfer),
- Data management and display, and
- Data fusion and analysis (e.g., analysis tools, leak detection, and decision-making).

These layers primarily comprise both physical and cyber components, with limited improvement in service levels (Xu, Xu and Li 2018). Several architectures with various layer models have been proposed for digital WDN. (Yuanyuan *et al.* 2017) introduced a bottom-up framework, outlining five layers for a digital WDN: the sensing layer, transport layer, processing layer, application layer, and unified portal layer. These layers are founded on the principles of IoT and cloud computing. Another digital WDN framework, featuring four stages, was designed to effectively manage the substantial volume of high-resolution sensor data and customized information, as outlined by Ribeiro and colleagues in 2015.

The concept of digital WDN has evolved significantly, and according to Li et al. (2020), the best practice digital WDN architecture comprises five layers, with each layer serving a distinct function within the network. However, there remains a degree of debate and a lack of comprehensive substantiation for many of the digital WDN frameworks discussed above. Some are primarily designed for specific purposes related to digital WDN objectives, while others focus on technological innovations, and still others aim to integrate information and communication technology (ICT) into these goals. The few frameworks that are applicable to education, research, and the public are not all-encompassing and fail to address all facets of digital WDN. Critical elements such as properties, metrics, and case studies are often missing, and there is a need for a systematic framework to guide future research and accelerate the implementation of digital WDN.

In this study, existing architectures are integrated and adapted to propose a systematic architecture for digital WDN. The proposed conceptual framework for smart water includes five layers (from bottom to top): the physical layer, the communication layer, the data storage and analysis layer, the benefits layer, and the application layer. These layers are designed to provide a systematic understanding of how digital WDN architecture is implemented. This conceptual

framework will be initially tested through a systematic literature review, followed by validation using real-world WDN data. Further, the digital WDN framework also integrate the security and data management aspect of WDN. This ensures that the framework covers all aspects of the WDN that are essential to deliver potable water in a secured and proper managed manner. Engineers can then utilize this framework to replicate digital WDNs for their specific purposes.

3.5 Systematic literature review

Based on the studies conducted by Assad (2022) and Khan (2016), this study adopted a systematic literature review (SLR) to review peer-reviewed published literature and gather information on the aspects involved in a WDN (sensors to ERP). In order to implement an SLR, Assad (2022) emphasizes the importance of research questions, data collection, and analysis. Whereas Khan et al. (2016), emphasize five steps, including (1) developing research questions, (2) searching for relevant sources of work with establishing inclusion and exclusion criteria, (3) assessing the quality of selected studies, (4) summarizing the data from the studies, and (5) interpreting the results. Based on this knowledge, Figure 3.2 summarizes the research strategy adopted for this study.

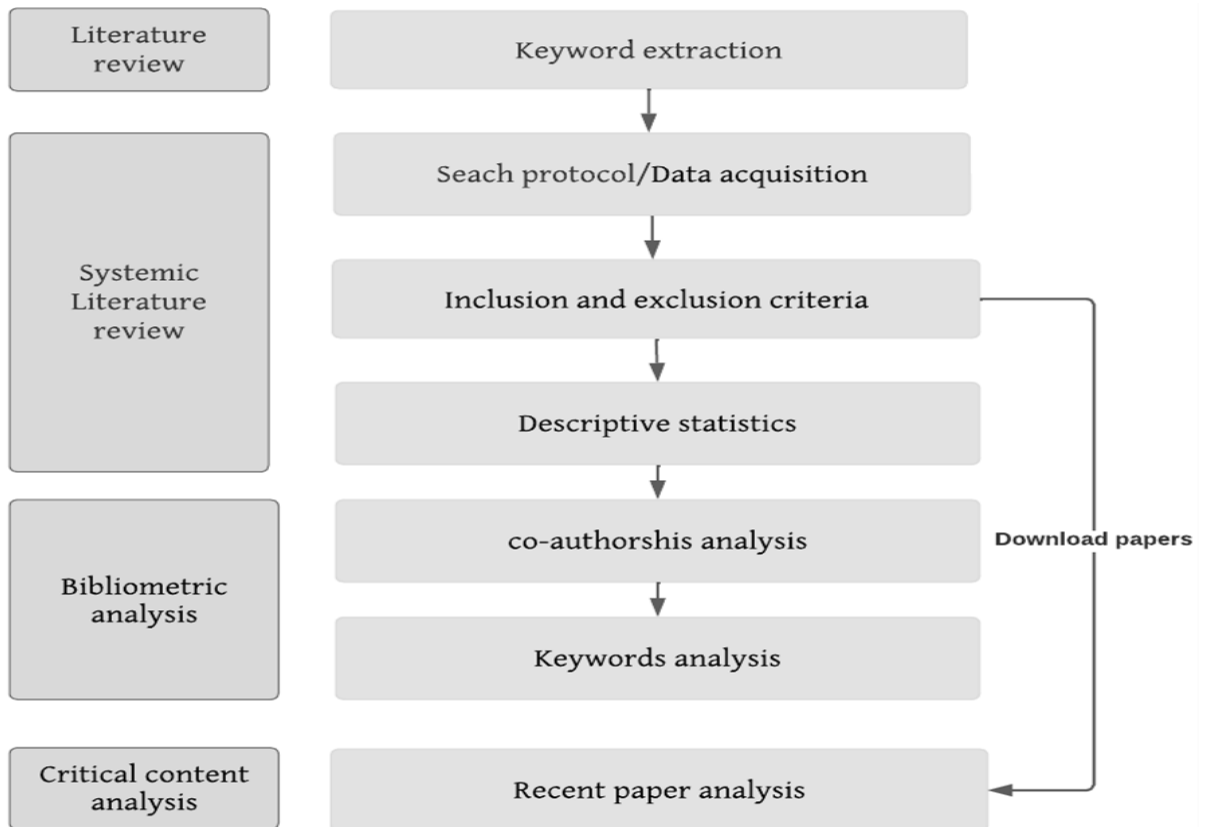


Figure 3.2: Research methodology framework (Authors own work)

3.5.1 Search string

The systematic literature review starts with the extraction of keywords from introductory literature to create a search string that will be used to query an abstract and citation database in order to gather data for bibliometric networks. The search term is shown in Table 3.1.

Table 3.1: Search string and inclusion criteria.

Search string	<p>(“Smart water system” OR “water distribution systems” OR “water network” OR “water supply” OR “water distribution”)</p> <p>AND</p> <p>(“pump as turbines” OR “operational technology” OR “pumps” OR “valves” OR “water flow sensors” OR “valves” OR “Programmable logic controller” OR “Siemens S7-200 PLC” OR “Submersible pumps”)</p> <p>AND</p> <p>(“smartness” OR “Wireless sensor networks” OR “4IR” OR “Industry 4.0” OR “Industry 4.0 for water services” OR “Real-time control” OR “Smart Water Grid” OR “smart water system” OR “smartness” OR “Water 4.0” OR “Water Digitalization” OR “Wireless sensor network” OR “cyber wellness” OR “Decision Making”)</p> <p>AND</p> <p>(“advanced leak detection technology” OR “automated water balancing” OR “Water quality” OR “Smart technology” OR “Water infrastructure” OR “Water management” OR “SCADA system” OR “Automatic control system”)</p> <p>OR</p> <p>(“cyber wellness” OR “Electricity conservation” OR “framework” OR “Integrated Business” OR “Model-based control” OR “Protocols”)</p> <p>OR</p> <p>(“Business Model” OR “Computer architecture” OR “Condition-based inspection” OR “configuration management” OR “information technology infrastructure library” OR “Infrastructure Asset Management” OR “Integration of SMEs” OR “interoperability of smart water systems” OR “Rational use of water” OR “Readiness” OR “Risk-Based Inspections” OR “Risk-Based Maintenance” OR “Simulation” OR “concept” OR “Security” OR “ERP”)</p>
Study focus	Water distribution network

Source	Academic journal, Articles, Books and conference papers
Language	English

3.5.2 Data acquisition

Given that Scopus is one of the most comprehensive research databases and covers a wide range of scholarly disciplines, the study used the Scopus database to conduct a systematic literature review (SLR). Using keywords extracted from the preliminary literature review, a new keyword string was created, which was then used to search Scopus for documents. Before filtering, 3851 documents were returned by the search string in Table 3. 1. To ensure that only the documents that are pertinent to WDN are downloaded, the subject area was restricted to engineering, information communication technology, mathematics, and environmental science using Scopus restriction functionality. After excluding documents that were neither published in the last decade (2012–2021) nor in the English language, the document count decreased to 2143. In order to fully document the introduction of 4IR in the water sector, a time frame of 2012–2016 has been chosen. The use of English is a crucial requirement for article uniformity and readability. However, Scopus limitations allow the download of only 2000 documents.

To analyze the papers using co-authorship and keyword co-occurrence techniques, the 2000 downloaded documents were exported to VOSviewer, as demonstrated. The clusters generated by the keyword analysis were used as the search string for queries against the Scopus database. The process for collecting secondary data was identical to that for the collection of primary data, except that 10 of the most frequently cited documents from the previous five years were downloaded for each cluster.

3.2.3 Inclusion and exclusion criteria:

The application of the inclusion and exclusion criteria, aided by Scopus' data filtering capabilities, ensured that only relevant documents for this study were obtained, thereby guaranteeing accurate results. Further, the process of inclusion and exclusion ensures that the downloaded papers are written in a language that the authors can comprehend, thereby mitigating any difficulty in performing content analysis. The criteria for inclusion and exclusion are listed below.

- Keywords extracted from literature reviews are used in articles;
- The article appears in English-language journals or conference papers; and
- The publication window is from 2012 to 2021.

Book chapters and articles published prior to 2022 were not included in this study.

3.5.4 Data cleaning

The final step in the data acquisition process to ensure high-quality outcomes is data cleansing. Examples of this cleansing include standardizing citation formats and correcting author and institution names. The most crucial step for this paper is keyword removal. By using thesaurus in VOSviewer, keyword cleansing minimizes the repetition of words and their synonyms and acronyms from downloaded documents.

3.5.5 Data analysis and interpreting

A two-tier qualitative analysis was used in this study to systematically review the retrieved literature. Bibliometric analysis was completed before critical content analysis. Bibliometric analysis was initially defined as "the application of mathematical and statistical methods to books and other media of communication" by Pritchard (1969). Since then, this technique has grown in acceptance (Donthu et al. 2021). In contrast to traditional literature reviews, bibliometric analysis explores the body of knowledge using quantitative and statistical methods. As a result, there is a lower chance of bias in the results (Xu et al. 2018). To ascertain the frequency of authors, publications, and prominent clusters within a specific subject area, network analysis was employed as a common bibliometric method. This technique examines author information, keywords, and abstract terms to uncover patterns and relationships (Al et al. 2012). VOSviewer was used to conduct bibliometrics for this study, including co-authorship and keyword analysis. VOSviewer is a network analysis tool that is open source; as a result, it was used in this study. The next step in this study examined the most recent and frequently cited publications through content analysis.

3.6 The development of CMDB in a SQL database

This part of the research adopted a qualitative research design to explore and understand the process of developing a CMDB for Johannesburg Water's water distribution infrastructure. The selection of Johannesburg Water was primarily driven by its proximity to the author in terms of location.

3.6.1 Database Design

Inspired by Matsumoto, Fujita, Endoh, Yamada, Sawada, and Kaneko (2021), this study embraced a structured approach to asset configuration management. This approach revolves around a data model comprising several key attributes, including Device_Classification, Part, Vendor, Product_Description, Version, Update, Edition Software_Edition, Target_Software, Language, Device_Class1, Device_Class2, Device_Class3, Target_Network, ID_Number, Location, Extend_Information, Time_Stamp, Network_Type, Physical_Address, Network_Address, Neighbor_Device and Master (Matsumoto *et al.* 2021). According to Matsumoto et al. (2021) this data model was developed to bridge the gap between information technology systems and operational technology. It is a strategic database design that not only facilitates the seamless management of asset configurations but also assists in identifying the

precise data requirements for building a CMDB. After the adoption of the data model, a Microsoft SQL (MSSQL) database was created, and one table was created based on the adopted data model.

3.6.2 Data Collection Methods

Three on-site visits to the Johannesburg Water Depot were carried out with the aim of gaining a comprehensive understanding of their water distribution infrastructure. On each occasion, qualitative data was collected through various means:

- **Direct Observations:** The researcher observed the control room firsthand; actively examined the water distribution infrastructure and carefully noted operational processes. This allowed for the witnessing of the day-to-day operations in real-time, providing valuable insights.
- **Informal Interviews:** In addition to observations, informal interviews with Johannesburg Water technical staff were conducted. These conversations yielded qualitative information and perspectives that complemented the observational data. These interviews allowed for a better understanding of the operations.
- **Document Analysis:** To further enrich the data collection process, extensive analysis of documents (Microsoft Excel files) and information shared by Johannesburg Water was performed. This encompassed data retrieved from SQL servers, SCADA and OPC sources. Analyzing this data not only provided a historical context but also allowed for the identification of various tags in the WDN.

By employing this multifaceted approach to data collection, a comprehensive and well-rounded dataset was compiled, which formed the foundation for my research and the analysis of Johannesburg Water's infrastructure and operations. In total, 10201 tags, including RTUs, flow meters, level meters, pumps, alarms, PSUs and pressure sensors, were shared in the form of an Excel document. The tag information also forms part of the Excel document.

3.6.3 Data cleaning and data uploading

In the development of the CMDB, the choice was made to utilize Microsoft SQL Server (MSSQL), an open-source SQL database server that was readily accessible. MSSQL was selected due to its structured and efficient data storage, management, and retrieval capabilities, making it an ideal platform for building the CMDB.

To populate the MSSQL database with data, Excel documents were extracted and transformed into tables within the SQL database. Typically, these tables contain essential attributes such as tag_id, description, vendor, and type. Subsequently, the database was connected to a Python script employing the pyodbc library. This Python library acts as a secure bridge between the script and the SQL database, enabling seamless data interaction.

To maintain data integrity within the CMDB, a primary key was established in the CMDB table, utilizing the ID_number, which corresponds to the tag_id found in the underlying tables. This primary key ensured that only unique tags were updated into the CMDB table, preventing the occurrence of duplicate entries.

The process involved the Python script's ability to consolidate and enrich data. It accomplished this by breaking down the tag descriptions to extract crucial information, such as the tag's location and type (e.g., sensor). These extracted details were then updated with the relevant attributes in the database, along with other pertinent information.

3.6.4 Assets relationships

The initial step involved leveraging asset location data to discern the spatial relationships between various assets. By considering the physical proximity of assets, it became possible to establish connections and dependencies between tags based on their real-world placement within facilities.

Additionally, valuable insights were derived from Excel data that contained information regarding remote terminal units (RTUs). This data provided a clear indication of which channel each RTU was connected to within the infrastructure. This crucial piece of information served as a foundational element for mapping out intricate relationships among tags, particularly those associated with reservoirs and towers.

3.6.5 Change management

An integral component within the CMDB is the "change" table, which plays a pivotal role in monitoring and documenting alterations made to the CMDB itself. This table encompasses several key attributes, including ID_number, new_ID_number, change description, requester, and time stamp.

The primary function of this "change" table is to serve as an audit trail, meticulously logging any alterations made to the CMDB. Specifically, it tracks the removal of tags from the WDN. Whenever a tag is removed, the corresponding information, including the ID number, is stored in this table. This comprehensive change tracking mechanism not only aids in maintaining data integrity but also provides transparency and accountability in the management of the CMDB. It enables easy tracking and analysis of historical changes, ensuring that the CMDB remains accurate and up to date.

3.8 Case Study

The study employs an exploratory case study methodology to elucidate the operational dynamics of Johannesburg Water's WDN. This research design is chosen to delve into the natural context of the phenomenon, aiming to acquire insights, formulate hypotheses, and establish a more thorough understanding of a subject that is relatively unknown or not well-defined. Exploratory case studies are particularly beneficial when the researcher possesses limited prior knowledge about the topic (Baskarada 2014).

Utilizing the CMDB to illustrate the interactions among assets and incorporating observational data, a narrative is constructed to provide an overarching interpretation of the collected data. Subsequent to the interpretation of findings, the final step involves the formulation of conclusions.

3.7 Digital maturity

The concluding phase of this research involved evaluating the maturity of Johannesburg Water's WDN. To gauge the level of maturity in the digital aspects of their WDN, the study adopted the AGS Digital Maturity Index. This index, specifically crafted by AGS, served as a comprehensive tool for assessing the digital maturity of WDNs. Typically, this maturing level has seven levels. The WDN was scored for each level, and the average was used as the maturity index of the WDN.

Overall, the study employs a combined qualitative and quantitative methodology to develop a digital framework for the digitalization of WDN. This comprehensive approach includes conducting a systematic literature review to develop a generic WDN, which is subsequently utilized to validate the framework. Additionally, the study involves the creation of a CMDB used to score the assets of the WDN, the development of a case study, and the evaluation of the digital maturity of the WDN.

Chapter 4– RESULTS AND DISCUSSIONS

This section emphasizes maintaining a sequential breakdown aligned with the methodology outlined in Chapter 3. The research details carried out in accordance with the established methodology are presented, and the outcomes are specifically highlighted. Chapter 4 aims to adhere to the sequencing set forth in Chapter 3, ensuring a structured and methodical presentation of the research process and its corresponding results. Typically, the research has four outputs: a digital WDN framework, generic WDN, CMDB, and the digital maturity of WDN. The digital WDN framework was developed through the adoption of a digital WDN architecture that comprises five layers, the demonstrated need to secure the WND, and manage assets in the WDN. Furthermore, this section elucidates the results of the systematic literature review. The systematic literature review served as the foundation for constructing a generic WDN, which, in turn, was employed for the validation of the WDN. Following this, a CMDB is established based on the data from Johannesburg Water. The CMDB functions as the authoritative source for the WDN, making it a crucial component of the subsequent case study development. Ultimately, the digital maturity of Johannesburg Water's WDN is assessed using the AGS maturity model.

