Linköping Studies in Science and Technology
Licentiate No. 1982

Sustainable Management of Wire-based Infrastructure

On the Multifaceted Challenges of Infrastructure Management in the Swedish Context

Eman Hegazy

LINKÖPING UNIVERSITY

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Abstract

Cities, as key players in global sustainable development, are linked to challenges and opportunities driven by urbanization's resource consumption and environmental impacts. This context highlights the critical role of urban infrastructure in fostering sustainability, particularly the role of wire-based infrastructure systems (WBIS). The management, maintenance, and renewal of WBIS are vital to ensuring their long-term efficiency, yet they present challenges across technical, environmental, and societal dimensions. The positioning of these systems beneath urban streets introduces complexities, from accelerated wear to costly excavations, with a wide range of environmental consequences. Beyond the physical implications, the financial, policy, and management practices governing WBIS also contribute to their sustainable development challenges. This study, centered on Linköping's water network in Sweden as a case study, aims to unravel these multifaceted dynamics and answer key research questions regarding the management, challenges, influencing factors, and strategies for improving the maintenance and renewal of urban WBIS. Based on a mixed method approach, the case study utilized both qualitative and quantitative methods, including interviews, workshops, and data analysis. The results highlighted Linköping's UWI challenges, encompassing aging infrastructure, limited renewal rates, and financial constraints. To navigate these challenges, the discussion advocated for a shift towards proactive renewal strategies. The conclusions emphasized the need for an increased funding, strategic planning, proactive coordination among diverse stakeholders, and a balanced approach in budgetary allocations, particularly in considering maintenance and renewal alongside other activities, as crucial for ensuring the longevity and sustainability of the WBIS.

Keywords: Infrastructure management, maintenance and renewal, Sweden, wire-based infrastructure.

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Despite that I spent a great part of my life moving from one country to another, from one phase to another, meeting many people from different cultures, and learning many lessons during this journey, my experience in Sweden, especially during my Licentiate studies, is truly unique.

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Linköping- 2024

Eman Hegazy

List of appended papers:

I am the first author of the three appended papers.

Contribution:
I was involved in the conceptualization, data collection, analysis, and writing of the three appended papers:

1. Hegazy, E., Anderberg, S., Krook, J. "Assessing Renewal Needs of Urban Water Infrastructure Systems- Case Study of Linköping in Sweden" in Conf. Proc. 1st WASET Int. Conf. on Infrastructure Management Systems, Zurich, 2023, pp. 6-20.

2. Hegazy, E., Anderberg, S., Krook, J. "Systems Lens: Towards Sustainable Management of Maintenance and Renewal of Wire-based Infrastructure: The Case of Water Network in the City of Linköping, Sweden" in Conf. Proc. 1st WASET Int. Conf. on Network Infrastructure Technologies and Systems, Lisbon, 2023, pp. 85-99.

3. Hegazy, E., Anderberg, S., Johansson, J. "Enhancing Infrastructure Renewal: Budget Analysis of Water System Case Study of Linköping City, Sweden". **Draft**

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1. INTRODUCTION

The growth of cities is one of the primary drivers of increasing resource use and greenhouse emissions, but cities can also contain potential solutions to many sustainability challenges. It is in cities where new developments of more sustainable practices can be introduced and implemented (McCormick et al., 2013). All cities, and their inhabitants, depend on wire-based infrastructure systems (WBIS)[1] to distribute essential and everyday services such as electricity, telecommunication, district heating, and water and sewage. These systems can be considered as the technological foundation of cities (Ingram & Brandt, 2013).

For securing continuous and efficient supply of these services, functions of WBIS need to be sufficient, resilient and well maintained (Pandit et al., 2017). As cities grow and networks age, a growing need for maintenance, renewal and expansion of subsurface infrastructure systems emerges. In recent decades, many cities in different parts of the world have witnessed an increasing malfunctioning and breakdowns in their WBIS due to decades of neglected maintenance and renewal needs (Rioja, 2013). Therefore, maintenance and renewal of WBIS is often considered one of the great challenges of cities around the world (Chester, 2019).

The current dominant practice of locating WBIS cables and pipes networks underneath the streets has a number of disadvantages. System components are readily worn and have a shorter service life in this subsurface location (Ingram & Brandt, 2013). Excavation operations for renewal and maintenance entail large costs, and cause huge disturbance to the life in the city, restricting many activities, and have environmental impacts related to the use of equipment, transportation, treatment of excavated dirt, and asphalting. High costs for excavation is an important reason for why discarded system parts are usually left in the ground, despite that they contain valuable base metals and environmentally hazardous materials (Krook et al., 2015).

The sustainability challenges of WBIS are not just a matter of their physical structure and subsurface position but also related to current policy and managerial practices (Ferrer et al., 2018; Xue et al., 2018). Although different WBIS are located in the proximity of one other, each system is often managed separately. Potential synergies in terms of reduced costs, environmental impacts and city interferences through coordinated excavation and maintenance are therefore seldom exploited (Krook et al., 2020).

Current management is often based on reactive approaches towards network maintenance and renewal, where solving the most acute problems is the priority (Berglund, 2009). System owners tend to take the functionality of the existing infrastructure for granted and neglect maintenance and renewal. As a result, most utility networks have an underlying debt due to decades of unmet maintenance and renewal needs (Rioja, 2013). In Swedish cities, important parts of these systems are already old and will have to be renewed within few decades (Skarendahl et al., 2016). Replacing aged WBIS represents a major challenge for network managers, as even if the rate of renewal has significantly been increased, it will take many decades before systems are replaced, entail massive costs, and significant increase in sustainability consequences related to excavation work (Krook et al., 2015). At the same time, this necessary renewal opens for opportunities to change current management practice to become more sustainable (Krook et al., 2020).

The urban water infrastructure (UWI) is the largest and oldest WBIS in Sweden and it provides a good example of the challenges and complexities of the urban utility management (Thomasson & Jonsson, 2022). The provision of clean and safe drinking water and taking responsible care of wastewater is a cornerstone of municipalities (Syssner & Jonsson, 2020). Water infrastructure encompasses a vast network of pipes for drinking water, wastewater and stormwater, treatment plants, and reservoirs. These systems must work seamlessly to ensure the uninterrupted water flow to every tap, household, and business. However, despite its undeniable importance, the management of water infrastructure remains a great and multifaceted challenge (Thomasson & Jonsson, 2022). As cities expand and evolve, so do the demands placed on their UWI. Increased population density, shifting demographics, and changing climate patterns further compound these challenges (Hermelin & Jonsson, 2021). The task of

[1] Wire-based Infrastructure Systems (WBIS) “Ledningsbundena infrastruktur” are the infrastructure systems (wires and pipes, often subsurface) that are responsible for distribution of services of electricity, telecommunication, district heating, water, and sewage.

maintaining the functionality of water infrastructure becomes increasingly challenging with the dynamic development of cities.

The urban water utility system has significant environmental and social impacts, ranging from energy consumption for water treatment to the consequences of neglecting maintenance and renewal needs of the water networks (Pathirana et al., 2021). The protection of water sources (Dinka, 2018), sustainable management processes (Gustafsson et al., 2019), and the minimization of water loss are central for ecological balance and conservation of a precious natural resource. Therefore, it is important to understand the current water infrastructure management and its challenges (Little, 2005).

1.1. Aim and Research Questions

This study aims to contribute to improved understanding of the challenges in connection with the management of WBIS in cities. It explores the management of the UWI in Linköping, Sweden, and its challenges with a particular emphasis on maintenance and renewal. This case is addressed via the following research questions:

1. What is the current status of the UWI and their management in terms of repair, maintenance, and renewal?

This research question investigates the current state of UWI and their management concerning repair, maintenance, and renewal. It examines operational, organizational, and policy aspects that govern these processes to provide an overview of network management practices. Building upon the insights gained from the examination of current practices, the adequacy of renewal rates in recent years was assessed, focusing on identifying conditions and needs in both the present and the future to determine if there is a risk of accumulating renewal debt. This analysis contributes to the sustainability, efficiency, and resilience of WBIS.

2. Which are the key challenges for increasing renewal and improving maintenance?

This question sheds light on the challenges and influential factors that impact the management of maintenance and renewal in water infrastructure. It explores the interconnected shortcomings and factors that shape management actions related to network maintenance and renewal.

3. How can these challenges be met?

The third research question focuses on potential strategies to meet the identified challenges to enhance the management, effectiveness, and sustainability of UWI, and WBIS in general.

1.2. Structure of the Thesis

This thesis consists of a cover essay and three appended papers. The cover essay has eight chapters. Chapter 1 contains the introduction, aim and research questions of the thesis, research approach and context, and the case study. Chapter 2 presents the research journey and the appended papers. Chapter 3 presents the background, including earlier research in Urban Infrastructure Management area, the challenges confronting WBIS, research in the Swedish context, and research on strategies to navigate towards sustainable management of WBIS. Chapter 4 introduces the basis for the research methodology, which builds on a systems approach and different analysis and assessment types. Chapter 5 presents research methods that have been applied in connection to data collection and analysis in the project. Chapter 6 presents the findings and is structured around the core research questions. Chapter 7 discusses the results and delves into identified influencing factors to UWI management. The conclusion in Chapter 8 summarizes the results of the thesis, reflects on contributions of the thesis towards the aim and to the research field, and points toward further future research needs related to WBIS management and sustainability.

2. RESEARCH APPROACH AND CONTEXT

This research adopts a holistic approach to the context of urban infrastructure management, with a particular focus on the potential for enhanced sustainability. In the context of central sustainable infrastructure management, the focus on maintenance and renewal is particularly crucial. The particular focus on maintenance and renewal in central sustainable infrastructure management is driven by the critical role these elements play in ensuring the longevity, reliability, and overall sustainability of urban infrastructure systems (Little, 2005). The emphasis on maintenance and renewal is rooted in the recognition that for infrastructure to be sustainable, it must not only be initially well-designed but also consistently and effectively managed over time.

Maintenance involves the routine upkeep, repairs, and servicing of infrastructure components to prevent deterioration and ensure that they continue to function optimally. Renewal, on the other hand, encompasses the strategic replacement or upgrading of infrastructure elements to keep pace with evolving technological, environmental, and societal needs. Both maintenance and renewal are indispensable components of a sustainable infrastructure management (Pathirana et al., 2021).

The sustainability of urban infrastructure relies on its ability to provide reliable services without significant interruptions over the long term. Achieving sustainability transition within infrastructure management cannot rely solely on isolated efforts. Developing long-term sustainable management of WBIS requires a combination of different measures and changes in today's practice (Xue et al., 2018). Sustainability transition in the infrastructure area will not be possible through individual efforts without will require coordinated technical, organizational, and regulatory changes (Little, 2005). Notably, the research in this field often tends to focus on singular aspects, such as specific locations or maintenance technologies, rather than considering the broader system dynamics (Von der Tann et al., 2020). This study contributes to the development of systemic knowledge that can serve as a basis for fostering sustainable urban infrastructure management.