4.1 Digital WDN Framework

The framework is developed through the adoption of the digital WDN architecture, integration of security, and data management database. Hence, the framework is made up of three distinct components including security, CMDB and WDN architecture. The structured architecture of the digital WND framework consists of multiple layers operating as a system in order to execute valuable functions and applications. These layers can be conceptualized as an assemblage of components, each possessing distinct properties and delivering specific advantages. The layers include the physical layer, communication layer, data storage and analysis layer, benefit layer, and application layer. Figure 4.1 depicts the digital WDN framework.

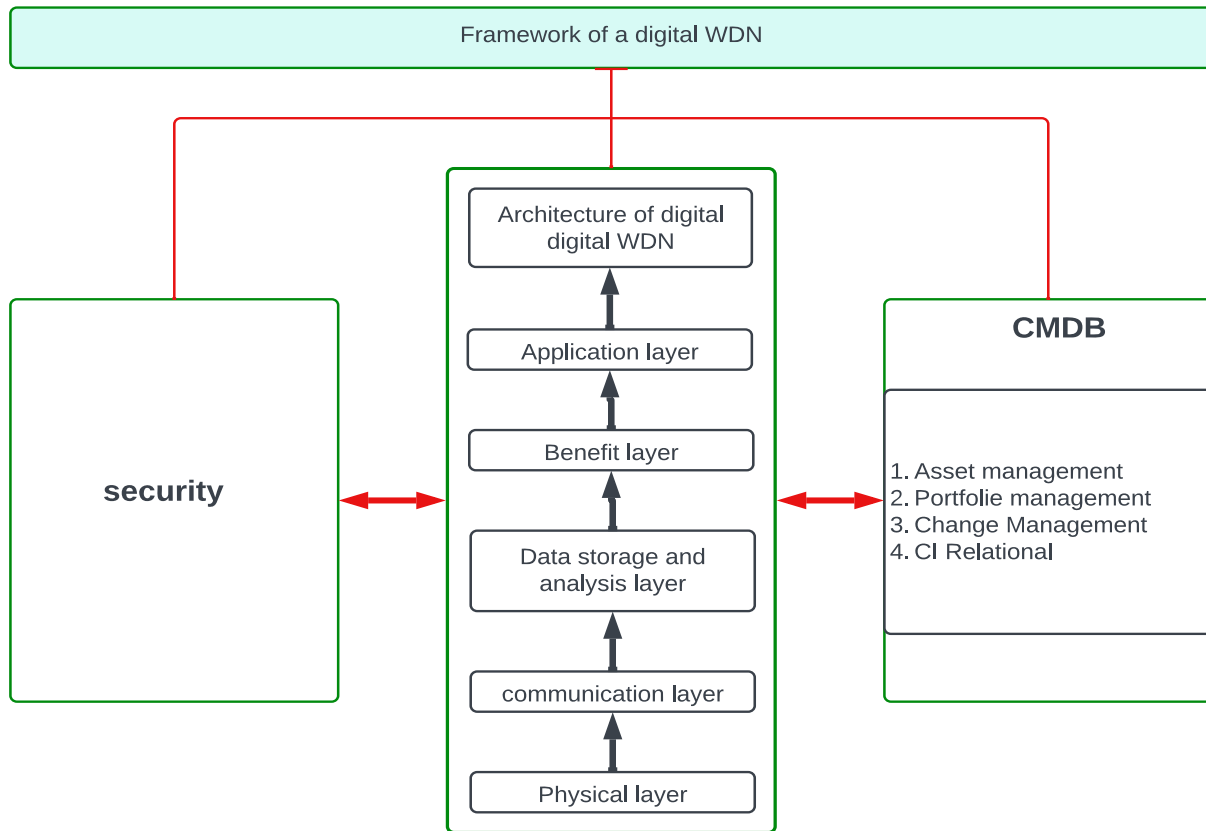


Figure 4.1: A proposed framework of a digital WDN

4.1.1 Physical Layer

The physical layers represent the physical components of a digital WDN; it comprises cyber components and traditional components. The traditional infrastructure includes the familiar components that are fundamental in building a traditional WDN; these components include but are not limited to pipes, tanks, pumps, and flow meters. These components, although traditionally not smart, can be connected to SCADA and serve as the foundation of a WDN. The cyber components include smart meters, smart sensors, smart valves, smart pumps, and smart actuators. The cyber components differentiate between traditional WDN and digital WDN. A traditional WDN uses the physical layer to record and monitor pressure and flow, while a digital WDN produces not only pressure and flow data but also diagnostic data that helps the digital WDN detect leaks more quickly and efficiently. In addition, for the integrated digital WDN, it is important that the interaction between physical and cyberinfrastructure is not neglected (Li, Yang and Sitzenfrei 2020).

Physical instruments, such as pipes, valves, and pumps, form the structural foundation for incorporating cyber instruments like smart meters and intelligent sensors. These physical

infrastructures generate data, which is collected, transmitted, processed, and merged using hardware, software, and internet-related services. In return, cyber instruments can be utilized to guide the operation and maintenance of these physical components by analyzing newly generated data and predicting their condition. For instance, automated meters can execute actions on devices, such as turning valves on and off, through bi-directional communication. Further, operating systems can design various smart sensors to discriminately address different issues. As a result, the digital component layer encompasses the functionalities of both physical and cyber infrastructures.

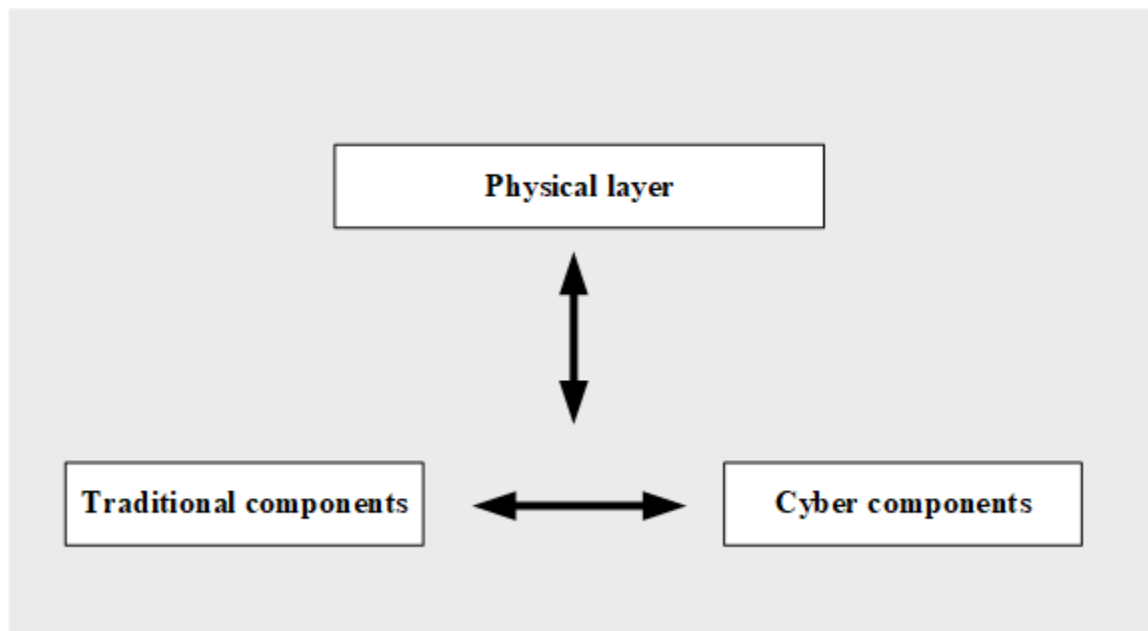


Figure 4.2: The physical layer components (Li, Yang and Sitzenfrei 2020).

Figure 4.2 emphasizes the interplay between the conventional components and the cyber components. The data generated within this layer is transmitted to the upper layers via remote communication methods.

4.1.2 Communication Layer

The advancement of the Internet of Things (IoT), combined with the availability of low-cost, low-power communication technologies, has sparked a continuous movement toward smart cities and intelligent infrastructure. This trend has been accompanied by the development of various communication protocols and monitoring modules. In theory, smart city applications can be compatible with a wide array of wireless communication technologies and protocols, ranging from short-range options like Bluetooth, Wi-Fi, and ZigBee to long-range cellular technologies such as

2G, 3G, 4G, and 5G networks. However, only a few of these standards can offer low-power, long-range data transmission capabilities at a rate suitable for monitoring infrastructure. Further, some radio technologies are highly energy-efficient, making them suitable for smart city applications (Sikimić *et al.* 2020).

Using these communication technologies in the WDN, the data gathered by cyber components in the physical layer is subsequently transmitted to the upper layers. In cases where tanks, pumping stations or other apparatus in a WDN have access to external power supplies, energy-efficient data transmission may not be a primary concern. However, when it comes to smart meters and pressure-monitoring devices, energy efficiency becomes a critical factor. These devices often need to operate for multiple years without external power sources, making low-power solutions crucial. Among the low-power wide area network (LPWAN) standards suitable for ultra-low-power machine-to-machine (M2M) communication, options such as narrowband IoT (NB-IoT), Sigfox, and long-range wide area networks (LoRaWAN) are particularly promising for monitoring smart infrastructure due to their energy-efficient capabilities.

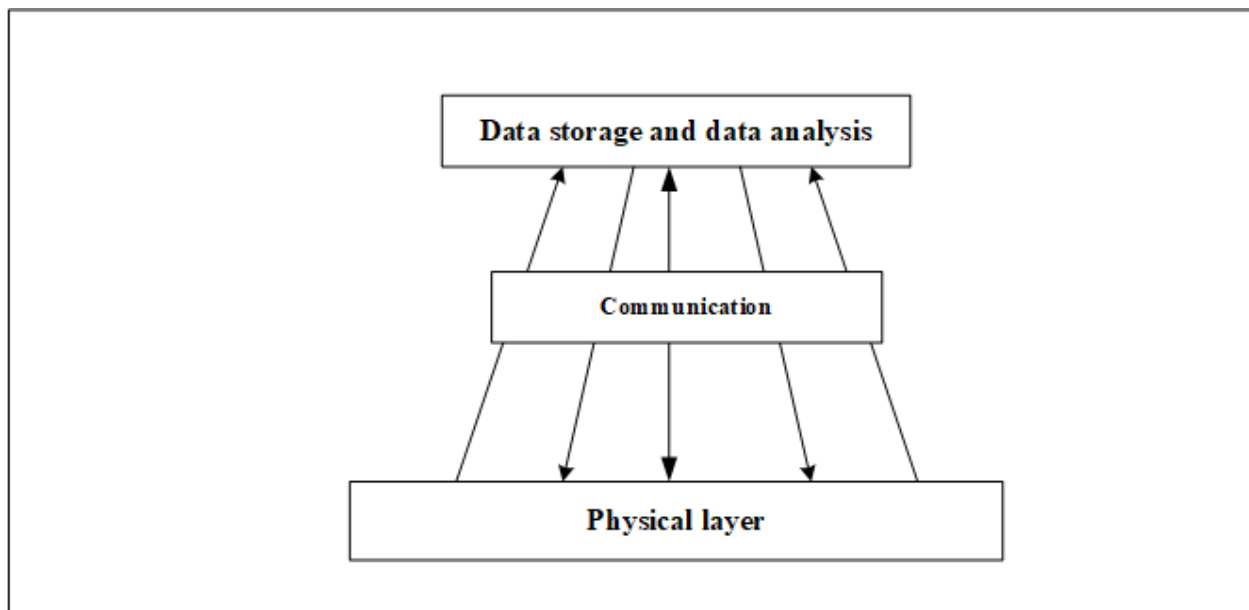


Figure 4.3: The communication layer components (Chaudhari, Zennaro and Borkar 2020).

Figure 4.3 illustrates the connection between the physical layer, data storage and data analysis, facilitated by the communication layer. Data transmission through the communication layer is bidirectional. This enables the physical layer to transmit the collected data to data storage and analysis. Further, it enables data storage and data analysis to send instructions to the physical layer's equipment, such as pumps and valves.

4.1.3 Data storage and data analysis

The data storage and data analysis layers are determined by the physical layer and the communication layer, as the different components and properties lead to various functions. For instance, a WDN equipped with flow and pressure sensors would be resourceful and capable of validating the analysis of pressure-driven modeling with a significant amount of data. In contrast, a digital WDN with temperature sensors can predict the rate of infiltration into the water systems using available temperature information. This layer's capabilities encompass intelligent sensing, simulation, diagnosis, warning, dispatching, disposal, and control, and it serves as the foundation of the digital WDN. However, this study does not describe how the function layer operates across the entire framework.

In addition to data storage, this layer assumes the responsibility of monitoring and controlling downstream apparatus. Typically, systems such as SCADA systems and PLCs are commonly employed to fulfill these functions.

4.1.4 Benefit Layer

The introduction of smart tools to WDN brings benefits such as decreased water loss, leakage and burst detection, reduced operational costs, reduced bills to customers, and reduced environmental impact. Key benefits with substantial financial implications, such as reduced financial losses and water savings, encompass extending the asset life cycle, achieving cost savings, enhancing energy sustainability, optimizing pressure and water quality, and gaining real-time insights into water consumption and consumer billing. In the benefits taxonomy, the initial two fall under business benefits, while the third is categorized as shared benefits. The last benefit falls under customer benefits. Similar to data storage and data analysis layer, the benefit layer is determined by the downstream layers. Generally, the benefit layer includes benefits such as prolonging asset life cycle and cost saving, reduce energy loss and improve system efficiency, optimize pressure supply and water quality, and obtain real-time water consumption and consumer Billing.

Prolong Asset Life Cycle and Cost Saving

The real-time property of a digital WDN enables utilities to integrate, analyze, and monitor data from various instruments; this enables water utilities to make informed decisions. The real-time monitoring of the conditions of valves, pumps, tanks, and pipelines can be used to develop risk-evaluated models that can then be used for maintenance and instrument replacement. Furthermore, this allows the water utilities to plan and schedule the replacement and maintenance of the assets efficiently and effectively, meaning that the right assets are repaired, replaced, and rebuilt. Thus, asset status monitoring in real-time could be regarded as an indicator of preventive maintenance and predictive replacement to prolong their service life and save money.

Reduce Energy Loss and Improve System Efficiency.

In a digital WDN or a traditional WDN, energy plays an important role; without energy, there is no clean water, and water can never be distributed. Energy is used in the WDNs to treat, extract, and distribute water for industrial, agricultural, and municipal use. Energy consumed by moving and handling the water is estimated to be 4% of total electricity consumption in the United States. Using the digital WDN tools, the water utilities are able to estimate the quantity of water that is needed per day and account for any water losses; thus, they are able to produce the exact required amount of water, which helps reduce energy consumption and encourages water conservation. Water leakage is another contributor to WDN energy consumption because additional energy needs to be added to pump and distribute water to replace the lost water. Smart tools enable water utilities to mitigate this challenge, leading to a decrease in energy consumption. Additionally, smart sensors enable water utilities to monitor pressure levels and notify of any pressure changes, this allows utilities to remotely optimize the network pressure to save energy.

Optimize Pressure Supply and Water Quality.

Water systems are equipped with cyber instruments to detect pollution. The real-time monitoring of water quality indicators, including pH, conductivity, free organic, total organic carbon, and turbidity, enables water utilities to continuously monitor the water contamination and assist in an effective response to mitigate the problem. As an example, the real-time water quality issue detection system called CANARY uses advanced monitoring technologies in combination with enhanced surveillance tools to collect, integrate, analyze, and communicate information that can provide a timely warning of potentially hazardous situations.

The physical layer allows the digital WDN to produce real-time data regarding the hydraulics and water quality in the network. The hydraulics are used to detect deficit pressure in the WDNs; thus, the water pressure can be minimized to the normal operating pressure, this helps alleviate the risk of pipe bursts and water leakages. The minimizing of pressure can be automated by using automated valves or smart gate operations that can adjust the pressure operating status. The real-time information from SCADA and hydraulics integration can also be used to predict operation consequences, predict boundary conditions, and know the status of the water systems, which allows operators to operate them more efficiently.

Obtain Real-Time Water Consumption and Consumer Billing.

Digital WDNs integrated with billing and consumption systems provide real-time metering information to end-users via various platforms, such as laptops, smartphones, or tablets connected to the internet. This real-time water consumption information empowers customers to become more conscious of their water use, helping them save water and reduce costs. Automated Meter Reading (AMR) and Automatic Meter Infrastructure (AMI) are key components of digital WDNs that offer real-time feedback on water usage to customers. This allows customers to make informed decisions regarding their water consumption habits and engage in water management efforts. In return, changes in demand patterns can assist engineers and operators in calibrating

their models, optimizing pump and valve schedules, and making timely and accurate adjustments to boundary conditions for efficient operation.

4.1.5 Application Layer

Within the application layer, there are typically three main aspects: public applications, government applications, and business applications. The application layer primarily focuses on catering to user needs and offering support for decision-making processes. What sets these three categories apart is their intended user base. Public applications are designed for consumers; government applications serve various public utilities; and business applications target markets and enterprises. Notably, these applications can also facilitate the gathering of feedback from their respective users, fostering continuous improvement and adaptation.