2.1. The Case: UWI Management in Linköping City

Linköping is located in the province of Östergötland, approximately 200 kilometers southwest of Stockholm. It is the capital of Östergötland County and the fifth largest municipality in Sweden in terms of population. It has a population of 167,457 inhabitants (Linköpings Kommun, 2023), and an area of 1,428 square kilometers (Linköping, 2023).

The management of UWI in Linköping is entrusted to TV, a utility company fully owned by the municipality. The municipality retains control through setting user tariffs and deciding the budget and, and TV's board includes municipal politicians. Decision-making authority lies with the Municipal Council (Kommunfullmäktige KF), while the Municipal Board governs municipal affairs (Linköpings Kommun, 2017). TV's activities also encompass facilities outside the municipality.

The rationale behind choosing Linköping as the focal point of the study is rooted in its representation of larger Swedish cities and its diverse UWI networks that span generations. Notably, a substantial portion of Linköping's infrastructure is relatively young due to the city's rapid growth post-1950. The ownership structure, being managed by one company Tekniska verken AB (TV), had simplified the identification of stakeholders, streamlined data collection processes, and facilitated subsequent analysis. This diversity within the case enhanced the study's overall applicability (Yin, 2003), making Linköping provides an ideal context for the study of management of its UWI.

2.2. Research Journey

Sustainable management of critical infrastructure was first introduced to my research career during my master's studies in Dundee University. This topic was further endorsed with the PhD opportunity mid-way of my second master's degree in Linköping University. As a master's student in design and sustainability specialization, looking into sustainable management of heating systems in residential environments, I got the chance to start with a PhD position in IEI, Linköping University.

With project funding from Formas, I got the opportunity to continue research in the sustainable management of WBIS. The goal was to explore management to a wider range of infrastructure networks, but due to time constraints, the focus was narrowed down to explore UWI in a case city, Linköping.

With the aim of gaining a better understanding of sustainable management of WBIS, the aspiration was to develop an overarching insight via UWI case, that could potentially extend to broader network contexts.

The research started with Paper II, where management practices of UWI were explored via literature inventory to infrastructure management context globally and in Sweden, as well as Interviews with TV staff. The literature foundation and interviews' inputs did not only help develop deeper knowledge of infrastructure management, but also shed light on the challenges and factors influencing current management practices of maintenance and renewal of WBIS.

One key challenge was the low renewal rate. There, the need to identify renewal needs emerged. Assessing renewal needs necessitated a deeper understanding of the current conditions of UWI and collecting updated management network data, which drove us to conduct further workshops. There, the idea for Paper I was developed based on the findings of analysis of the current state of UWI and its renewal needs. The assessment gave insights into the implications of the lack of renewal, and the importance of strategic planning for maintenance and renewal, in order to sustain functionality of the systems towards more sustainable performance.

These two papers were presented at international conferences on infrastructure management and systems and published in their proceedings books.

The implications of the lack of renewal fostered further exploration into the factors that influenced this lack. Financial constraints were a major contributing factor, which led to analysis of budgeting management of UWI in Paper III. The analysis employed both qualitative and quantitative methods in order to unveil the factors that led to the current low renewal rate, suggesting strategies towards long-term sustainable performance of the systems.

In addition to the written papers, most of the collected empirical materials have not been used in any publications yet, and they hold the potential for extended exploration in future research.

2.3. The Appended Papers

The three appended papers contribute in different ways to the aim of the thesis. Paper I provides analysis of the current state of UWI in Linköping and their needs for improved maintenance and renewal. Paper II sheds light on the challenges faced by system owners in managing maintenance and renewal, highlighting the barriers for a more sustainable management. Paper III emphasizes the importance of budget distribution in influencing infrastructure renewal and management decisions, further deepening the understanding of factors affecting UWI management. Together, these papers offer insights into improving the management of UWI and addressing the research questions posed in the thesis. Table 1 links papers contributions to the thesis research questions. Overviews of the appended papers are presented in Table 2, with more details about papers' focus, research questions, methods, and contributions.

Paper I

Paper I provides an analysis of the UWI's current state and the adequacy of renewal in Linköping, Sweden. It directly addresses RQ1, and offers insights by quantitatively evaluating renewal needs and the potential risks associated with insufficient renewal. It is also related to RQ2 and RQ3 by identifying key challenges in UWI management, shedding light on the factors that shape and limit renewal actions, offering suggestions and strategies for improving the overall management of UWI.

Paper II

Based on qualitative methods, Paper II investigates the current management practices, and emphasizes limitations in addressing repair, maintenance, and renewal needs. It particularly contributes to RQ2 by providing insights into the challenges encountered by system owners in managing these networks, and understanding the obstacles that hinder proactive maintenance and renewal. Lastly, Paper II contributes to RQ3 by investigating how system owners cope with these challenges and seek improvements in their management practices.

Paper III

Paper III examines how the budget frames influence the network management activities, particularly towards maintenance and renewal. It particularly contributes to RQ2 by exploring the factors and challenges associated with budget distribution, shedding light on their influence on renewal efforts, but it also addresses RQ3 via a discussion on how to achieve a balance between renewal and other demands.

Table1 Papers Contributions to the Thesis Research Questions.

Papers/ RQs	**RQ1**	**RQ2**	**RQ3**
Paper 1	X		
Paper 2	X	X	X
Paper 3		X	X

Table 2 Overview of the Appended Papers.

Papers	**Paper I**	**Paper II**	**Paper III**
Focus	. Assessment of the current status and renewal needs of water networks and their management	. Analysis of the management and its challenges with a particular focus on explaining the limitations to renewal and proactive maintenance	. Analysis of the budget process and its outcomes
RQs	1. What is the current status of water and sewerage networks? 3. How are the networks managed in terms of repair, maintenance, and renewal? 3. What are the causes of damage, leaks, and interruptions? 4. Is the renewal adequate, or is there a risk of accruing a renewal debt?	1. How do system owners plan, prioritize, finance, and execute maintenance and renewal of water networks in practice? 2. How do policy and organizational factors influence management practices of water networks? 3. What challenges do system owners face in managing maintenance and renewal, and how do they cope with them? 4. What are the barriers to renewal and proactive maintenance of the systems?	1. How is the budget for water infrastructure developed and decided? 2. What influences its frames and how is it allocated? 3. What influences its outcome in terms of maintenance and renewal? 4. Which are the major challenges for improving maintenance and increasing renewal of the urban water infrastructure in order to secure the long-term functionality of the systems?
Methods	The investigations are all connected to the study of the UWI management in the city of Linköping and based on qualitative data from literature and interviews with local practitioners, as well as quantitative data on the networks and their management.		
	. Quantitative assessment of the physical conditions and renewal needs.	. Quantitative assessment of the physical conditions and renewal needs.	. Quantitative assessment of the physical conditions and renewal needs.
Contributions	. Addresses RQ1 by providing a detailed analysis of the current status of water and sewerage networks, and an assessment of the risks for an increasing renewal debt. . Contributes also to RQ2 by showing how the renewal debt is likely to increase if renewal rates are not increased.	. Addresses RQ1 by providing a detailed analysis of the current status of water and sewerage networks, and an assessment of the risks for an increasing renewal debt. . Contributes also to RQ2 by showing how the renewal debt is likely to increase if renewal rates are not increased.	. Addresses RQ1 by providing a detailed analysis of the current status of water and sewerage networks, and an assessment of the risks for an increasing renewal debt. . Contributes also to RQ2 by showing how the renewal debt is likely to increase if renewal rates are not increased.

3. BACKGROUND

3.1. Urban Infrastructure Management

Previous research in the field of WBIS management has predominantly consisted of technology focused investigations, often examining specific technologies, systems, or infrastructure configurations rather than suggesting pathways for the future. These studies have provided valuable insights into existing management challenges but have generally overlooked the importance of understanding management settings, practices, and their influencing factors (Xue et al., 2018; Von der Tann et al., 2020).

According to Von der Tann et al. (2020), the need for better management was recognized in the recent decade by experts in engineering and urban planning disciplines. The relevance of subsurface infrastructure management has also been acknowledged in the broader context of urban development and sustainability. Professionals with diverse backgrounds, including tunneling engineers, urban planners, and legal experts, have contributed to the discourse e.g., Admiraal and Cornaro 2018. These studies have often been limited in scope, focusing on specific tasks or projects, and missing a holistic understanding of subsurface infrastructure management. Improvement potentials are looked at independently, and the influences systems have on each other are only analyzed for specific interactions (e.g., the risk of water pipe bursting and the associated flooding for tube tunnels). Consequently, management strategies and models have often been grounded in technical knowledge rather than systemic principles.

Previous research has also addressed the social, legal, actor, and institutional aspects of subsurface infrastructure management. Social aspects were often highlighted as important in connection with sustainable development and implementation. Gustafsson et al. (2019) examined challenges in implementing strategic spatial planning for environmental sustainability in local authorities, using a Swedish case study. The study found that integration of environmental perspectives depends on local policy emphasis and the capacity of administrative management systems to drive transformative planning practices. Based on interviews and document analysis, the study underscored the interplay between local policy priorities and administrative procedures in shaping environmental sustainability within strategic spatial planning. Von der Tann et al. (2018) discussed the vital role of the subsurface in shaping cities, emphasizing its influence on urban development, stability, and sustainability. With growth predictions and climate change in mind, this article highlighted the increasing importance of considering interdependencies between urban planning objectives and the subsurface. Initiatives in the UK related to changes in urban subsurface management and governance were reviewed, revealing that many planning topics involving the subsurface are often addressed only at the project level, neglecting their wider impact on the development of the city. The study highlighted the untapped potential of the subsurface for sustainable city development. These studies explored institutions as crucial starting points for sustainable planning and management. However, due to the diversity of legal and institutional environments, as well as actors and planning laws across regions and cities, they have primarily focused on regional contexts. While these investigations have identified important management challenges from various perspectives, they have not fully addressed the need for systemic knowledge concerning management practices.

Assessment of infrastructure characteristics and the interrelations between system components have been addressed by several scholars. Star (1999) and Graham and Marvin (2002) studied the theme of the linkages between technological and urban studies. Hommels (2005) presented the scarcity of technology research in urban studies, while Geels (2004) investigated the co-evolution of society and technology and explored socio-technical systems in cities by incorporating a social factor to sectoral systems of innovation combining institutional theory to socio-technical systems. Calls for more sustainability and systemic approaches to urban subsurface infrastructure planning and management have been reiterated, aligning with a broader trend toward viewing cities as complex systems (Moffatt & Kohler, 2008). Von der Tann et al. (2020) highlighted some systemic approaches applicable for sustainable management of underground space and subsurface infrastructure, including urban development, actor, and institutional perspectives. Xue et al. (2018) focused on achieving Infrastructure Sustainability (IS) in the Architecture, Engineering, and Construction (AEC) industry through Project

Management Practices (PMPs). The study developed conceptual frameworks for both PMPs and IS. Four key factors (Culture, Strategy, Implementation, and Reflection) were identified for measuring PMPs, aligning with the plan-do-check-action (PDCA) cycle ideology. Additionally, four metrics (Project Economy, Organizational Integration, Social Utility, and Environmental Implication) were established for IS, covering project, organizational, and macro levels. The study contributed to the knowledge of construction project management and sustainable infrastructure development by providing theoretical measurement frameworks for both PMPs and IS.