- **Public applications** are designed for use by the general public or consumers. They may include web browsers, social media apps, entertainment apps, and other software that individuals use for personal purposes. These applications often support user interaction, information retrieval, and communication.
- **Government applications** are designed for use by government agencies, officials, and departments. These can include applications for managing public records, providing government services online, and facilitating communication and collaboration among government entities.
- **Business applications** are designed for use in commercial and organizational settings. They include a wide range of software used for various business functions, such as CRM, enterprise resource planning (ERP), accounting, project management, and more. Business applications support decision-making, data analysis, and the efficient operation of organizations.

The public application serves the purpose of providing real-time data and information to consumers, encouraging them to offer feedback on billing and consumption in a digitally matured WDN. This feedback loop not only contributes to water conservation efforts but also aids in cost-saving measures. Further, it is crucial to emphasize public awareness regarding digital WDN and its role in water conservation. Greater community involvement can be fostered by providing citizens with comprehensive information on water conservation and digital WDN. However, the use of manual flow meters and their installation may raise concerns about privacy and government intrusion.

The government application, on the other hand, is geared towards water utilities, distinct from the public-focused applications. Water utilities are responsible for the construction and maintenance of the water system, including tasks like pipe replacement, instrument installation, and data center establishment. The sensors deployed by water utilities play a vital role in gaining insights into the digital WDN functionality. The data collected by these sensors serves as valuable support for government decision-making processes.

In contrast, business applications within the digital WDN landscape primarily center on sensor and real-time software development. However, there is a notable absence of comprehensive standards or guidelines for evaluating these intelligent products. To address this, the application and evolution of digital WDN can expedite the evaluation process based on market feedback and contribute to the establishment of rules and standards for the smart water market. Additionally, the application layer's effectiveness depends on the specific purpose of data acquisition. Given the complexity of various applications and communication processes, a single protocol is not universally suitable. Instead, ongoing development focuses on multi-protocol handling devices tailored for specific purposes. These devices promote communication through existing or emerging protocols and offer open, programmable interfaces for customization, facilitating market testing and feedback. This approach ensures greater interoperability within the digital WDN.

4.1.6 Security

Ensuring security is essential in a WDN for several reasons; thus, it is a fundamental component of this digital WDN framework. Security measures in WDN are critical to safeguarding public health (Hasan and Deininger 2004). Any compromise in the integrity of the water supply, such as contamination or tampering, can have severe consequences for the safety of the community relying on that water. Security protocols help prevent intentional or unintentional contamination of the water supply (Teixeira *et al.* 2022). Unauthorized access to water sources, treatment facilities, reservoirs, or distribution points can pose a significant risk to the quality of the water (Berglund *et al.* 2022). Security measures are necessary to protect the physical infrastructure of the water distribution system. This includes reservoirs, treatment plants, pipelines, and pumping stations. Damage or disruption to this infrastructure can result in service outages and pose a threat to public welfare.

With the integration of digital technologies in water distribution systems, the network becomes vulnerable to cyber threats (Tuptuk *et al.* 2021). Security measures are crucial to defend against cyberattacks, such as ransomware or unauthorized access to control systems, which could disrupt water supply operations. There are often regulations and standards in place to ensure the security and quality of water distribution (Edokpayi *et al.* 2020). Adhering to these regulations is not only a legal requirement but also essential for maintaining public trust and confidence in the water supply.

Security in a WDN contributes to preparedness for emergency situations (Zhang *et al.* 2020). Rapid response and recovery from incidents, whether they are physical or cyber-related, are crucial to minimizing the impact on water distribution and public health. Security considerations are integral to effective asset management within a WDN. Protecting physical assets and ensuring the secure operation of digital components contribute to the overall longevity and reliability of the network (Yang *et al.* 2020). A secure and well-managed WDN enhances public perception and trust. Security breaches or water quality issues can erode public confidence in the reliability and safety of the water supply.

In summary, security in WDN is essential for protecting public health, ensuring the integrity of the water supply, and maintaining the resilience and reliability of the infrastructure. Thus, in a digital WDN framework where digital technologies play a significant role in monitoring and control, security becomes even more crucial to defend against emerging cyber threats and to protect sensitive data integral to the network's operations.

4.1.7 Configure management database.

CMDB can help water utilities optimize the WDN by documenting and creating relationships between assets in the WDN (Hummelholm 2019). It is an integral part of a digital WDN framework for several reasons. A CMDB provides a comprehensive and up-to-date inventory of all components and assets within the WDN (Alén 2020), which includes physical assets (pipes, pumps, valves) as well as digital components (sensors, control systems). This visibility is crucial for effective network management. In a WDN, proper configuration of assets and components is essential for optimal performance. A CMDB allows for centralized configuration control, ensuring correct setup and coordinated operation of all elements (Medupe 2009).

A digital WDN is subject to changes, upgrades, and expansions. A CMDB facilitates effective change management by tracking modifications to the network's configuration (Patel *et al.* 2019). This helps in understanding the impact of changes and ensures that they are implemented in a controlled and organized manner. The CMDB helps in tracking the lifecycle of assets (Rose 2016) within the water distribution network and provides information on asset installation dates, maintenance history, and potential replacement or upgrades. This aids in efficient asset management and planning.

By having a clear understanding of the network's configuration, operators can optimize resources and energy consumption. This is particularly important in a WDN where efficient water distribution and energy conservation are key considerations. The CMDB provides a foundation for effective fault management. In the event of issues or disruptions in the network, having detailed information on the configuration allows for quicker identification of the problem source and facilitates timely resolution.

Monitoring the performance of assets and the overall network is crucial for maintaining service quality. The CMDB plays a role in performance monitoring by providing baseline data and allowing operators to set benchmarks for optimal performance (Medupe 2009). In a digital WDN framework where technologies like IoT sensors and smart control systems are prevalent, the CMDB becomes even more critical. It acts as a central repository for information on these digital components, enabling seamless integration and interoperability.

Regulatory compliance is a significant aspect of water distribution. The CMDB assists in ensuring that the network adheres to regulations by providing a record of configurations and changes. It also aids in generating reports for compliance purposes. In a digital WDN, protecting data related to the network's configuration is essential. The CMDB should be designed with security measures to safeguard sensitive information, ensuring the integrity and confidentiality of configuration data.

Overall, a CMDDB is integral to the effective management, optimization, and resilience of a water distribution network. In the context of a digital WDN framework, it becomes a central component for integrating and managing digital technologies, providing a foundation for efficient operation and maintenance of the network. In order to test and validate the digital WDN framework, bibliometric analysis was adopted to build a detailed generic WDN.

4.2 Systematic literature review: Keyword co-occurrence analysis

In preparation of a systematic literature review (SLR), the preliminary literature review systematically compiled all essential keywords. These keywords collectively constitute a search string, instrumental in extracting pertinent documents from the Scopus database. Table 4.1 presents the authors and the associated keywords extracted during the initial literature review. Subsequently, the documents retrieved from Scopus were subjected to bibliometric analysis, aiming to develop a comprehensive generic WDN.

Table 4.1: The summary of keywords and authors

Authors	Keywords
(Alabi et al. 2019)	Water 4.0, Water Digitalization, Integrated Business, Business Model, Industry 4.0
(Franco et al. 2019)	SCADA systems, Protocols, Security, Computer architecture, Wireless sensor networks, water distribution systems
(Magal and Word, 2012)	Trust, Perceived Ease of Use, Perceived Usefulness, Attitude, Simulation, ERP and Education, Educational Technology
(Ali et al. 2021)	An automatic control system, Programmable Logic Controller (PLC), Siemens S7-200 PLC, water flow sensors, submersible pumps, Wireless communication network
(Chofreh et al. 2016)	Sustainable enterprise resource planning, Implementation, Master plan, Concept, Methodology
(Nthutang and Telukdarie 2018)	Integration of SMEs, Industry 4.0 for water services, Smart water network, interoperability of smart water systems, advanced leak detection technology, and automated water balancing
(Vilanova and Balestieri 2014)	Water supply utilities, Electricity conservation, Rational use of water
(Shilenge and Telukdarie, 2021)	4IR, operational technology, information technology infrastructure library, configuration management
Creaco et al. 2019	Model-based control, Real-time control, Water distribution, Valves, Pumps, Pump as turbines
Li et al. 2020	smart water system; framework; smartness; cyber wellness

Analyzing the intellectual structure and prominent topics within research domains involves utilizing the co-occurrence of keywords as a methodology, as outlined by Donthu et al. in 2021. In order to enhance the clarity and interpretability of the map, a dataset consisting of 2000 documents sourced from Scopus was queried with a threshold of 20 for keyword frequency, resulting in the identification of 452 keywords using VOSviewer. To prevent duplication and redundancy, as well as to substitute keywords with their synonyms, the keywords were transformed into thesaurus files using Microsoft Excel. Utilizing the "all keywords" selection in tandem with the thesaurus file

resulted in the removal of 128 keywords, all with the same threshold, through fractional counting from 2011 to the present in titles and abstracts within the research community, as visualized using VOSviewer. Apart from "water distribution systems," the most frequently appearing keywords included "water quality," "leakage detection," "contamination," "internet of things," and "water management."

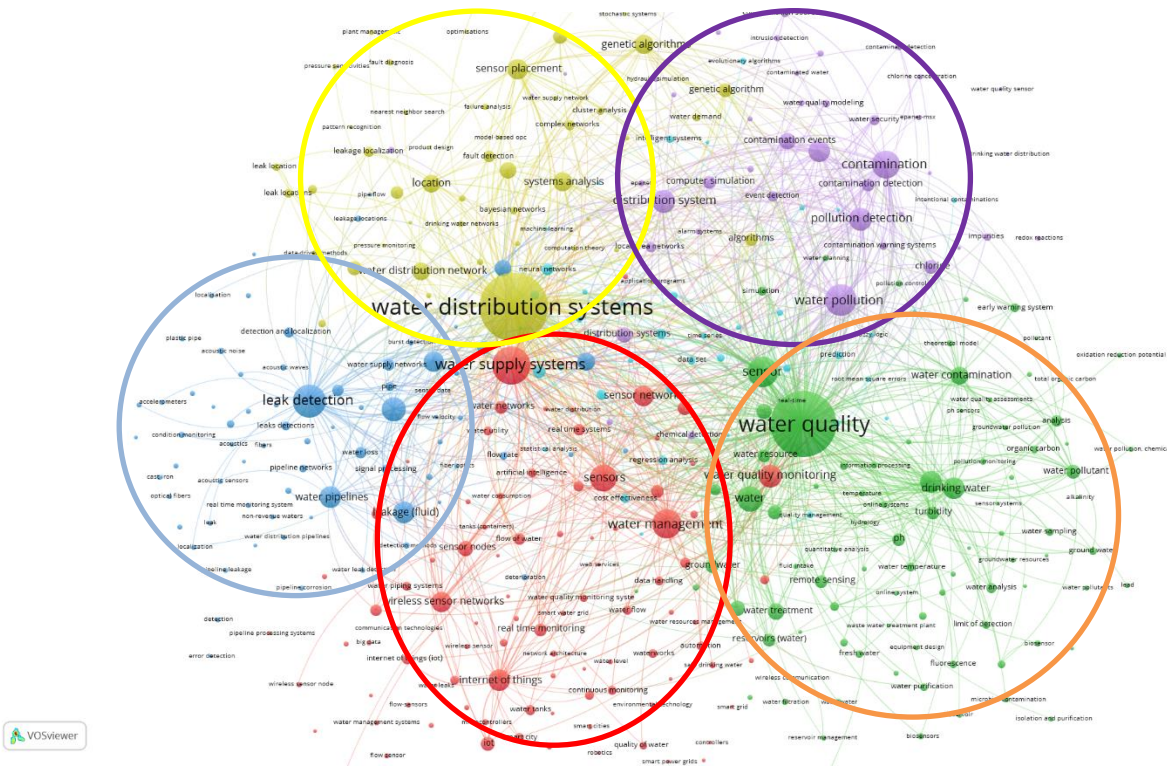


Figure 4.4: Keywords network map for authors

Figure 4.4 illustrates five distinct clusters, encompassing WDN, water quality, leak detection, pollution detection/contamination, and water management. Notably, there is a robust interconnection between WDN and the topics of water quality, leak detection, pollution detection/contamination, and water management. The pronounced association between WDN and water quality, as well as pollution detection/contamination, suggests that challenges related to water quality and pollution are significantly gaining traction as sustainability issues within the realm of WDN research. Additionally, the correlation between WDN and leakage implies that WDN grapples with leakage-related challenges.

Furthermore, the connection between WDN and water management can be interpreted as indicative of the challenges faced by WDN in terms of effective water management. Lastly, in

response to potential water shortages, an "early warning" authority has been established along with a dedicated team to facilitate essential medical intervention.

Perveen (2023) highlights the adoption of various frameworks worldwide, all aimed at ensuring the provision of safe drinking water. One such example is the drinking water quality framework implemented in South Africa. This framework plays a crucial role in enhancing the quality of drinking water by gathering data on the occurrence of water-related diseases, such as diarrhea (Hodgson and Manus 2006). Under this framework, the Department of Health (DoH) takes on the responsibility of monitoring the quality of drinking water, with a specific focus on identifying potential health hazards, including indicators of faecal contamination.

Overall, Figure 4.4 provides an overview of five distinct clusters, one of which is centered around WDN. Additionally, it showcases numerous keywords. Meanwhile, Table 4. 2 presents the top 10 keywords along with their occurrence frequencies and the strength of the connections between them.

Table 4.2: Top frequent keywords

Keywords	Links	Total link strength	Occurrences	Year
water quality	610	6620	476	2017
leak detection	368	1513	146	2018
Sensor	523	2379	132	2017
water pollution	469	2017	130	2017
water management	505	1742	112	2018
Contamination	365	1610	104	2017
fibre optic sensors	303	1010	88	2017
Pipelines	256	896	78	2018
internet of things	301	961	77	2019
pollution detection	315	1215	76	2017

The majority of the keywords originate from the years 2017 and 2018. In 2017, within the WDN cluster, "water quality" emerged as the most prominent keyword, closely followed by "sensors." In 2018, "leak detection" took the lead as the trending keyword, followed by "water management." In 2019, "internet of things" claimed the top spot. However, for the years 2020 and 2021, none of these trending keywords made it into the top 10. This could be attributed to factors such as the COVID-19 pandemic, which may have led to a decrease in publications during these years, or it could signify a higher degree of diversity in publications.

To delve deeper into the objectives of this study, the relationships between the four clusters and WDN were analyzed through keyword co-occurrence. Specifically, the relationships between WDN and water quality, WDN and leak detection, WDN and water management, and WDN and contamination, will be explored as these connections are most relevant to the study.

4.2.1 Water distribution network and water quality

The Scopus search, which employed the keywords "water distribution network" and "water quality," yielded a total of 1 737 documents spanning the years 2013 to 2022. These documents were subsequently exported to VOSviewer for the purpose of conducting a keyword co-occurrence analysis. Figure 4.5 visually represents the results of this keyword co-occurrence analysis.

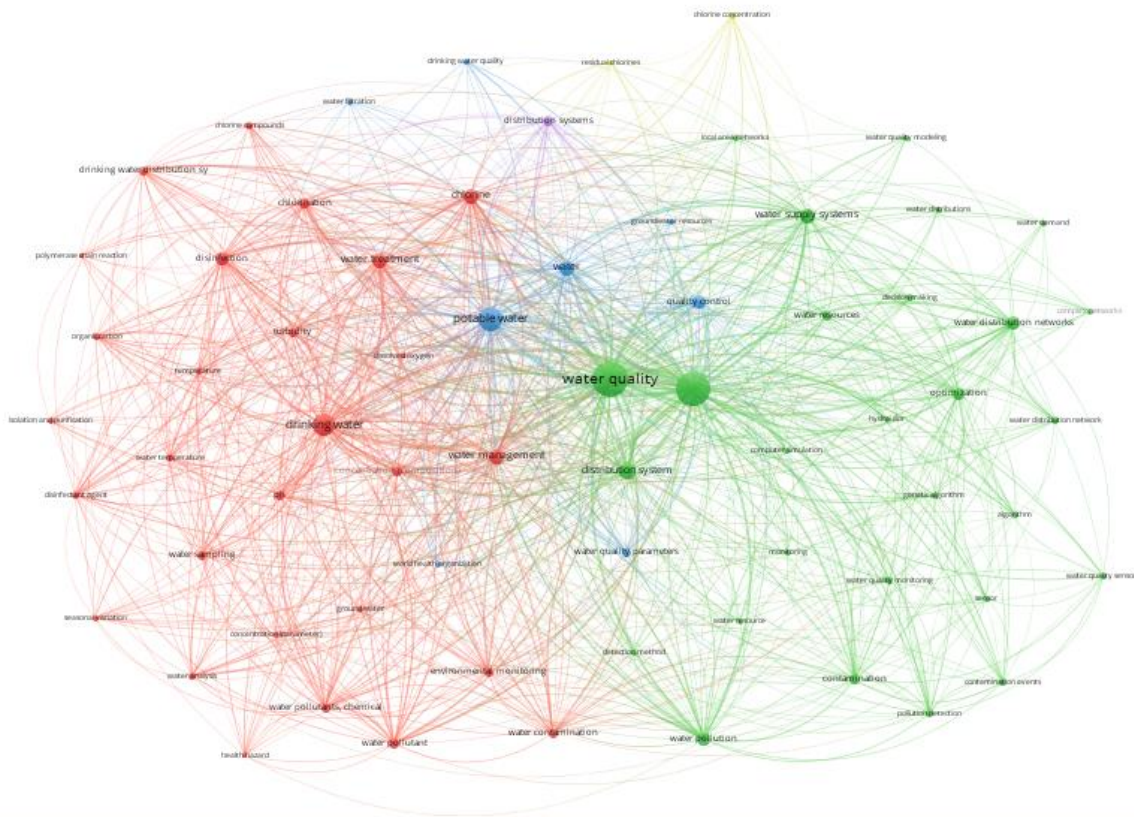


Figure 4.5: Keywords network map for search string “Water distribution system” and “water quality”.

Under this particular cluster, it is noteworthy that the most frequently appearing keyword is "potable water," closely followed by "chlorine." This observation aligns with expectations since potable water quality typically takes center stage in studies related to water quality, and chlorine is a commonly used chemical for the purification of drinking water. The relationship between these keywords is intuitive. Table 4.3 provides a summary of the link strength values between various keywords, offering further insights into their relationships and associations.

Table 4.3: Top frequent keywords and link strength among keywords

	potable water	Chlorine	quality control	water purification	chlorination	water contamination	pH	turbidity	water temperature	organic carbon
potable water	0	157	121	87	77	90	67	67	46	144
Chlorine	157	0	35	81	81	25	55	31	38	37
quality control	121	35	0	38	11	26	14	12	38	10
water purification	87	81	38	0	48	45	29	43	21	31
Chlorination	77	81	11	48	0	11	22	11	16	18
water contamination	90	25	26	56	11	0	19	13	7	6
pH	67	55	14	29	22	19	0	36	32	19
Turbidity	67	31	12	43	11	13	36	0	15	16
water temperature	46	38	38	21	16	7	32	15	0	12
organic carbon	114	37	10	31	18	6	19	16	12	0

The strongest link was observed between "potable water" and "chlorine," while the most fragile link existed between "organic carbon" and "water contamination." Notably, five out of the top 10 keywords were related to water quality indicators, encompassing terms like "chlorine," "turbidity," "pH," "water temperature," and "organic carbon." In a study carried out by Muharemi et al. (2019), a comprehensive examination of water quality was conducted, involving the monitoring of six water quality indicators: chlorine dioxide, pH value, redox potential, electric conductivity, turbidity, and temperature. Various sensors were employed to provide early indications of any alterations in water quality.

Further, a range of machine learning models, including logistic regression, linear discriminant analysis, support vector machines (SVM), artificial neural networks (ANN), deep neural networks (DNN), recurrent neural networks (RNN), and long short-term memory (LSTM), were employed

to assess which model exhibited superior performance in monitoring water quality parameters. The study's conclusion revealed that none of the models demonstrated the capability to effectively monitor and detect water quality challenges (Muharemi et al. 2019).

Technologies, equipment and Systems

Among the equipment and technologies featured in the keyword network analysis, "pump" and "sensors" stood out with link strengths of 215 and 117, respectively. The inclusion of "GIS" as the sole system in this network, with a link strength of 181, suggests its relevance within the research domain. Further, the IoT emerged as the only representative of 4IR technologies in this network, boasting a link strength of 185. This signifies a noteworthy interest among researchers in incorporating 4IR technologies into this research area. Notably, "real-time" is a keyword that commanded considerable attention, featuring a link strength of 483. This suggests that water researchers are keenly focused on the real-time monitoring of water quality, reflecting a strong interest in the timeliness and immediacy of data in this field.

4.2.2 Water distribution network and leak detection

In the search for "water distribution network" and "leak detection" in Scopus with a publication year range of 2013 to 2022, a total of 260 results were retrieved. These documents were then exported to VOSviewer for the purpose of conducting keyword co-occurrence analysis. Figure 4.6 visually represents the results of this keyword co-occurrence analysis.

support vector machine (SVM). Building upon the use of accelerometers, similar to El-Zahab et al. (2018), this system leverages their ability to accurately quantify vibration magnitudes. In this study, accelerometer data is collected and transmitted via wired cables from the sensor node to a data acquisition board. From there, it is further transmitted to a server gateway, where it undergoes analysis to detect relevant events. The one-dimensional CNN and support vector machine are employed for data analysis, enhancing the accuracy and efficiency of water leakage detection. Table 4.4 provides a summary of the connections and relationships between various keywords found within this cluster, shedding light on the key themes and concepts within this research domain.

Table 4.4: Top frequent keywords and link strength among keywords

	<i>pipelines</i>	<i>detection method</i>	<i>detection and localization</i>	<i>machine learning</i>	<i>fibre optic sensors</i>	<i>leak locations</i>	<i>potable water</i>	<i>water loss</i>	<i>artificial intelligence</i>
<i>Pipelines</i>	0	9	5	4	5	4	6	2	1
<i>detection method</i>	9	0	5	8	3	3	1	5	2
<i>detection and localization</i>	5	5	0	5	4	1	5	1	1
<i>machine learning</i>	4	8	5	0	1		3	2	3
<i>fibre optic sensors</i>	5	3	4	1	0	1	2	1	1
<i>leak locations</i>	4	3	1		1	0	1	1	1
<i>potable water</i>	6	1	5	3	2	1	0	1	
<i>water loss</i>	2	5	1	2	1	1	1	0	2
<i>Monitoring</i>	6	1	1	1		1	2	2	
<i>artificial intelligence</i>	1	2	1	3	1	1		2	0

In the keyword co-occurrence analysis within the WDN research cluster, the most robust link was observed between "detection methods" and "pipelines," indicating a strong focus on methods for detecting leaks within pipelines. Conversely, the weakest links were found between "artificial intelligence" and "monitoring," suggesting a lesser emphasis on the application of artificial intelligence in monitoring within this context. Within the context of WDN and leakage detection, two 4IR technologies, namely "machine learning" and "artificial intelligence," emerged prominently. Additionally, "fibre optic sensor," an emerging technology, ranked among the top 10 keywords. This implies that emerging and 4IR technologies significantly influence research into water leakage methods within WDN, highlighting a shift towards advanced technological approaches in this domain.

Water leakages pose a significant challenge within WDN, as highlighted by Zhang et al. in 2019. The results presented in this context indicate the existence of various methods for detecting and localizing these leaks. The keyword "detection and localization" suggests that there are

approaches available for pinpointing the precise locations of water leakages within these networks. In a study conducted by Rojek and Studzinski in 2019, an algorithm for leak detection and localization was developed. This algorithm leveraged multi-layer perceptron (MLP) and Kohonen neural networks as part of a comprehensive subsystem. This subsystem integrated a GIS, a SCADA system, and a hydraulic model of the water supply network. Such an integrated approach reflects the multidisciplinary nature of addressing water leakage challenges within WDNs.

Technologies, equipment and systems

The apparatus featured within this domain encompasses various components, including sensors like accelerometers, which represent an emerging technology in the field of WDN. Additionally, acoustic sensors, turbines, robotic devices, pressure-reducing valves, and pressure sensors constitute other essential equipment within this research cluster. Furthermore, the technologies associated with the 4IR that find application in this context encompass artificial intelligence, machine learning, IoT, and deep learning. Moreover, the SCADA system was utilized within this sphere.

4.2.3 Water distribution network and water management

Restricting the publication years to the period between 2013 and 2022, a Scopus query combining "water distribution network" and "water management" produced a dataset of 1 240 documents. These documents were downloaded and subsequently exported to VOSviewer for the purpose of conducting a keyword co-occurrence analysis. Figure 4.7 provides a visualization of the results of this keyword co-occurrence analysis.

Table 4.5: Top frequent keywords and link strength among keywords

	WATER PURIFICATION	POTABLE WATER	WATER QUALITY	WATER SAMPLING	CHLORINE	CHLORINATION	PH	OPTIMIZATION	WATER CONSERVATION	WATER POLLUTION
WATER PURIFICATION	0	183	130	37	134	116	63	9	12	29
POTABLE WATER	183	0	149	33	110	90	51	16	37	44
WATER QUALITY	130	149	0	35	83	53	33	39	49	38
WATER SAMPLING	37	33	35	0	19	21	8	1	3	3
CHLORINE	134	110	83	19	0	88	42	12	16	13
CHLORINATION	116	90	53	21	88	0	36	7	10	9
PH	63	51	33	8	42	36	0	3	4	10
OPTIMIZATION	9	16	39	1	12	7	3	0	24	6
WATER CONSERVATION	12	37	49	3	16	10	4	24	0	8
WATER POLLUTION	29	44	38	3	13	9	10	6	8	0

The most robust association was observed between "water purification" and "potable water,". As stated by Arsene et al. (2022), global issues surrounding water quality and water leakage underscore the urgency of effective water resource management. The utilization of the IoT offers innovative approaches to enhance water management, ultimately enabling a more efficient use of this limited resource (Arsene et al. 2022). Presently, a significant challenge faced by municipal corporations worldwide is the detection of unidentified leaks within WDNs. To address this problem, Grace, Stephen, Paul and Thusnavisk (2019) proposed a system that employs IoT technology to identify and locate pipeline leaks during the distribution of water. This system utilizes a Raspberry Pi as the central device, collecting data from various subordinate nodes and transmitting it to the cloud. Upon the detection and localization of a leak, the system promptly sends a notification to the user's mobile device via a dedicated app.

Technologies, equipment and Systems

The equipment featured within this research cluster comprises pumps, sensors, and water tanks. In this particular context, the only system employed is GIS. Furthermore, the 4IR technologies that are relevant to this domain encompass the IoT and big data.

4.2.4 Water distribution network and contamination

When narrowing the publication years to the period between 2013 and 2022, a Scopus search using the keywords "Water distribution network" and "contamination" yielded a total of 777 documents. These documents were subsequently exported to VOSviewer for the purpose of

conducting a keyword co-occurrence analysis. Figure 4.8 provides a visual representation of the results obtained from this keyword co-occurrence analysis.

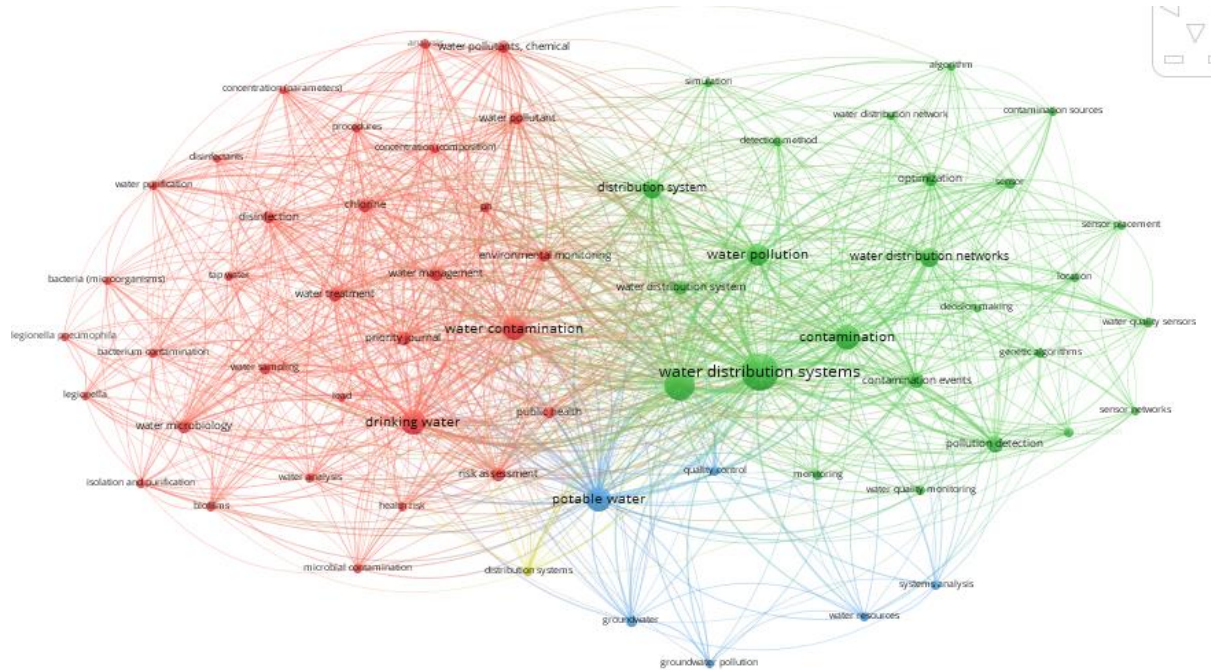


Figure 4.8: Keywords network map for search string “Water distribution system” and “contamination”.

Within this cluster, the keyword that appeared most frequently was "water quality," closely followed by "potable water." To provide a succinct overview of the relationships between various trends in this cluster, Table 4.6 has been prepared to summarize the relevant information.

Table 4.6: Top frequent keywords and link strength among keywords

	water quality	potable water	water microbiology	chlorine	water management	Bacterium	water sampling	water purification	pollution detection	Escherichia coli
water quality	0	162	44	51	54	31	38	28	85	35
potable water	162	0	26	37	37	23	29	20	31	29
water microbiology	44	26	0	18	20	35	21	16	3	21
Chlorine	51	37	18	0	14	13	13	17	10	10
water management	54	37	20	14	0	17	11	36	3	6
Bacterium	31	23	35	13	17	0	17	14	2	14
water sampling	38	29	21	13	11	17	0	11	2	11
water purification	28	20	16	17	36	14	11	0	3	5
pollution detection	85	31	3	10	3	2	2	3	0	5
escherichia coli	35	29	21	10	6	14	11	5	5	0

The most robust connection existed between "water quality" and "portable water". As highlighted by Smith et al. (2017), water contamination stands as one of the paramount global challenges. To address the issue of water quality within WDN, Saravanan et al. (2018) proposed a novel SCADA system that seamlessly integrates with IoT technology for real-time water quality monitoring. Saravanan et al. (2018) identified a major gap in their study: the prevalent use of SCADA systems built atop PLCs, which makes incorporating new sensors into the existing infrastructure cumbersome. They incorporated parameters such as temperature, turbidity, and colour into the system, enabling real-time monitoring to assess water quality within the WDN.

Sorensen et al. (2018) proposed the implementation of online fluorescence spectroscopy as a means of real-time assessment of the microbial quality of drinking water to combat water contamination arising from microorganisms within the WDN. There is substantial research indicating that wastewater typically exhibits more pronounced fluorescence signals associated with dissolved organic matter (DOM) compared to clean water, especially at specific excitation/emission wavelength pairs. Consequently, fluorescence spectroscopy holds promise as a valuable indicator for assessing the contamination of natural water sources intended for drinking purposes, as demonstrated in the work of Stedmon, Seredyńska-Sobecka et al. (2011).

As established in the study conducted by Stedmon et al (2015), online fluorescence spectroscopy stood out as a reliable indicator for assessing the microbial quality of untreated drinking water. This innovative approach exhibits the capacity to be employed across the entirety of the water supply chain, making it possible to detect changes in water quality that could potentially indicate the presence of enteric pathogens, as emphasized in the findings by Sorensen, Vivanco, et al. (2018).

Technologies, equipment and Systems

The equipment associated with this research area comprises pumps and sensors. In terms of systems, the research predominantly involves GIS, RTU, PLC, and Supervisory Control and SCADA systems. Additionally, the 4IR technologies that play a significant role in this domain encompass IoT, artificial intelligence, and big data.

The keyword co-occurrence analysis aligns with the findings of the content analysis, as the equipment, technologies, and systems identified in the maps of the four clusters are consistent with the content analysis. To consolidate this information, Table 4.7 has been compiled to provide a comprehensive summary of all the equipment and technologies extracted from the content analysis.

Table 4.7: The summary of equipment systems used to solve water quality challenges.

Authors	Kind of approach	Equipment	Systems
(Muharemi et al. 2019)	experimental (field)	Flow, temperature and colour smart sensors, Arduino uno board	SCADA
(Sorensen et al. 2018)	experimental (field)	Temperature, Chlorine dioxide, pH, redox potential, electric conductivity, turbidity	
(Saravanan et al. 2018)	experimental (field)	telemetered UviLux fluorimeter, temperature sensors	
(El-Zahab et al.2018)	experimental (field)	Accelerometers	
(Marmarokopos et al. 2018)	experimental (laboratory)	Accelerometers	

Both keyword co-occurrence and content analysis highlight that water utilities or researchers are showing interest in bringing in 4IR to mitigate some of the challenges faced by WDN. The 4IR technologies that appear in the analysis include artificial intelligence, IoT, and machine learning. Table 4.8 summarizes the equipment, systems and technologies that are used in a WDN per keyword occurrence of the four clusters.

Table 4.8: The summary of equipment, systems and technologies extracted from various clusters.

Layer	Equipment
-------	-----------

Physical	sensors, accelerometer, acoustic sensors, turbines, robots, pressure reducing valves, pressure sensors, pumps, water tank and PLC
Communication	RTU
Data storage and data analysis	SCADA
Benefit Layer	WDN Monitoring, Pressure regulation, Leakage management, and Water quality monitoring
Application Layer	GIS

The observation that the equipment and technologies listed in Table 4. 8 also correspond to those found in the preliminary literature review indicates a degree of consistency in the research findings. It is not surprising that certain business systems like ERP (Enterprise Resource Planning) do not appear in the keyword co-occurrence of the four clusters, as these clusters primarily focus on technical challenges within the context of WDN.