Recent infrastructure research has shown an increasing tendency towards employing systems perspective on different levels. Pathirana et al. (2021) discussed the evolution of Infrastructure Asset Management (IAM) with a specific focus on Water Infrastructure Asset Management (WIAM). IAM was introduced as a dynamic process that allocates resources to ensure continuous delivery of organizational or societal assets. Responding to poor infrastructure maintenance, IAM emphasizes prioritizing maintenance and renewal using risk-based approaches. The paper highlighted the evolving demands on IAM due to increasing complexity in asset systems, including multifunctionality, adaptative capacity, and nature-based infrastructure. Whyte et al. (2020) discussed systems approaches to infrastructure, highlighting the complexity and interconnectedness of infrastructure systems and emphasizing the need for integrated modeling and multi-criteria indicators. It is argued for a shift in infrastructure approaches, starting from the natural environment and encompassing societal use, supporting a systems-based view. Gim & Miller (2022) discussed infrastructure resilience in the context of climate change and stressed the importance of understanding institutional interdependencies in social, ecological, and technological systems. A framework for institutional analysis is proposed, which consider vertical, lateral, and longitudinal interdependencies, thus embracing a systems perspective in infrastructure planning and management. Thomas et al. (2019) examined the relationship between human and socio-technical system capacities for infrastructure resilience. This study draws on concepts from resilience engineering and psychology. It identifies 18 system capacities and 23 human capacities that influence infrastructure resilience and explores their interconnectedness, demonstrating the importance of a systems perspective. However, despite that some recent studies have explored perspectives of urban infrastructure management from a systemic lens, there remains a notable gap in systemic knowledge concerning the diverse factors that influence management practices within subsurface infrastructure systems in the current state of research.

3.2. Management Challenges

The challenges of managing WBIS combine concerns related urban expansion, aging infrastructure, fiscal constraints, stakeholder collaboration, environmental consequences, and awareness gaps (Little, 2005; Pathirana et al., 2021). Tackling these challenges demands a comprehensive approach that combines technical capacity with strategic foresight and collaborative engagement among a multitude of stakeholders (Krook et al., 2020). This convergence is crucial for the resilience, efficiency, and sustainability of these foundational urban systems (Pandit et al., 2017).

The management of WBIS presents challenges that necessitate strategic solutions (Pathirana et al., 2021). One pressing challenge stems from the continuing expansion of cities, which places heightened demands on WBIS to deliver essential services like electricity, telecommunications, and water supply. This urban growth highlights the urgency for maintenance, planned renewal, and expansion of these systems to accommodate rapid growth of populations and urban development (McCormick et al., 2013). Yet, the complexity lies in the fact that a significant portion of infrastructure components is located underground, entailing environmental consequences of labor-intensive, costly, and potentially disruptive maintenance and renewal (Krook et al., 2020).

A substantial hurdle arises from the aging of existing infrastructure systems (Pathirana et al., 2021). The gradual erosion of reliability and efficiency as these systems mature can generate more frequent disruptions and service breakdowns (Ingram & Brandt, 2013). Consequently, managing maintenance and renewal of aging WBIS components becomes central to ensure uninterrupted service provision and avoid potential safety hazards. Neglecting maintenance and renewal needs entails building up renewal debt that will be inhibited by future generations (Rioja, 2013).

Financial constraints form another obstacle. The financial requisites for maintaining, renewing, and expanding WBIS can be substantial, often setting municipal budgets in competition with other urban priorities (Pathirana et al., 2021). Managing the allocation of resources while prioritizing investment in infrastructure within the context of broader urban development initiatives demands proactive planning, budgetary maneuvering, and optimal resource utilization (Little, 2005).

Moreover, the complexity of coordination among diverse stakeholders further compounds the challenge. Effective WBIS management necessitates collaborative efforts across governmental bodies, utility corporations, regulatory entities, and urban planners (Xue et al., 2018). Navigating differing interests, regulations, and operational strategies among these stakeholders often leads to a comprehensive approach that inhibits streamlined management practices (Pathirana et al., 2021).

In the context of global interest of environmental sustainability, the ecological consequences of infrastructure management emerge as a challenge (Pandit et al., 2017). Cities striving for sustainable growth must confront the environmental footprint associated with infrastructure activities (McCormick et al., 2013). Mitigating the ecological impact of these activities, including curtailing emissions and waste during excavation, presents a multifaceted challenge that invites innovative and holistic solutions (Xue et al., 2018; Von der Tann et al., 2020).

Another underlying challenge is the lack of awareness regarding the importance of maintaining and renewing infrastructure (Pathirana et al., 2021). This lack of understanding among the general public, policymakers, and stakeholders can hinder the necessary investments and initiatives required for sustainable infrastructure management (Little, 2005; Xue et al., 2018). Addressing this gap through education and effective communication becomes necessitated to garner support for the essential maintenance of WBIS.

3.3. Urban Infrastructure Challenges in Sweden

In an inventory of urban infrastructure research in Sweden, Anders & Mattsson (2011) highlighted central research gaps and future research needs. Notable research gaps were observed, particularly in relation to sustainability. Firstly, lack of research-based understanding regarding the connections between sustainable development and urban infrastructure. Secondly, insufficient research on the challenges associated with urban infrastructure management. Moreover, there is lacking knowledge regarding the sustainability implications of different management strategies, technology choices, and institutional configurations, including policy and legislation. Anders & Mattsson (2011) emphasized that these shortcomings hinder the development of tailored and effective solutions to address contemporary sustainability challenges, making it challenging to identify the necessary measures to drive meaningful change.