The equipment, systems, and technologies, especially those related to the 4IR, that have been identified through these analyses can be regarded as best practices in the realm of WDN. However, it is important to acknowledge that keyword co-occurrence analysis tends to highlight the most frequently used and researched technologies, potentially omitting fewer common ones. The field of WDN is diverse and may involve specialized or region-specific technologies that may not appear in the keyword analysis but are still relevant in certain contexts. Figure 4.9 depicts the generic WDN.

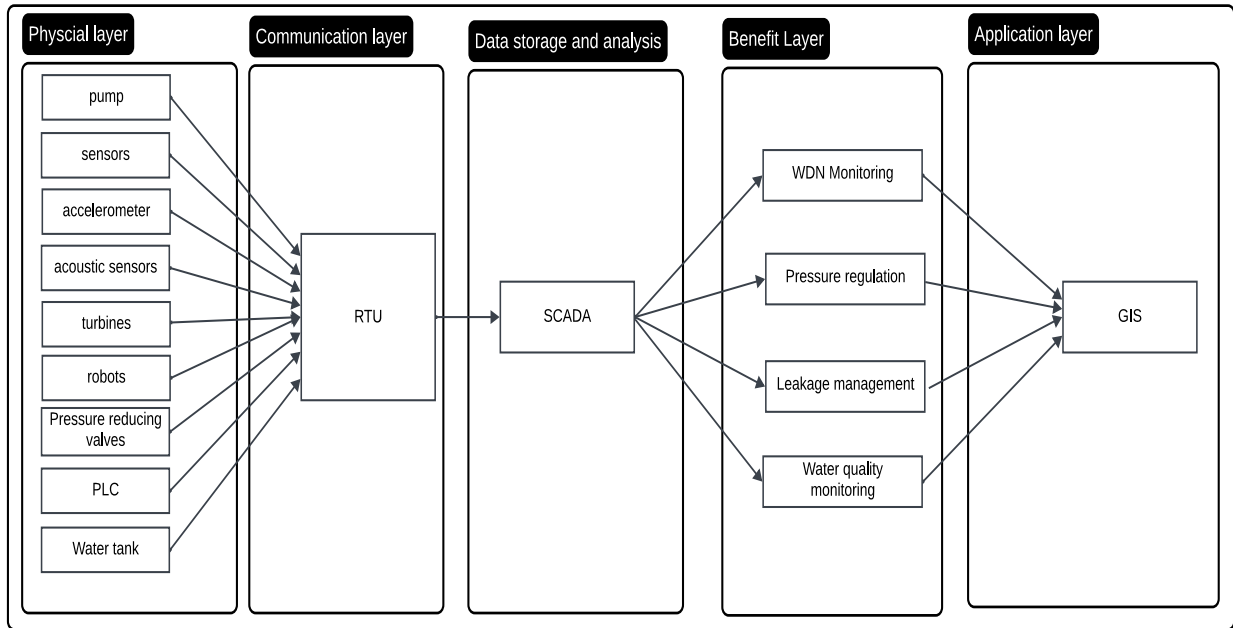


Figure 4.9: Generic WDN

Overall, the systematic literature review (SLR) results in a generic WDN consisting of five layers that interact with each other to cater to consumer needs. In order to further validate the framework, a CMDB was developed using the Johannesburg Water WDN.

4.3 Configuration management database

Johannesburg Water possessed information regarding tags within their OPC, SQL server, and SCADA systems. However, the relationships among these CIs or tags were not defined. Furthermore, there is no documentation to record the replacement of one tag with another. In order to establish relationships between the CIs and better understand how data flows from sensors to the enterprise ERP system, it is important to adopt CMDB to create the relationships between the tags. Further, CMDB acts as an asset management database for OT tags that are active in the Johannesburg Water WDN. Furthermore, the CMDB serves as the authoritative source for the WDN and can be used to validate the framework, particularly the architecture of the framework.

In this effort to develop the CMDB, data pertaining to CIs was extracted from the SCADA systems and OPC, including various attributes that describe these tags. The resulting data set was typically presented in Excel format, making it accessible and manageable for further analysis and integration.

Figure 4.10 provides an overview of the attributes present in the CMDB. These attributes encompass critical information about the CIs including Device_Classification, Part, Vendor,

Product_Description, Version, Update, Edition Software_Edition, Target_Software, Language, Device_Class1, Device_Class2, Device_Class3, Target_Network, ID_Number, Location, Extend_Information, Time_Stamp, Network_Type, Physical_Address, Network_Address, Neighbor_Device and Master.

Typically, in a CMDB, additional attributes such as installation dates and warranty expiration dates are also included. However, it is worth noting that in this study, data related to the tags' installation dates and warranty expiration was unavailable or could not be obtained. By thoroughly documenting these attributes and their associated CIs, Johannesburg Water enhances its ability to manage, monitor, and maintain its operational infrastructure effectively. This systematic approach to data collection and management aids in the organization's decision-making processes and contributes to the overall reliability and efficiency of the WDN.

	Column Name	Data Type	Allow Nulls
	Device_Classification	varchar(120)	<input checked="" type="checkbox"/>
	Part	varchar(120)	<input checked="" type="checkbox"/>
	Vendor	varchar(120)	<input checked="" type="checkbox"/>
	Product_Description	varchar(120)	<input checked="" type="checkbox"/>
	Version	varchar(120)	<input checked="" type="checkbox"/>
	[Update]	varchar(120)	<input checked="" type="checkbox"/>
	Edition	varchar(120)	<input checked="" type="checkbox"/>
	Software_Edition	varchar(120)	<input checked="" type="checkbox"/>
	Target_Software	varchar(120)	<input checked="" type="checkbox"/>
	Language	varchar(120)	<input checked="" type="checkbox"/>
	Device_Class1	varchar(120)	<input checked="" type="checkbox"/>
	Device_Class2	varchar(120)	<input checked="" type="checkbox"/>
	Device_Class3	varchar(120)	<input checked="" type="checkbox"/>
	Target_Network	varchar(120)	<input checked="" type="checkbox"/>
▶	ID_Number	varchar(120)	<input type="checkbox"/>
	Location	varchar(120)	<input checked="" type="checkbox"/>
	Extend_Information	varchar(120)	<input checked="" type="checkbox"/>
	Time_Stamp	varchar(120)	<input checked="" type="checkbox"/>
	Network_Type	varchar(120)	<input checked="" type="checkbox"/>
	Physical_Address	varchar(120)	<input checked="" type="checkbox"/>
	Network_Address	nvarchar(1)	<input checked="" type="checkbox"/>
	Neighbor_Device_1	varchar(120)	<input checked="" type="checkbox"/>
	Master	varchar(120)	<input checked="" type="checkbox"/>
			<input type="checkbox"/>

Figure 4.10: The design model for CMDB

In the Johannesburg Water SQL server, the ID_Number functions as the primary key, just as in a relational database, a primary key is a unique identifier that enables efficient data retrieval and organization within a table. It is important to emphasize that each table can only have one primary key to ensure data integrity and uniqueness.

Similarly, within the context of the CMDB, the ID_Number is also employed as the primary key. This consistent usage of the primary key maintains uniformity and data integrity across the database. The construction of the primary key at Johannesburg Water adheres to a structured format that combines specific components:

- **Location of the Device in the WDN:** This component signifies the precise physical location of the device within the network.
- **Device classification:** This aspect categorizes the device based on its type or purpose.
- **Unique Number:** A numerical value that serves as a distinct identifier for each individual device of the same type at the same location.

For instance, a level meter situated in Pimville in Soweto, its primary key, following this naming convention, would be "pmvl-level-1".

The CMDB data model was thoughtfully designed to incorporate all the necessary information required to comprehensively understand any OT asset. Table 4.9 provides a detailed explanation of the CMDB attributes and their meanings, further enhancing the utility of the CMDB's effectiveness in asset management and related processes.

Table 4.9: Table of Attributes and Explanations for Device and Product Data

Attribute	Explanation
Device_Classification	The classification of the device, such as its type or category (e.g., Level Meters, Alarms, PLC, SCADA, sensor, etc).
Part	A reference or identifier for a specific part or component of a device or system
Vendor	The manufacturer or provider of the device or product.
Product_Description	A brief description of the product or device.
Version	The version number of the product or device.
Update	Information about any updates or patches applied to the product or device.
Edition	The specific edition or variant of the product.
Software_Edition	The edition or version of the software associated with the device or product.
Target_Software	The software or application targeted or used by the device.
Language	The language settings or localization of the device or software.
Device_Class1	A hierarchical classification for the device (e.g., high-level category).
Device_Class2	A secondary level of classification for the device.

Device_Class3	A tertiary level of classification for the device.
Target_Network	The network to which the device is intended to connect.
ID_Number	A unique identifier or serial number for the device.
Location	The physical location or placement of the device.
Extend_Information	Additional information or details about the device or product.
Time_Stamp	The timestamp indicating when the data was recorded or updated.
Network_Type	The type of network connection (e.g., wired, wireless, cellular).

The CMDB was developed with several primary objectives in mind, including OT asset management, historian, and the integration of asset information.

- **OT Asset Management:** The CMDB functions as a critical tool for effectively managing operational technology (OT) assets. It assists in organizing and tracking vital information related to these assets.
- **Historian of OT:** By retaining comprehensive records of OT assets and their associated attributes, the CMDB acts as a historical repository, allowing for insights into asset performance and changes over time.
- **Integration of Asset Information:** The CMDB streamlines the integration of asset information with incident management and change management processes. This integration enhances decision-making and ensures efficient management of asset-related incidents and changes.

The asset management system was thoughtfully designed with a central objective in mind: to provide robust support for a variety of services within the operational technology (OT) environment. Additionally, the system was intended to facilitate a clear and comprehensive understanding of this complex environment for the various teams involved.

One of the valuable capabilities of the CMDB is its capacity to quantify the number of tags installed within the WDN. As depicted in Figure 2. 21, the CMDB reports that there are 10 201 tags within the Johannesburg Water WDN. However, it is essential to exercise caution when interpreting Figure 4.11, as it may not necessarily represent the absolute and accurate count of tags within the Johannesburg Water WDN.

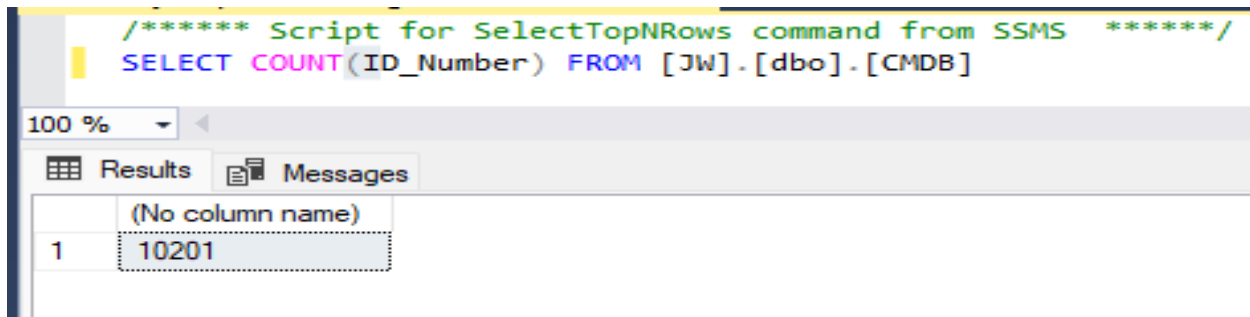


Figure 4.11: Number of tags stored in the CMDB.

The reliability of this count depends on the accuracy and completeness of the data input into the CMDB. Factors such as data quality, consistency, and updates can influence the precision of this information. Therefore, while the CMDB provides a valuable estimate of the number of tags, it is essential to recognize that this number might not always provide an entirely accurate reflection of the actual tags present within the Johannesburg Water WDN. Continuous data maintenance and verification processes are necessary to ensure the CMDB remains a reliable resource for asset management and decision-making within the OT environment.

A configuration management database is a database that stores information about assets, but it alone does not constitute a comprehensive asset management solution. It serves as a foundational element and a starting point for creating an asset management solution. The CMDB is essential for storing asset-related data, but the process of keeping it accurate and updated is equally important. Employing asset discovery solutions is necessary to maintain an updated CMDB, although these details are not relevant to the specific context discussed in this work. The solution should be designed to automatically transmit data to the CMDB and update asset information without requiring manual intervention. This automated process is particularly valuable for populating the CMDB initially, as manually inputting information for a large number of devices would be highly labor-intensive. However, it is important to note that automatic updates should be handled with care. In cases where an update could change an attribute that should not change automatically, such as an IP address, the automated update should be prevented. Instead, a notification should be sent to the Operational Technology (OT) security team to perform a manual check and make any necessary updates.

This helps ensure the integrity and security of the asset data within the CMDB. There are numerous scenarios where a manual update of the configuration management database (CMDB) becomes necessary, particularly when an asset is retired or experiences adjustments due to a change process. In instances of asset retirement, the responsibility falls upon the asset owner to report this to the relevant department, ensuring that the CMDB is kept up to date. Conversely, when changes occur, it is explicitly specified within the change process itself who is accountable for updating the documentation, including the CMDB.

For instance, when dealing with network devices, the onus for documenting changes lies with the OT security team once the Network Operations Center (NOC) has executed the change. This collaborative and process-driven approach ensures that the CMDB accurately reflects the evolving state of assets and their configurations.

4.3.2 CI relationships

Beyond the management of actively used assets, Configuration Management Databases (CMDBs) play a crucial role in mapping relationships between Configuration Items (CIs) or tags. These relationships serve as a critical component in assessing the potential impact of removing a CI on the entire operational process. Figure 4.12 provides a visual representation of the dependencies associated with the MTU having an ID_Number of Radio-CH1. This MTU is responsible for receiving data from RTUs installed in reservoirs and towers. 10 RTUs located in different locations are depicted. Further, the CIs or tags found under each RTU can be determined by replacing ID_number (Radio-CH1) with a relevant ID_number (e.g., BEREA_FRM) under the “SELECT” query.

The screenshot shows a SQL query window with the following query:

```
SELECT TOP(10) [Device_Classification]
, [Vendor]
, [Product_Description]
, [Device_Class1]
, [Device_Class2]
, [Device_Class3]
, [Target_Network]
, [ID_Number]
, [Location]
FROM [JW].[dbo].[CMDB]
WHERE Target_Network='Radio-CH1'
```

The results table is as follows:

	Device_Classification	Vendor	Product_Description	Device_Class1	Device_Class2	Device_Class3	Target_Network	ID_Number	Location
1	RTU	SSE	Berea telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	BEREA_FRM	Berea
2	RTU	SSE	Brixton telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	BRIXTN_FRM	Brixton
3	RTU	SSE	Bryanston telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	BRYAN_FRM	Bryanston
4	RTU	SSE	Hector nomis telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	C-HCTNP_FRM	Hector Nomis
5	RTU	SSE	Crosby telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	CRSBY_FRM	Crosby
6	RTU	SSE	Dunkeld telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	DNKLD_FRM	Dunkeld
7	RTU	SSE	Hurst hill telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	HRTHL_FRM	Hurst Hill
8	RTU	SSE	Ilove telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	ILOVO_FRM	Ilove
9	RTU	SSE	Linbro park telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	LNBRP_FRM	Linbro Park
10	RTU	SSE	Parktown telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	PRKTN_FRM	Parktown

Figure 4.12: CI relations of RTUs

The significance of these relationships becomes evident when considering the potential consequences of removing this MTU from the network. Without this MTU, upstream tags would cease to receive crucial data, disrupting the flow of information within the system. Furthermore, since the RTU also provides vital logic to the reservoir, its removal would jeopardize the entire operation, potentially leading to a system-wide failure.

In essence, this example underscores the significant role that CMDBs and relationship mapping play in assessing the ripple effects of CI changes within a complex system, enabling informed decision-making and risk mitigation strategies.

4.3.3 change management and historian

It is a common practice among water utilities to update tags as they age, or as newer technologies become available. This proactive approach helps utilities enhance their processes and ensure they stay up to date with the latest technologies. However, the way these changes are tracked varies across utilities, with some using Excel sheets while others may not have a tracking system in place.

The Configuration Management Database (CMDB) offers valuable functionalities, including change management and historical tracking, which can greatly benefit water utilities. In the CMDB developed for this specific study, the change management feature plays a crucial role. When a tag is replaced by a newer one, the CMDB captures information about the new tag and stores it in the CMDB table. Simultaneously, pertinent details about the replaced tag are preserved in the change table. This dual-storage approach ensures compliance with established change management processes, providing transparency and accountability.

Moreover, the change table acts as a historian by documenting these changes and saving them in the database. Over time, this historical data enables utilities to gain insights into asset performance and how it has evolved. By analyzing the change history, utilities can make informed decisions about maintenance, upgrades, and optimizations, ultimately enhancing the efficiency and reliability of their WDNs. In the upcoming section, there will be a case study that highlights how the CIs work together to serve the residents of Johannesburg.

4.4 Case study: Johannesburg Water

Johannesburg Water, commonly known as Joburg Water, operates as a municipal entity within the city of Johannesburg. Its primary mission is to provide a substantial volume of approximately 1.6 billion liters of clean, potable water daily to serve the city's sizable population of around five million people (Sioga, 2020). The main source of this potable water supply is Rand Water. Additionally, Johannesburg maintains wastewater treatment facilities that play a role in augmenting the potable water supply.