During the recent decade, the urban infrastructure has increased and Thomasson & Jonsson (2022) found that notable advancements have been made, particularly in relation to neglected maintenance in Sweden, increased environmental requirements and climate change, and the dynamics of population growth and how it impacts infrastructure requirements.

As accomplished by Thomasson & Jonsson, 2022, the problems of outdated infrastructure and neglected maintenance have increasingly been addressed. In the 1950s through the mid-1970s, substantial investments in water and sewerage were made all over Sweden (Haraldsson (2019). However, since then a decline in investments in these networks can be observed (Jonsson & Syssner, 2016). As a result, there has been a noticeable growth in maintenance debt over time, necessitating substantial reinvestments in the current infrastructure (Carlsson et al., 2017).

Syssner & Jonsson (2020), Haraldsson (2019) and Carlsson et al. (2017), have all emphasized the repercussions of this maintenance deficit. Emphasizing that the long-term lack of maintenance leads to increased costs (Graham & Thrift, 2007). This neglect not only diminishes the value of fixed assets but also escalates the risk of technical issues and interruptions (Moss, 2008).

The most significant costs arising from this negligence are not in the form of repair and interruptions but stem from the impacts of these issues on the quality of drinking water and the environment (Walther,

2016). Such effects had already been observed in Swedish municipalities. In the municipality of Laxå, the CEO of the municipal water and sewerage company estimated that approximately 30 percent of water pumped into the pipeline networks was lost due to poorly maintained infrastructure (Thomasson & Jonsson, 2022). This situation led to increased energy consumption, heightened costs, and a detrimental impact on the environment, as noted by the CEO (Thomasson & Jonsson, 2022).

Increasing environmental requirements and concerns of the effects of climate change create further needs for investments in water infrastructure. To meet more stringent environmental standards, it is essential to modernize existing facilities and networks. The urgency for infrastructure modernization has several reasons. Firstly, it arises from the historical expansion of infrastructure in the 1950s, 60s, and 70s, which no longer aligns with contemporary environmental requirements. Secondly, this need is influenced by the evolving knowledge about water purification and emerging technical solutions (Thomasson & Jonsson, 2022).

Thomasson & Jonsson (2022) claim that knowledge about water treatment and technology is in a constant state of evolution. Therefore, sustaining a water supply that is not only compliant with legal mandates but also environmentally sustainable necessitates a continuous process of development and updating of existing infrastructure. In addition, there is a pressing need to adapt existing infrastructure to cope with challenges posed by climate change. This involves enhancing the capacity to handle extreme weather events, and ensuring a reliable water supply during drought periods

The understanding of how changes in population impact infrastructure requirements for both growing and shrinking municipalities has also increased. Haraldsson (2019) emphasized that the dynamics of population growth or decline necessitate adjustments to the existing infrastructure. This does not only apply to rapidly growing municipalities but also to those experiencing a decrease in population (Syssner & Jonsson, 2020). Investments are crucial for accommodating a growing population, requiring adjustments in pipeline networks, treatment plant capacities, and the development of new residential areas (Thomasson & Jonsson, 2022). Conversely, for shrinking municipalities, the focus is on reducing infrastructure capacity to avoid unnecessary financial burden on the users (Syssner & Jonsson, 2020). Municipalities with increasing populations demonstrate a greater willingness to allocate funds and resources for necessary infrastructure investments, while the willingness is notably lower in shrinking municipalities (Haraldsson, 2019).

Walther (2016) highlighted that inadequate utilization of systems can lead to technical issues, addressing the importance of proper capacity adjustments. The case of Valdemarsvik municipality was used by Jonsson & Thomasson (2017) as example of proactive adaptation to a declining population, utilizing annual reports and budgets to highlight maintenance and investment needs in water and sewerage infrastructure. By documenting and addressing these needs, municipalities not only enhance their financial management in compliance with legal requirements but also promote transparency and accountability to citizens and the media, fostering a democratic approach to infrastructure maintenance and development.

3.4. Navigating Towards Sustainable WBIS Management

Effectively addressing management challenges faced by WBIS requires a holistic and comprehensive approach (Von der Tann et al., 2020). By synergizing strategies, policies, and actions, WBIS can further chart a course towards sustainable management that benefits both present and future generations. Previous studies s have suggested a number of strategies that support the navigation towards sustainable management of WBIS:

- **Collaborative Governance**

"Collaborative Governance" (Ansell & Gash, 2008, Gray, 1989) refers to a cooperative and inclusive approach to decision-making and management, particularly in complex and interconnected systems or organizations. It involves multiple stakeholders, such as government bodies, private entities, community representatives, and experts, working together to address issues and achieve common goals. Collaborative governance is a vital concept in modern infrastructure management (Pathirana et al., 2021). It recognizes the complexities of decision-making structures and ownership boundaries and

emphasizes the need for proactive coordination, transparent communication, clear responsibilities, and aligned goals (Little, 2005).

Navigating complex decision-making structures and ownership boundaries requires collaborative governance. Coordination between different infrastructure networks (Keck et al., 2017), such as water, district heating and traffic systems is essential. By fostering transparent communication, clear responsibilities, and aligning goals (Little, 2005), the management can further overcome conflicts and streamline efforts. A collaborative approach not only ensures efficient operations but also enhances resilience in the face of sustainability challenges of WBIS (Xue et al., 2018).