The extensive WDN managed by Johannesburg Water spans a total length of 12 288 kilometers. Within this network, there are 127 reservoirs and water towers, as well as 37 water pump stations. For the wastewater management aspect, Johannesburg Water oversees an intricate network comprising 11 710 kilometers of wastewater networks, which are connected to 38 sewerage pump stations.

Johannesburg Water's commitment to environmental sustainability is exemplified by its treatment of a significant volume of 926 million liters per day of sewage at six wastewater treatment works

(WWTW). Notably, one of these treatment works includes a biogas-to-energy plant, where methane gas is converted into a valuable source of energy (Sioga 2020). This innovative approach reflects the organization's dedication to responsible and eco-friendly practices in managing wastewater and harnessing renewable energy resources.

The water infrastructure managed by Johannesburg Water is categorized as an integrated urban water system. This classification stems from the incorporation of various essential components, including a drinking water distribution system, water treatment plants, stormwater systems, and wastewater collection systems. For the purposes of this case study, our primary focus will be on the WDN.

Similar to a standard WDN, the Johannesburg Water WDN comprises a fundamental set of components, such as pipes, valves, pumping stations, reservoirs, and pressure-reducing valves. These core elements are strategically distributed across six distinct regions within Johannesburg. These regions are identified as region A, region B, region C, region D, region E, and region F. Figure 4.13 serves to visually highlight the geographical boundaries of these six Johannesburg Water regions, providing an overview of their spatial distribution within the city.



Figure 4.13: The Johannesburg water regions (Sioga 2020).

4.4.1 Physical layer

The physical layer of the Johannesburg Water WDN consists of 127 reservoirs and towers distributed throughout the six regions. The reservoirs are used to store potable water supplied by Rand Water. In some areas, particularly those with high gravity, the reservoirs work hand in hand with the towers. Each reservoir or tower is equipped with water level meters to measure the water level in the reservoir, which ensures that the operators are aware whenever the reservoir is about to overflow or run dry. Further, there are pumps in the reservoirs that are used to pump water to fill the towers and drive water to the surrounding areas. Furthermore, flow meters are installed to measure the flow of water from and to the reservoirs. All this operating apparatus is connected to the RTUs that are available in every reservoir. The RTU is where the process control logic is set. The RTU has a radio module that helps each reservoir station or tower communicate with the master terminal unit (MTU).

In order to measure the full reservoir level accurately, non-contact level sensors are adopted by Johannesburg Water according to the level of the full reservoir. For reservoirs with more than 20 meters of water level, RADAR level transmitters are used, while ultrasonic level transmitters are used for reservoirs with less than 20 meters of water level. Ultrasonic or RADAR level transmitters allow simple and reliable non-contact level measurement of water levels in reservoirs. Microprocessor-controlled electronics transmit a pulse at the surface of the water, which is reflected back to the antenna. In order to determine the reservoir's water level, the "round trip" flight time is calculated. Figure 4.14 shows the type of level sensors that are used by Johannesburg Water to measure the water level across 144 reservoirs.

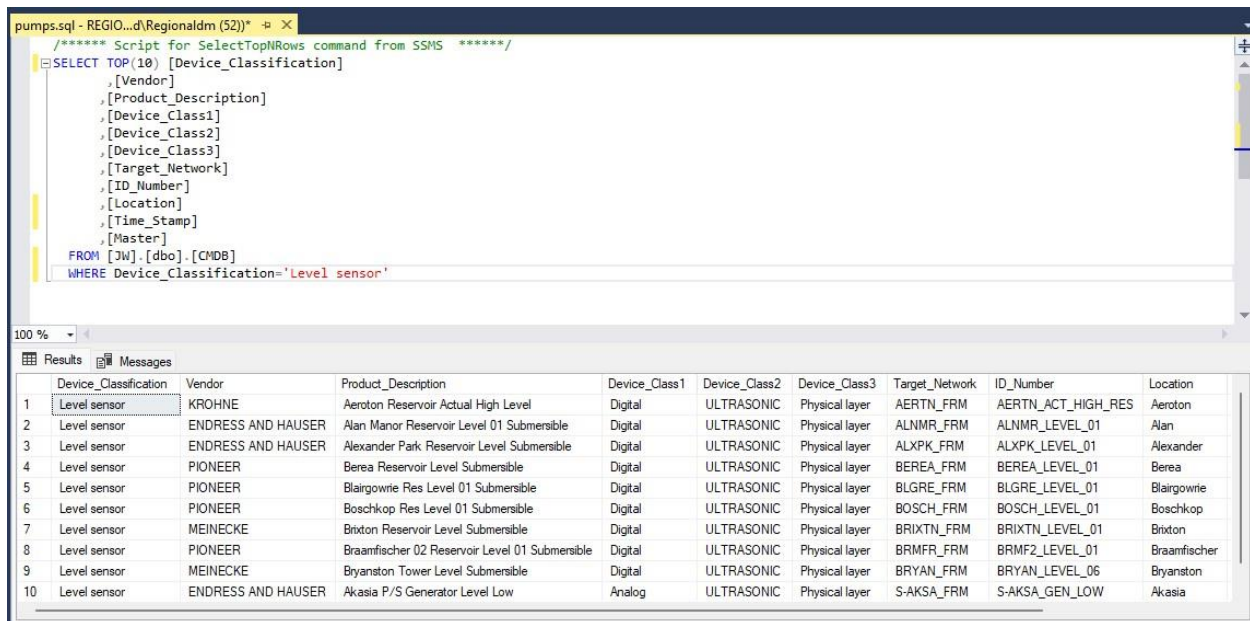


Figure 4.14: Level meters captured in the CMDB.

It highlights that the 10-level sensors installed at Johannesburg Water WDN are ultrasonic. The primary_ID (ID_Number) of the RTU that each level sensor is connected to is highlighted under the Target_Network column. The data was retrieved by querying the JW database to return the top 10 level of sensors stored in the CMDB. These 10-level sensors are the level sensors displayed when scrolling through the CMDB table. Figure 4.14 also provides a description of the level sensors, along with the name and make of the sensor (the vendor), among other level sensor information. In a reservoir, Johannesburg Water usually installs two water level sensors to ensure the quality of the measured values. In cases where there is a deviation between the two measured values, responsive maintenance will be triggered. The water level sensors, along with the pumps and flow meter, are connected to the RTU that is available at every reservoir station.

As previously highlighted, in the reservoirs, pumps are used to pump the water to the top of the towers and drive water to the consumers. In an area with a larger water demand, pumping stations are adopted instead of just a few pumps. This is true in an area such as Region F, where two pumping stations are installed in order to pump water into two towers. The water is pumped from four reservoirs with a total volume of 114.1 million liters. Figure 4.15 highlights the pumps that are found in some reservoirs in the WDN.

```

/***** Script for SelectTopNRows command from SSMS *****/
SELECT TOP(10) [Device_Classification]
, [Vendor]
, [Product_Description]
, [Device_Class1]
, [Device_Class2]
, [Device_Class3]
, [Target_Network]
, [ID_Number]
, [Location]
, [Time_Stamp]
, [Master]
FROM [JW].[dbo].[CMDB]
WHERE Device_Classification='pump'

```

	Device_Classification	Vendor	Product_Description	Device_Class1	Device_Class2	Device_Class3	Target_Network	ID_Number	Location
1	Pump	Boyd Brown	Berea Pump 01 Run	Analog	centrifugal	Physical layer	BEREA_FRM	BEREA_RUN_01	Berea
2	Pump	Sulzer	Crosby Pump 01 Run	Analog	centrifugal	Physical layer	CRSBY_FRM	CRSBY_RUN_01	Crosby
3	Pump	Salweir	Florida North PS Pump 01 Run	Analog	centrifugal	Physical layer	FLDNT_FRM	FLDNT_RUN_01	Florida
4	Pump	Mather and Platts	Forest Hill Pump 01 Run	Analog	centrifugal	Physical layer	FRSTH_FRM	FRSTH_RUN_01	Forest
5	Pump	Worthington-Simpson	Helderkrain Pump 01 Run	Analog	centrifugal	Physical layer	HLDKN_FRM	HLDKN_RUN_01	Helderkrain
6	Pump	Worthington-Simpson	Horizon Pump 01 Run	Analog	centrifugal	Physical layer	HORTW_FRM	HORZN_RUN_01	Horizon
7	Pump	KSB	Illovo Pump 01 Run	Analog	centrifugal	Physical layer	ILOVO_FRM	ILOVO_RUN_01	Illovo
8	Pump	KSB	Orange Farn LL Pump 01 Run	Analog	centrifugal	Physical layer	ORFLL_FRM	ORFLL_RUN_01	Orange
9	Pump	Halberg	Rabie Ridge Pump 01 Run	Analog	centrifugal	Physical layer	RBRDG_FRM	RBRDG_RUN_01	Rabie
10	Pump	Braybar	Robertville Pump 01 Run	Analog	centrifugal	Physical layer	C-ROSET_FRM	RBTVL_RUN_01	Robertville

Figure 4.15: Pumps captured in the CMDB.

Another important apparatus that forms part of the reservoirs is the flow meters (Figure 4.16), which are used to measure the flow rate of water fed into the reservoirs and the water flowing out of the reservoirs. It is important to note that in addition to some of the items discussed above, there are other supporting items that are installed in the reservoir station, including the alarm and the uninterruptible power supply (UPS), among others. The alarm system is used to detect intruders in the station, while the PSU is used as an electrical backup. These items are all connected to the RTUs.

The screenshot shows a SQL Server Enterprise Manager query window with the following query:

```

/***** Script for SelectTopNRows command from SSMS *****/
SELECT TOP(10) [Device_Classification]
, [Vendor]
, [Product_Description]
, [Device_Class1]
, [Device_Class2]
, [Device_Class3]
, [Target_Network]
, [ID_Number]
, [Location]
, [Time_Stamp]
, [Master]
FROM [JW].[dbo].[CMDB]
WHERE Device_Classification='Flow meter'

```

The results table contains the following data:

Device_Classification	Vendor	Product_Description	Device_Class1	Device_Class2	Device_Class3	Target_Network	ID_Number	Location
Flow meter	KROHNE	Alan Manor Res Inflow 01 R01-IN-01	Digital	EMF FULL BORE	Physical layer	ALNMR_FRM	ALNMR_FLOW_01	Alan
Flow meter	KROHNE	Alexander Park Res Inflow 01 R01-IN-01	Digital	EMF FULL BORE	Physical layer	ALXPK_FRM	ALXPK_FLOW_01	Alexander
Flow meter	PIONEER	Berea Res Inflow 01 R01-IN-01	Digital	ULTRASONIC	Physical layer	BEREA_FRM	BEREA_FLOW_01	Berea
Flow meter	FLOWMETRIX	Blairgowrie Res Inflow 01 R01-IN-01	Digital	ULTRASONIC	Physical layer	BLGRE_FRM	BLGRE_FLOW_01	Blairgowrie
Flow meter	PIONEER	Boschkop Res Inflow 01 R01-IN-01	Digital	ULTRASONIC	Physical layer	BOSCH_FRM	BOSCH_FLOW_01	Boschkop
Flow meter	Dalian	Brixton Res Inflow 01 R01-IN-01	Digital	ULTRASONIC	Physical layer	BRIXTN_FRM	BRIXTN_FLOW_01	Brixton
Flow meter	Dalian	Braamfischer 02 Inflow Total 01	Digital	ULTRASONIC	Physical layer	BRMFR_FRM	BRMF2_FTOT_01	Braamfischer
Flow meter	SIEMENS	Bryanston Res Outflow 02 R-OUT-02	Digital	EMF FULL BORE	Physical layer	BRYAN_FRM	BRYAN_FLOW_01	Bryanston
Flow meter	Dalian	Constantia Kf WT Inflow Total 01	Digital	ULTRASONIC	Physical layer	CONST_FRM	CONST_FTOT_02	Constantia
Flow meter	SIEMENS	Cosmo City Inflow Total 01	Digital	EMF FULL BORE	Physical layer	COSMO_FRM	COSMO_FTOT_01	Cosmo

Figure 4.16: Flow meters captured in the CMDB.

Johannesburg Water uses different pipelines to transport potable water. Johannesburg Water usually uses large concrete pipes with varying diameters to supply water from the reservoirs. A concrete pipeline supplies potable water to the surrounding areas from the Fairlands water reservoir. These concrete pipelines are essential components of the water distribution system, ensuring a consistent and reliable supply of clean drinking water to residents and businesses. Concrete pipelines are durable and can withstand the pressures and environmental conditions associated with water transportation. It is resistant to corrosion and degradation, ensuring the longevity of the pipeline. Typically, no apparatus is installed in the main pipelines; however, apparatus such as pressure-reducing valves and valves are installed in the subnetworks.

Pressure-reducing valves and valves also form part of the physical layer. These apparatuses are installed throughout the WDN. Pressure-reducing valves are devices used to control and lower the water pressure within a pipeline. Pressure reduction valves (PRVs) prevent pipe bursts, leaks, and other issues caused by excessive pressure. They work by reducing the incoming water pressure to a predetermined level before it enters a particular section of the pipeline. Valves in the WDN are used to control the flow of water, isolate sections of the network for maintenance or repairs, and regulate pressure.

To monitor and moderate pressure in the network, pressure sensors are used. Pressure sensors are strategically placed throughout the WDN, typically at key junctions, critical points, and areas with varying elevations. These sensors continuously measure the pressure within the pipes and

transmit this data to a central control system. This allows operators to have an up-to-date understanding of pressure conditions across the network.

Overall, the physical layer of Johannesburg Water is made of various apparatuses that work together to ensure a constant flow of water through different regions. This intricate network is designed to ensure that residents, businesses, and other consumers receive a consistent supply of clean and safe drinking water. The Johannesburg Water's apparatuses are distributed across the six regions. Further, the Johannesburg Water reservoirs are automated and monitored from two depots, the Fennel Road depot and the Southdale depot. To achieve this, Johannesburg Water uses two communication methods in their network.

4.4.2 Communication layer

In the Johannesburg Water reservoirs, RTUs are installed. The RTUs that are installed at reservoir stations are used to control the pumping of the water. The RTUs use the water level information that is read from the water level sensors to determine if the reservoir is full of water or not. If the reservoir is full, the RTUs have the ability to switch off the pumps, thereby stopping the water from being fed into the reservoirs. If the reservoir is running out of water, the reservoir can switch on the pump-to-pump water. The RTU, the ladder logic (or other programming), and the attached sensors and actuators form a feedback control loop. This helps the water utility by reducing water overflow and flooding at reservoir stations. The switching off of the pumps when the reservoir is full can also be done manually. The RTUs play an important role in terms of monitoring. The RTU in the reservoir station is also responsible for sending other data to the three MTUs, including the water level, flow rates, and status of the tags, among other things. These tags connected to the RTU can be digital or analog. Figure 4.17 depicts some of the RTU installed in some of the Johannesburg water reservoirs and towers.

```

/***** Script for SelectTopNRows command from SSMS *****/
SELECT TOP(10) [Device_Classification]
, [Vendor]
, [Product_Description]
, [Device_Class1]
, [Device_Class2]
, [Device_Class3]
, [Target_Network]
, [ID_Number]
, [Location]
, [Time_Stamp]
, [Master]
FROM [JW].[dbo].[CMDB]
WHERE Device_Classification='RTU'

```

Device_Classification	Vendor	Product_Description	Device_Class1	Device_Class2	Device_Class3	Target_Network	ID_Number	Location
1 RTU	SSE	Allan Manor telemetry	Digital	Multi I/O	Communication layer	Radio-CH3	ALNMR_FRM	Allan Manor
2 RTU	SSE	Bryanston telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	BRYAN_FRM	Bryanston
3 RTU	SSE	Comiemore telemetry	Digital	Multi I/O	Communication layer	Radio-CH2	CRMRE_FRM	Comiemore
4 RTU	SSE	CROWN GARDENS telemetry	Digital	Multi I/O	Communication layer	Radio-CH3	CRNGD_FRM	CROWN GARDENS
5 RTU	SSE	EAGLES NEST telemetry	Digital	Multi I/O	Communication layer	Radio-CH3	EAGLE_FRM	Eagles Nest
6 RTU	SSE	Fairlands telemetry	Digital	Multi I/O	Communication layer	Radio-CH2	FAIRLD_FRM	Fairlands
7 RTU	SSE	FOREST HILL telemetry	Digital	Multi I/O	Communication layer	Radio-CH3	FRSTH_FRM	Forest Hill
8 RTU	SSE	Ilove telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	ILOVO_FRM	Ilove
9 RTU	SSE	Linbro park telemetry	Digital	Multi I/O	Communication layer	Radio-CH1	LNBRP_FRM	Linbro Park
10 RTU	SSE	Northcliff tower telemetry	Digital	Multi I/O	Communication layer	Radio-CH2	NCFWT_FRM	Northcliff

Figure 4.17: RTUs captured in the CMDB.

The RTUs send the data to the three MTUs with the help of radio modules. The radio modules transmit data through radio frequencies. Two regions share one MTU. The radios RTU sends the packet of data. A data packet is a unit of data made into a single package that travels along a given network path. The packet contains operation data (e.g., water level) and information that helps identify the reservoir station. The frequency of the RTU is adjusted based on the location of the reservoir; a reservoir in the same region will have the same radio frequency. Further, the packet data will be sent to the same MTU as mentioned earlier. In a case where the RTU is unable to send the data to the MTU, the data is sent to another reservoir, where the local RTU server acts as a repeater for the remote RT; thus, the data will be forwarded to the MTU.