To navigate the complexity of WBIS management, policy frameworks must be adaptive (Lemer, 1996). By actively incorporating sustainability principles into policies and regulations (Little, 2005), municipalities can ensure long-term viability of networks. By clarifying ownership boundaries, considering a broader range of factors, and integrating long-term sustainability into planning practices, it becomes feasible to pave the way for effective governance that transcends immediate challenges (Xue et al., 2018).

- **Strengthening Organizational Capacity**

Enhancing organizational capacity is central for sustainable WBIS management. Overcoming financial constraints necessitates innovative funding mechanisms (Pathirana et al., 2021). Exploring public-private partnerships, securing grants, and embracing sustainable financing models (Little, 2005) can alleviate budget limitations. Moreover, investing in technical capabilities (Lemer, 1996), staff training, and data management can foster operational efficiency and resilience, ultimately leading to successful maintenance and renewal.

- **A Risk-based Approach**

Implementing a risk-based approach to prioritize immediate operational needs while enhancing high-risk infrastructure condition is crucial (Pathirana et al., 2021). The risk-based approach prioritizes acute cases of leaks or contaminations, as long as operations linked to risk and consequential pipelines. Risk and consequential pipelines are the lines assessed as risk objects where there are potential breakdowns with major consequences (Fellman, 2007). However, to ensure alignment with broader sustainability goals, it's important to integrate this strategy with proactive initiatives (Little, 2005). By actively addressing both immediate and long-term infrastructure needs, organizations can further strike a harmonious balanced approach towards maintenance and renewal for more sustainable management (Xue et al., 2018).

- **Embracing Innovative Solutions**

Embracing innovative solutions signifies a proactive approach by further leveraging new and advanced approaches, technologies, and materials to address challenges or improve existing systems (Pathirana et al., 2021; Little, 2005). Organizations can utilize this approach to further develop sustainable WBIS management and contribute to environmental preservation e.g., the use of plastic-based materials and trenchless technologies in UWI.

Plastic pipes offer benefits such as durability, ease of installation, and longevity. They are known for their resistance to corrosion (Arthur et al., 2020), lightweight nature, and cost-effectiveness (Nia, Othman, & Naseri). This choice reflects a commitment to creating infrastructure that endures over time, requires minimal maintenance, and is efficient in its operation. However, the utilization of plastic-based materials may require an assessment of its environmental impact.

Trenchless technologies can minimize environmental disruption during infrastructure projects. Trenchless technologies reduce the need for extensive excavation (Bergman, 2022), which can have a detrimental impact on local ecosystems and communities. This approach not only demonstrates a forward-thinking practice but also aligns with the goal of environmental preservation.

- **Climate-Resilient Strategies**.

Given the increasing concern towards the impact of climate change, adopting climate-resilient strategies can be valuable. Stormwater management emerges as a critical domain (Pathirana et al., 2021). The risk-based approach to stormwater management can be bolstered by long-term planning and investment. By incorporating climate change projections into stormwater strategies, the management can further proactively manage flood risks, safeguard water quality, and ensure the sustained functionality of vital infrastructure.

4. RESEARCH METHODOLOGY

4.1. Systems Approach

A systems approach is a holistic and interdisciplinary methodology employed to address complex challenges and manage systems (Richardson, 2004). The importance of system knowledge in this study is that it enables a comprehensive and interdisciplinary approach that enhances understanding of the multifaceted challenges related to sustainability, the diverse factors influencing current WBIS management practices for maintenance and renewal, and the consideration of diverse viewpoints from multiple stakeholders and scientific disciplines (Von der Tann et al., 2020, Xue et al., 2018). As stated by Von der Tann et al. (2020), "*A systems approach to urban underground or subsurface management requires an awareness of a multitude of perspectives and scales as well as the interdependencies between those and tools to examine them*."

This systemic approach is driven by the recognition that the transformation towards more sustainable infrastructural management necessitates a departure from isolated measures. Instead, it relies on a comprehensive approach that encompasses coordinated and collaborative actions and changes (Pandit et al., 2017). These collective efforts aim to enhance the long-term durability of WBIS and facilitate their joint maintenance and renewal. In this context, systems perspective serves as a means to comprehend the existing conditions of WBIS management and explores avenues for enhancing sustainability (Sterman, 2012).

WBIS encompass not only technical elements but also non-technical and time-dependent components such as people, processes, and policies, making them a prime example of "complex" systems (Richardson, 2004). Within this framework, the systems perspective facilitates a comprehensive approach that aids in understanding all technical and non-technical elements of WBIS, leading to a better understanding of the overall functionality of these systems (Von der Tann et al., 2020). Commonly described as the "holism principle," this perspective acknowledges that the sum of the parts of a system or sub-system interacts on different levels, resulting in outcomes or functions that surpass individual system elements (Richardson, 2004).

The management of WBIS is acknowledged as a multifaceted and challenging, driven by the interplay of a multitude of factors (Coutard, 2002; Geels, 2004). The lack of essential knowledge regarding the impact of these factors on current WBIS management practices supports systems complexity (Von der Tann et al., 2020). The systems perspective enables the examination of current WBIS practices as outcomes of various intertwined factors and conditions that influence at different levels (Xue et al., 2018, Geels, 2004).