The radio frequency used by Johannesburg Water's Remote Terminal Units (RTUs) falls within the ultra-high frequency (UHF) range, specifically between 400 and 450 MHz. UHF two-way radio waves have a more limited range compared to very high-frequency (VHF) waves, but they offer broader frequency spectrum coverage with minimal interference from other users.

UHF radios operate at a higher frequency, which means they consume battery power more quickly. This can be a drawback if devices do not have easy access to charging stations. However, UHF radios have an advantage in urban settings, as they are better at penetrating barriers like concrete, steel, and wood. This makes them suitable for use in both indoor and outdoor environments, especially in urban areas with numerous high-rise buildings like the City of Johannesburg.

There are three MTUs, as depicted in Figure 4.18, called radio channels; each channel accommodates two regions. This can be visualized in the CMDB that will be discussed later. The radio channels have different frequencies. The first channel has a frequency of 440.0625 MHz, the second radio channel has a frequency of 440.650 MHz, and finally, the third radio channel has a frequency of 445.650 MHz.

```

/***** Script for SelectTopNRows command from SSMS *****/
SELECT TOP(10) [Device_Classification]
, [Vendor]
, [Product_Description]
, [Device_Class1]
, [Device_Class2]
, [Device_Class3]
, [Target_Network]
, [ID_Number]
, [Location]
, [Time_Stamp]
, [Master]
FROM [JW].[dbo].[CMDB]
WHERE Device_Classification='RTU' AND Target_Network='OPC'

```

	Device_Classification	Vendor	Product_Description	Device_Class1	Device_Class2	Device_Class3	Target_Network	ID_Number	Location	Time_Stamp	Master
1	RTU	SSE	channel 1 telemetry	Digital	NULL	Communication layer	OPC	Radio-CH1	Fennel	2022-09-13 19:01:00.000	Yes
2	RTU	SSE	channel 2 telemetry	Digital	NULL	Communication layer	OPC	Radio-CH2	Harrison	2022-09-13 19:05:00.000	Yes
3	RTU	SSE	channel 3 telemetry	Digital	NULL	Communication layer	OPC	Radio-CH3	Harrison	2022-09-13 19:04:00.000	Yes

Figure 4.18: MTU stored in CMDB.

Besides monitoring the water level and water flow from reservoirs, Johannesburg Water also monitors pressure in the pipelines; however, the communication protocols between the two systems are a bit different. The reliable pressure measurement of WDN requires the use of pressure sensors. In the Johannesburg WDN, pressure sensors are installed in the pipelines across all six regions. The purpose of the pressure sensors is to ensure that the WDN is operated within an acceptable pressure range. This is important because pressure is one of the main causes of pipe bursts and water leakages in the WDN. Therefore, pressure should be monitored to avoid water loss.

The pressure sensors within the WDN are connected to GPRS (general packet radio service) data loggers. These loggers use the H7210 GPRS DTU (data transfer unit), which is designed as an integrated module. The GPRS module incorporates various communication protocols, including PPP, TCP/IP, DDP, and others.

To set up the pressure monitoring points, each one is equipped with a GPRS terminal module and assigned a SIM card with GPRS functionality as part of the network infrastructure. The central station needs to have a fixed IP address. With these components in place, a wireless wide area network is established, allowing the central station to connect to the monitoring points via IP addresses. This setup enables transparent data transmission.

To configure the GPRS communication module with the SIM card, various parameters need to be set. These parameters include the transmission rate, data bits, communication parameters, parity settings, mobile center details, service code, access point name, DTU identification, local communication port, and the IP address of the data service center. These settings are essential for the proper functioning and communication within the network.

The GPRS sends the data to the control room for processing. Unlike the water level data, the data from the pressure monitoring is not displayed in the Adroit SCADA system. The information is displayed by an independent system called Aquas.

Overall, there are three master terminal units at the Johannesburg Water WDN; each MTU services two regions. The first MTU is called channel 1 service region A and B, the second MTU is called channel 1 service region C and D, and finally, the third MTU, also known as channel 3 service region E and F.

Master Terminal Units (MTUs) play a crucial role in the control and monitoring of various physical quantities within a system. They are connected to remote terminal units (RTUs) via communication links, and their primary function is to periodically poll the RTUs to collect data related to the controlled system. This data often includes information about voltage, pressure, water levels, and more.

Operators typically display the collected data on a human-machine interface (HMI), which provides them with a real-time view of the physical processes. The HMI serves as a platform that enables operators to not only observe but also interact with the system. This interaction can involve adjusting operating parameters.

For instance, an operator may modify settings related to high and low water levels, which can have a significant impact on the system's behavior. The MTU, RTU, communication link, HMI, and operator collectively create a second supervisory feedback control loop. This loop allows for monitoring and, when necessary, controlling the system's performance and behavior in response to changing conditions or requirements.

4.4.3 Data storage and data analysis layer

Supervisory Control and Data Acquisition (SCADA) systems are vital components in a WDN for real-time monitoring and control. These systems enable the continuous surveillance of the entire water distribution system. This monitoring is achieved through data acquisition processes that include tasks like meter reading and regularly checking the status of sensors. Data is collected at specific intervals, which can vary depending on the system's requirements.

SCADA systems are designed to handle a multitude of data elements, referred to as "points". Each point usually represents a monitor or sensor within the system. These points can be categorized as either "hard" or "soft". Hard points typically correspond to physical sensors or monitors, while soft points are associated with software-based calculations or applications.

Data elements collected from both hard and soft points are continuously recorded and logged. This history is maintained with timestamps, allowing for retrospective analysis and monitoring. The data is typically accessed and managed through the SCADA system's interface. In the case of Johannesburg Water, they utilize Adroit SCADA, which provides advanced monitoring and warning capabilities. This system allows for the optimization of reservoir measurements by monitoring a vast network of reservoirs in real-time. The SCADA system, alongside OPC (OLE {object linking and embedding} for process control) communications and real-time simulation systems, provides an integrated and comprehensive solution for effectively managing and controlling their WDN.

Monitoring in the context of Johannesburg Water involves the use of RTUs and radio modules. These components play a crucial role in transferring data from remote reservoirs to central depots for analysis and management. The RTUs are responsible for collecting mission-critical data from various sources in the field. This data includes information related to input and output (I/O) mapping, pump operations, trip statuses, water levels, and flow rates. To ensure timely data transmission and reduce potential delays, a dual approach is implemented. The collected data is sent to a second RTU for translation before it is transmitted to the central station. This strategy is designed to enhance data transmission efficiency. The translated data is then received by the OPC system and is simultaneously directed to both the Adroit SCADA system and an SQL Server for real-time data analysis and storage.

This multi-layered approach to data transmission and management ensures that critical information is swiftly and accurately processed and made available for monitoring and control within the WDN. OPC is a set of standards and specifications that were developed collaboratively by leading automation suppliers in partnership with Microsoft. These standards are designed to promote interoperability and enable the integration of software and systems in the realms of process control and manufacturing automation.

OPC specifications define a common set of objects, interfaces, and methods that facilitate the seamless exchange of data and information between different components and systems in industrial and manufacturing applications. The foundation for OPC was based on Microsoft's OLE COM (component object model) and DCOM (distributed component object model) technologies. By creating a common framework for data exchange and communication, OPC has played a crucial role in making SCADA systems open and accessible for a wide range of process control applications. It has helped standardize the way data is shared and managed, promoting greater interoperability and flexibility within the industrial automation and control domain.

4.4.4 Benefit Layer

Johannesburg Water's water distribution infrastructure employs a comprehensive monitoring and control system for its potable WDN. This system utilizes a combination of radio and cellular communication technologies to enable real-time monitoring and control of various aspects of the WDN. Specifically, at the pumping stations, the Adroit Human-Machine Interface (HMI) is used to monitor critical parameters, including current levels, temperatures, loads, and pumping pressures.

The purpose of this monitoring is to provide early warnings for potential issues within the network. In the event of anomalies or issues, this system can trigger actions within the network to address them.

Furthermore, this system supports the integration of GIS technology to zone and manage meters effectively. This zoning helps ring-fence or isolate specific areas within the network for improved management and control. Overall, the combination of radio, cellular, and HMI technologies allows Johannesburg Water to efficiently manage and monitor its potable WDN, ensuring reliable and high-quality water supply to its customers.

A) Control and monitoring

Johannesburg Water's water distribution infrastructure boasts an extensive and comprehensive WDN monitoring and control system that spans the entirety of their potable water network. This achievement is made possible through the integration of a hybrid communication approach utilizing both radio and cellular technologies. Within their pumping stations, the Adroit Human-Machine Interface (HMI) serves as a critical tool. This HMI system actively monitors various parameters, including currents, temperatures, loads, and pumping pressures. Its primary purpose is to provide early warnings and alerts, ensuring that the network remains responsive and well-prepared for any potential issues. Additionally, this data is seamlessly integrated with Geographic Information Systems (GIS), allowing for the timely zoning of meters to establish protective measures and ring-fence vulnerable areas within the network.

Johannesburg Water's SCADA system plays a crucial role in monitoring the water storage capacity across its extensive network of reservoirs. The integration of the Adroit advanced warning system further enhances their capability to optimize reservoir measurements. This dynamic approach offers several tangible business benefits to both Johannesburg Water and its customer base. Firstly, it enables the prevention of overflow situations, which can result in not only a loss of revenue but also undermine Johannesburg Water's ongoing efforts to minimize unaccounted for water (UFW). By avoiding overflow, the utility ensures that valuable water resources are efficiently managed and conserved.

Moreover, this system contributes to the mitigation of unsafe conditions that may arise due to overflows. By minimizing the risk of overflows, the safety of both the water infrastructure and the community it serves is significantly enhanced. Equally important is the reduction in supply interruptions, which can occur when reservoirs run dry. By proactively managing reservoir levels, the system helps ensure a consistent and uninterrupted water supply to Johannesburg Water's customers, enhancing overall service reliability and customer satisfaction.

Beyond the immediate cost savings and safety enhancements, the implementation of a predictive maintenance system facilitated by Adroit SCADA offers Johannesburg Water an avenue for improving the accuracy of their reservoir volume and capacity assessments. This increased precision allows the utility to make informed decisions when ordering water reservoir volumes, optimizing their resource management practices. Importantly, these operational efficiencies

translate into savings that can be passed on to consumers, resulting in more cost-effective services. Additionally, the automated data acquisition and control capabilities of the SCADA system eliminate the need for expensive overtime labor associated with physically manning the stations. By automating these processes, Johannesburg Water not only reduces operational costs but also ensures 24/7 monitoring and control, thereby enhancing the reliability and responsiveness of their WDN.

B) Prolong Asset Life Cycle and Cost Saving

The capability to accurately measure water pressure within the WDN equips Johannesburg Water with a powerful tool for maintaining optimal pressure levels. This optimization strategy plays a pivotal role in reducing the occurrence of pipe bursts and water leakages throughout the network. Consequently, this proactive approach not only safeguards critical assets like pipelines but also extends their lifespan, resulting in significant cost savings.

By consistently monitoring and controlling water pressure within the WDN, Johannesburg Water can minimize stress on the infrastructure. This, in turn, reduces the likelihood of pipe bursts and the associated water leakages. Preventing these incidents not only saves water but also preserves the integrity of the network, ultimately leading to prolonged asset life. In a broader context, this approach aligns with Johannesburg Water's commitment to efficient resource management, infrastructure sustainability, and fiscal responsibility. It underscores the utility's dedication to providing reliable and cost-effective water services to its community.

4.4.5 Application Layer

Johannesburg Water utilizes various social media accounts as part of its communication strategy with the public. These social media platforms serve as channels through which the organization provides regular updates on the status of the WDN. Whenever Johannesburg Water has scheduled maintenance activities that may impact consumers, notifications and messages are promptly shared via these social media accounts. Furthermore, members of the public are encouraged to report incidents such as water leakages, water quality issues, and pipe bursts through these social media channels.

In addition to its presence on social media, Johannesburg Water also maintains an official website that serves a similar purpose. The website serves as an additional platform for disseminating information to the public, including updates on the WDN and planned maintenance activities. This website, in conjunction with the organization's social media accounts, collectively constitutes the public application aspect within the application layer. These digital channels play a pivotal role in ensuring efficient communication and engagement between Johannesburg Water and its consumers.

To facilitate effective and high-quality communication with its consumers, Johannesburg Water made the strategic decision to implement Microsoft Dynamics CRM in the year 2006. This Customer Relationship Management (CRM) system has been instrumental in enhancing the

organization's ability to manage interactions with customers efficiently. Microsoft Dynamics CRM provides Johannesburg Water with a robust platform to:

- **Manage Customer Interactions:** The CRM system allows Johannesburg Water to centralize and streamline customer interactions. It helps in tracking communications, inquiries, and service requests, ensuring that customer inquiries are handled promptly and effectively.
- **Track Customer Data:** The organization can maintain comprehensive customer profiles with CRM. This includes information about customer preferences, historical interactions, and account details. Having access to this data enables better-informed decision-making and personalized communication with consumers.
- **Identify Improvement Opportunities:** By analyzing the data stored within the CRM system, Johannesburg Water can identify trends, patterns, and areas where customer satisfaction can be improved. This data-driven approach allows the organization to proactively address issues, reduce response times, and enhance overall service quality.
- **Enhance Customer Satisfaction:** Ultimately, the adoption of Microsoft Dynamics CRM contributes to improving overall customer satisfaction. Consumers benefit from more efficient and responsive services, leading to a positive experience when interacting with Johannesburg Water.

By leveraging CRM technology, Johannesburg Water has demonstrated its commitment to enhancing communication and service quality, thereby ensuring that consumers receive timely and effective support for their water-related needs. The CRM constitutes the business application aspect within the application layer. Another application that forms part of the business application is SAP ERP.

Johannesburg Water has implemented SAP ERP to efficiently manage the business aspects of their operations. SAP ERP is a comprehensive software solution that helps organizations streamline and integrate various business processes, such as finance, human resources, procurement, and more. By utilizing SAP ERP, Johannesburg Water has achieved several key objectives, including efficient business operations, integrated data management, financial management, supply chain management, human resource management, and analytics and reporting.

Overall, the implementation of SAP ERP enhances the organization's ability to run its business operations smoothly, make informed decisions, and improve overall efficiency in managing its resources and services. This technology enables Johannesburg Water to meet its operational and administrative needs effectively while focusing on providing high-quality water services to the public.

4.4.6 Security in Johannesburg Water WDN

In order to prevent unauthorized access to reservoirs, Johannesburg Water has implemented a comprehensive security system for its reservoirs, particularly focusing on intruder detection and

alarm systems. The system is designed to detect unauthorized individuals entering the reservoir control rooms. Intruder alarms are likely equipped with sensors that can detect motion, heat, or other indicators of a potential security breach. The alarm sensors are powered by uninterruptible power supplies (UPS). UPS systems provide a constant power supply even during load shedding or power outages, ensuring that the security system remains operational.

The alarms are connected to RTUs. RTUs are devices that monitor and collect data from sensors. This connection allows the alarms to transmit information to the depots, indicating any detected intrusion. The RTUs serve as an interface between the local alarms and the central monitoring system. The alarms are configured to send information about detected intrusions to the depots. This centralized monitoring likely enables swift response and coordination of security measures in the event of an incident. The primary goal of this system is to enhance the security of the reservoirs by quickly detecting and responding to potential intruders. This is crucial for safeguarding water infrastructure and ensuring the integrity of the water supply.

The fact that the alarm sensors are powered by UPS indicates a proactive approach to addressing power interruptions. This feature ensures that the security system remains operational even during load shedding, a common occurrence in certain areas.

Overall, this security setup demonstrates a thoughtful integration of technology to protect critical infrastructure. The combination of intruder detection, constant power supply, and remote monitoring capabilities enhances the overall security posture of the reservoirs managed by Johannesburg Water.

From the decision this far, it has become clear that there are signs of digitalization in the Johannesburg Water WDN. In order to measure the digital maturity of the Johannesburg WDN, the AGS digital maturity index was adopted.

4.5 Digital maturity

The CMDB is often referred to as "the truth of the system" because it offers a consolidated and precise view of the organization's IT and OT assets. With comprehensive documentation of their IT and OT assets in place, Johannesburg Water is now well-equipped to assess their digital maturity using the AGS Digital Maturity Index. Appendix A provides a detailed overview of the AGS Digital Maturity Index, which evaluates the maturity of the WDN from the sensor level to the SCADA system. This index comprises seven distinct levels, each representing a different facet of digital maturity. These levels include basic IT capabilities, network sensorization and digitization, SIG (geographic information system), automated data collection and modeling, operational management and maintenance systems, optimization systems and planning systems and predictive systems.

By employing this index, Johannesburg Water can gauge the maturity of their digital assets and processes across these seven key levels. This evaluation provides valuable insights into the

utility's readiness for digital transformation, helping to identify areas for improvement and optimization within their WDN.

4.5.1 Level 1: Basic IT capabilities

The first level of the AGS Digital Maturity Index focuses on fundamental IT capabilities, including email systems, basic desktop software, CRM, and basic cybersecurity measures. WDN demonstrates a high level of readiness in this regard. One notable cybersecurity best practice is the separation of the IT and OT domains within the Johannesburg Water WDN. This practice, as suggested by Alabi (2019), enhances cybersecurity by isolating operational technology from information technology. As a result, Johannesburg Water receives a perfect score of 10/10 in basic cybersecurity.

In 2016, Johannesburg Water adopted Microsoft Dynamics 365 CRM as a strategic move to enhance customer service and foster stronger relationships with its customers. This CRM system empowers Johannesburg Water to effectively manage customer interactions, track valuable customer data, and identify opportunities to enhance overall customer satisfaction. In the realm of CRM, Johannesburg Water earns a flawless score of 10/10. Overall, Johannesburg Water's WDN successfully covers all aspects of Level 1 of the AGS Digital Maturity Index, which amounts to a total of 20 points. This demonstrates the utility's commitment to foundational IT capabilities and cybersecurity, as well as its dedication to delivering superior customer service.

4.5.2 Level 2: Network sensorization and digitization

Level 2 of the AGS Digital Maturity Index delves into the capabilities of the WDN regarding the monitoring of water flow, water pressure, and data transmission via wireless communication technologies. Additionally, this level considers the incorporation of cadastre in digital format—a database containing comprehensive spatial and descriptive information about land parcels, buildings, and other geographic features.

Johannesburg Water's WDN exhibits a high level of proficiency in several key aspects:

- **Measurement of Pressure, Flow Rates, and Water Levels:** The utility has the capacity to accurately measure water pressure, flow rates, and water levels in its reservoirs. RTUs are employed for monitoring flow rates and water levels in reservoirs, while the aqueous system is used to gauge pipeline pressure.
- **Telemetry System: Johannesburg Water employs two telemetry systems:** GPRS and radio RTU. While GPRS for monitoring pressure receives a perfect score of 10/10, the radio RTU scores 5/10 due to its unidirectional nature. It is noteworthy that telemetry systems for monitoring water levels in the reservoirs are typically bi-directional, allowing for remote control, but this feature is not fully implemented in Johannesburg Water's system. The average score for telemetry, considering both GPRS and radio RTU, is 7.5.
- **Integration of Cadastre in Digital Format:** The utility has successfully integrated cadastre in digital format into its system, scoring a perfect 10/10. This integration ensures

that the Johannesburg Water team has access to comprehensive spatial data through the SCADA system.

In summary, Johannesburg Water's WDN demonstrates strong capabilities in pressure and flow measurement, as well as the incorporation of digital cadastre data. While the telemetry system exhibits room for improvement, particularly regarding bidirectionality, the utility's overall performance at Level 2 of the AGS Digital Maturity Index reflects its commitment to harnessing advanced technologies for enhanced water network management.

4.5.3 Level 3: SIG, automated data collection and modeling

Level 3 of the AGS Digital Maturity Index focuses on the data collection capabilities within the WDN and the presence of a digitalized network model, particularly a hydraulic model. In this context, Johannesburg Water's WDN exhibits specific strengths and limitations:

- **Data Collection Capabilities:** Johannesburg Water demonstrates a certain level of proficiency in data collection, primarily using the Adroit SCADA system. This system integrates the cadastre in digital format and offers GIS capabilities. However, it is important to note that the SCADA system in Johannesburg Water's WDN is primarily employed for monitoring processes and lacks the capability to directly control these processes. As a result, it scores 5/10 in this regard.
- **GIS Capabilities:** The GIS capabilities of the SCADA system are highly effective, earning a perfect score of 10/10. This indicates that Johannesburg Water has robust capabilities for geographic information system integration, enhancing its spatial data management.
- **Hydraulic Model:** Unfortunately, Johannesburg Water's WDN does not possess a hydraulic model, resulting in a score of 0/10 in this aspect. A hydraulic model is a crucial tool for simulating and optimizing the flow of water within a network.

In summary, Johannesburg Water demonstrates strong capabilities in terms of GIS integration and data collection through its SCADA system. However, the absence of a hydraulic model limits its ability to conduct comprehensive network simulations and optimizations. These aspects collectively reflect the utility's position at Level 3 of the AGS Digital Maturity Index, highlighting areas for potential improvement in network modeling and process control.

4.5.4 Level 4: Operational management and maintenance systems

At Level 4 of the AGS Digital Maturity Index, the focus shifts to evaluating the capabilities of operational management and maintenance systems within the WDN. Johannesburg Water demonstrates a robust set of systems and tools in this regard, contributing to the efficiency and sustainability of their operations:

- **Work Management System:** Johannesburg Water's Work Management System plays a pivotal role in planning, scheduling, and tracking fieldwork. This system ensures that tasks are executed in a timely manner and adhere to the required quality standards. It

receives a perfect score of 10/10, underscoring its effectiveness in managing operational tasks.

- **Asset Management System:** The Asset Management System tracks the entire lifecycle of Johannesburg Water's physical assets, encompassing water treatment plants, pipelines, and pumping stations. This system aids in planning asset maintenance and replacement, thus ensuring the long-term sustainability of critical infrastructure. It also earns a flawless score of 10/10.
- **Customer Information System:** Johannesburg Water's Customer Information System is a comprehensive platform for managing customer accounts, billing, and payments. It provides customers with access to their account information and facilitates the reporting of issues such as leaks and water quality concerns. This system contributes to efficient customer service and engagement.
- **Geographic Information System:** Utilizing GIS technology, Johannesburg Water effectively maps their assets, monitors the condition of their infrastructure, and plans for future development and maintenance. GIS is a crucial tool for spatial data management and decision-making.
- **Data Management System:** Johannesburg Water's Data Management System, powered by MSSQL, serves as a centralized hub for storing, analyzing, and sharing data collected from various systems and sensors. This system supports data-driven decision-making and enhances overall operations.

In addition to these systems, Johannesburg Water has implemented a Maintenance Management System (MMS) that plays a pivotal role in managing infrastructure and asset maintenance activities. Both the Work Management System and the Maintenance Management System received a perfect score of 10/10, highlighting their critical importance in ensuring the reliability and longevity of the utility's assets.

Collectively, these systems and tools demonstrate Johannesburg Water's commitment to efficient operational management, asset sustainability, customer service, and data-driven decision-making at Level 4 of the AGS Digital Maturity Index.

4.5.5 Level 5: Optimization systems

Level 5 of the AGS Digital Maturity Index focuses on the evaluation of optimization systems within the WDN. These optimization systems are integral to enhancing the efficiency and effectiveness of WDNs, with the primary goal of ensuring the efficient delivery of high-quality water. Such systems typically encompass real-time control systems, hydraulic models, leak detection systems, and water quality monitoring systems.

It is noted that Johannesburg Water's WDN currently lacks an optimization system. Consequently, it scores 0 at this level, indicating the absence of technologies and techniques aimed at optimizing WDN operations. While optimization systems represent an advanced stage of digital maturity, their implementation can significantly enhance network efficiency, reduce losses, and improve service quality. The absence of such systems in Johannesburg Water's WDN highlights an area

where potential future investments and developments could further enhance the utility's overall operational performance.

4.5.6 Level 6: Planning systems

Level 6 of the AGS Digital Maturity Index evaluates the capabilities of planning systems within the WDN. This includes assessing the presence of domestic flow metering systems and integrated asset management systems, both of which play crucial roles in enhancing network efficiency and resource management.

- **Domestic Flow Metering:** Johannesburg Water's WDN has taken steps to implement domestic flow meters in households and industries throughout Johannesburg. While most of these meters are currently read manually, the adoption smart meters in this area are being considered. The utility scores 6/10 for domestic flow metering systems, indicating progress in monitoring water consumption at the residential and industrial levels.
- **Integrated Asset Management System:** Unfortunately, Johannesburg Water's WDN currently does not have an integrated asset management system in place. This results in a score of 0/10 for this aspect, highlighting an area where there is room for future development and optimization in terms of asset lifecycle management.

Incorporating integrated asset management systems can enable organizations to better manage and optimize the lifecycle of their assets, improving efficiency, reliability, and cost-effectiveness. The consideration of smart meters for domestic flow metering reflects a commitment to enhancing data collection and management, which is integral to efficient water resource planning and distribution. Overall, while Johannesburg Water has made strides in some aspects of planning systems, such as domestic flow metering, there remains an opportunity to further enhance asset management capabilities for continued improvement in WDN operations.

4.5.7 Level 7: Predictor systems

Level 7 of the AGS Digital Maturity Index focuses on evaluating the capabilities of digital twins and AI systems within the WDN. Digital twins are advanced models that replicate physical assets or systems, allowing for real-time monitoring and analysis, while AI systems leverage artificial intelligence to enhance network management and decision-making.

It is noted that the Johannesburg Water's WDN does not currently have either a digital twin or an AI system in place. As a result, both areas receive a score of 0/10 at this level, signifying the absence of these advanced technologies within the network. While digital twins and AI systems represent cutting-edge advancements in WDN management, their implementation can bring about significant benefits, including improved efficiency, predictive maintenance, and optimized resource allocation. Johannesburg Water may consider exploring opportunities to integrate these technologies in the future to further enhance the performance and resilience of its WDN. Table 4.10 summarizes the digital maturity index for Johannesburg Water's WDN, highlighting the

utility's strengths and areas where future investments and advancements may be pursued to enhance its digital maturity and overall operational performance.

Table 4.10: Digital maturity of Johannesburg Water’s WDN

		Johannesburg Water
		2022
		Level 1- Basic IT capabilities
Description	Number of Points	
Cybersecurity system	10	10
Customer relationship manager	10	10
		Level 2—Network sensorization and digitization
Flow gauges	10/3	3
Pressure gauges	10/3	3
Telemetry system	10/3	2
Cadastre in digital format	10	10
		Level 3—SIG, automated data collection and modeling
Digitalized network model	10	10
GIS system	10	10
SCADA system	10	10
		Level 4—Operational management and maintenance systems
Work order management system	10	0
Maintenance system	10	0
		Level 5—Optimization systems
Flow-monitoring system	10	10
Optimization system	10	0
		Level 6—Planning systems
Domestic flow metering systems	10	10

Integrated asset management system	10	5
		Level 7—Prediction systems
Digital twins	10	0
AI systems	10	0
Total	150	93
Total (%)		62%

The overall digital maturity Johannesburg Water WDN is calculated using the following equation 1.

$$Digital\ maturity^{utility\ JW} = \frac{\sum_{t=1}^n points\ \frac{utility\ JW}{item\ t}}{\sum_{t=1}^n points\ \frac{max}{item\ t}} \dots \dots \dots (1)$$

The sum of scores per level is first determined. Then the overall score is calculated by dividing it by the maximum possible score (150). The maturity index for Johannesburg Water WDN was determined to be 62%. Overall, Johannesburg Water's WDN demonstrated strong capabilities in pressure and flow measurement, as well as the incorporation of digital cadastre data. While the telemetry system exhibited room for improvement, particularly regarding bidirectionality, the utility's overall performance at Level 2 of the AGS Digital Maturity Index reflected its commitment to harnessing advanced technologies for enhanced water network management. Further, the maturity index highlighted that Johannesburg Water demonstrated strong capabilities in terms of GIS integration and data collection through its SCADA system. While Johannesburg Water has made strides in some aspects of planning systems, such as domestic flow metering, an opportunity to further enhance asset management capabilities for continued improvement in WDN operations remains. While Johannesburg Water has made strides in some aspects of planning systems, such as domestic flow metering, an opportunity to further enhance asset management capabilities for continued improvement in WDN operations remains.

Chapter 5– CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In answering research question 1, it was found that water utilities across the globe are adopting 4IR technologies, such as machine learning, in order to optimize water management. Further research highlights that software with the capability of preventing issues such as service disruptions, losses, fraudulent activities, asset conditions and failures, communication glitches, supply and demand equilibrium, pressure and flow optimization, and water quality concerns is being adopted by water utilities. Furthermore, water utilities are adopting a new method of wireless communication in WDN, such as LPWAN, which is suitable to support 4IR technology such as IoT. Finally, water utilities are adopting IoT sensors such as accelerometers and acoustics to detect water leakages in the WDN.

Research question 2 revealed that CMDB provides the optimal database design for a repository of all data associated with a digital WDN. The CMDB provides robust support for a variety of services within the operational technology (OT) environment. The CMDB has several functionalities, including OT asset management, history, and integration of asset information. CMDB is a database repository that stores information about assets. Further, CMDB plays a crucial role in mapping relationships between configuration items (CIs) or tags. These relationships serve as a critical component in assessing the potential impact of removing a CI on the entire operational process. Furthermore, the CMDB offers valuable functionalities, including change management and historical tracking, which can greatly benefit water utilities.

In order to answer research question 3, the digital framework. The framework for digital WDN is made up of three distinct components, including security, CMDB and architecture. The architecture under the digital WDN framework consists of five layers, including the physical layer, communication layer, data storage and analysis layer, benefit layer, and application layer. Using the systematic literature review bibliometric keyword analysis, the equipment, systems, and their uses were determined. Based on this information, a generic WDN was developed. The validation of the framework using generic WDN highlights some of the equipment and systems that were used by typical WDN in the five layers of the framework.

Further, the framework was validated using the Johannesburg Water WDN. The Johannesburg Water apparatus is distributed across the six regions; further, the Johannesburg Water reservoirs are automated and monitored from two depots: the Fennel Road Depot and the Southdale Depot. In order to achieve this, Johannesburg Water uses two communication methods in their network. There are three master terminal units at the Johannesburg Water WDN: each MTU services two regions. The MTU, radio modules, RTU, and GPRS form part of the communication layer, while the physical layer of Johannesburg WDN consists of typical equipment such as level sensors, pumps, and flow meters, among others. The data storage and data analysis layer is made up of an SQL database, an OPC, and a SCADA system, while the application layer is made up of social media accounts, CRM, a website, and SAP ERP.

The CMDB highlights the possibility of storing physical layer and communication layer CIs. Further, the CMDB highlights asset management, CI relations, change management, and historian capabilities. The CMDB is essential for storing asset-related data, but the process of keeping it accurate and updated is equally important. In order to maintain an updated CMDB, it is necessary to employ asset discovery solutions. Further, CMDB relationship mapping plays an important role in assessing the ripple effects of CI changes within a complex system, enabling informed decision-making and risk mitigation strategies. Finally, the measurement of the digital maturity of the Johannesburg Water WDN using the AGS maturity index shows that the WDN has a maturity index of 62%. Further, the maturity index highlights that Johannesburg Water demonstrates strong capabilities in terms of GIS integration and data collection through its SCADA system. While Johannesburg Water has made strides in some aspects of planning systems, such as domestic flow metering, there remains an opportunity to further enhance asset management capabilities for continued improvement in WDN operations. Johannesburg Water's WDN demonstrates strong capabilities in pressure and flow measurement, as well as the incorporation of digital cadastre data. While the telemetry system exhibits room for improvement, particularly regarding bidirectionality, the utility's overall performance at Level 2 of the AGS Digital Maturity Index reflects its commitment to harnessing advanced technologies for enhanced water network management.

5.2 Recommendations

The following recommendations are suggested for further research based on the research findings:

- Further validation of the digital WDN framework, with a focus on security. Validation through real-world implementation in an actual WDN.
- Further validation of the digital WDN framework using WDN that has adopted modern technologies such as IoT, robotics, and digital twin, among others.
- The development of the CMDB is based on the data structure used in this research, but the CIs are manually validated in the CMDB.
- The development of CMDB is based on the data structure used in this research but also includes software CIs such as SCADA, GIS, and OPC, among others.
- Full scale development of CMDB that will include all the CIs in a WDN.

5.3 Limitations of this study

The development of the CMDB during the study faced challenges related to data integration and completeness impacting the overall reliability of the CMDB as a representation of the WDN. Further, the use of the AGS maturity model for assessing digital maturity may have inherent limitations, such as subjective judgments in scoring or potential bias. Furthermore, opting for a single case study design have limit the study's ability to capture diverse perspectives and variations in the digitalization of different WDN.

5.4 Future work

Based on the findings and limitations of this study, future research includes:

- **Comparative case studies:** Conduct comparative case studies across different water utilities or regions to explore variations in the implementation and outcomes of WDN digitalization. This can enhance the generalizability of findings.
- **Longitudinal studies:** Undertake longitudinal studies to track the evolution of digitalization efforts in WDNs over time. This approach can provide insights into the sustainability and long-term impacts of digital initiatives.
- **Advanced digital technologies:** Investigate the integration and impact of emerging technologies (e.g., Internet of Things, artificial intelligence) in enhancing the efficiency and resilience of WDNs. Assess the feasibility and benefits of adopting cutting-edge solutions.
- **Benchmarking digital maturity for developing countries:** Develop and refine digital maturity models specifically tailored to the water sector in developing countries. Benchmark the digital maturity of different water utilities to establish industry standards and best practices.

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Appendices

Appendix A: Digital maturity index table.

Description	Number of Points	Type of System in Place			System Operation		
		Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Level 1—Basic IT capabilities		No system or methodology in place					
Cybersecurity system	10		Generic approach or methodology followed	Dedicated system in place			
Customer relationship manager	10						
Level 2— Network sensorization and digitization							
Flow gauges	10/3		System covering the most important sections of the network	Most of the network (>80% of consumption) covered, monitored, and automated			
Pressure gauges	10/3						
Telemetry system	10/3						
Cadastral in digital format	10						
Level 3—SIG, automated data collection and modeling							
Digitalized network model	10		Generic approach or methodology followed	Dedicated system in place			
GIS system	10						
SCADA system	10				Either: 1. No system or methodology in place 2. Existing system or methodology not in use	Only basic capabilities used	Full capabilities used
Level 4— Operational management and maintenance systems							
Work order management system	10						
Maintenance system	10						
Level 5— Optimization systems							
Flow-monitoring system	10						

Optimization system	10						
Level 6— Planning systems							
Domestic flow metering systems	10						
Integrated asset management system	10						
Level 7— Prediction systems							
Digital twins	10						
AI systems	10						