4.2. Assessing the Management of Urban Infrastructure

Assessing the maintenance and renewal of WBIS encompasses a multifaceted process characterized by various assessment and analysis techniques. This process entails the inspection of components such as pipes, wires, and equipment to examine their condition (Pathirana et al., 2021) and remaining operational lifespan (Lemer, 1996). Key data points, including age, type, materials, geographic areas, interruptions, and historical maintenance and renewal records, constitute essential considerations. Regular assessments and inspections are crucial for issue identification and the formulation of enhancement strategies. The operational efficiency of WBIS is inherently linked to its condition, with inadequate maintenance potentially leading to malfunctions, service quality, and diminished system performance.

Through the evaluation of infrastructure conditions, experts can analyze accumulated data to provide recommendations pertaining to renewal or replacement requisites. This process often entails the development of long-term asset management plans that outline schedules for renewing various elements of the infrastructure system. Municipal authorities must deliberate over replacement costs and assess whether the existing system adequately serves the community's needs (Little, 2005). The age of the infrastructure serves as a critical determinant (Pathirana et al., 2021), dictating the urgency of renewal actions, as aging components are more prone to reaching their functional limits and necessitating replacement.

The materials employed within the infrastructure assume a role in predicting the lifespan of its components. Diverse materials exhibit varying lifespans and sensitivities to different forms of

deterioration, including corrosion, cracking, and scaling. Material analysis serves as a tool for identifying components that mandate renewal, subsequently guiding the selection of suitable replacement materials (Ilg et al., 2016). Understanding of the characteristics of different WBIS, including those facilitating water supply, sewage treatment, and drainage, is crucial. These varied systems inherently possess distinct requirements and functions, mandating customized approaches to their renewal processes.

Furthermore, the analysis incorporates considerations of the geographical placement of infrastructure systems. In certain instances, system performance may be significantly influenced by their location (Almoghathawi & Barker, 2019), particularly in areas prone to flooding and harsh climatic conditions (Pathirana et al., 2021). In such contexts, renewal initiatives gain prominence as mechanisms to enhance infrastructure reliability and sustainability, ensuring robust functionality even in challenging environmental scenarios.

Dealing with renewal needs, financial requirements, and renewal debt entails quantifying renewal needs based on the total network length, highlighting the proportion of lines requiring replacement, their lengths, costs, and potential debt implications. The budgeting analysis delves into the allocation of resources for emergency response, infrastructure renewal, and proactive preventive measures (Little, 2005). This holistic examination of budget frameworks and financial strategies addresses both immediate and long-term considerations, aiming for effective management and sustainable advancement of WBIS.

5. RESEARCH METHODS

The case study is based on a mixed methods approach, combining qualitative and quantitative methods, to examine the current state and management of the urban water infrastructure.

5.1. Data Collection

The data collection encompassed interviews, workshops, and collection of documents and water system data. Interviews started with an initial round of interviews with municipal officials and water utility managers were performed in both Linköping and other cities (Malmö and Helsingborg). The contacts with the local water utility, TV, were central for the collection of local data on the local water management. Table 3 provides an overview of the interviews and workshops.

This diverse group of stakeholders, consisting of city officials and water utility managers, was selected based on their specific positions in connection with the local water management. By gathering insights from these individuals, the study gained valuable perspectives on the practices and challenges in connection with local water infrastructure management.

Table 3 Information About the Respondents.

Interviews			
NO.	**Respondents' Position**	**Date**	**Time-min.**
Int.1	Group leader project, water and sewage networks AB, Malmö	06/10/2020	60
Int.2	Group Manager, Nordvästra Skånes Water and Sewage AB, Helsingborg	07/10/2020	60
Int.3	Head of Planning & Projects, water and sewage, Tekniska verken, Linköping	26/10/2020	60
Int.4	Business Unit Manager Management Network, Tekniska verken, Linköping	06/11/2020	60
Int.5	Deputy CEO, water network, Tekniska verken, Linköping	17/11/2020	60
Int.6	Acting CEO, electricity network, Tekniska verken, Linköping	01/12/2020	60
Int.7	Representative of the board of Tekniska verken, and for the municipality	13/01/2023	60
Workshops			
NO.	**Workshops' Focus**	**Date**	**Time-min.**
WS.1	Head of department, water management network, Operation, and investigation	24/08/2022	120
WS.2	Water management network- database and Trimble support	04/10/2022	120 + 240
WS.3	Water management network- budget and finance	22/09/2022	120 + 240
WS.4	Database and Trimble support	30/09/2022	240
WS.5	Water management network- budget and finance	14/11/2022	120 + 240
WS.6	Database and Trimble support	24/11/2022	240

5.1.1. Interviews

The interviews were performed both by video calls and face-to-face. They were based on a semi-structured approach, characterized by pre-planned question categories coupled with the flexibility to resequence or modify questions as needed. This ensures that the interview remains tailored to each respondent's perspective (Adams, 2015). This methodology facilitates exploration of predefined key themes. Approached by open-ended questions, the interview guide consisted of themes related to network management such as organizational management processes, challenges, maintenance and renewal considerations, and proposed measures. The complete interview guide is available in the online Appendix (1), which is accessible at the provided link.

https://docs.google.com/document/d/1UmSjCDhApjVza4NyQ5or2aifk6v47ZrmOd5nzAsybdc/edit?usp=sharing)

5.1.2. Workshops and Collection of Network Data and Documents

Six workshops were held at the premises of TV with members of its water management team. An overview of these workshops and their main focus is presented in Table 3. During these workshops, participants engaged in interactive presentations and discussions on diverse issues related to the UWI and their management. These sessions also served as platforms for the exchange of valuable data. The workshops were designed to encourage participants to share their viewpoints, unveil challenges and prospects. The introductory workshop focused on introducing the project and the overarching purpose of the workshops, which included addressing management challenges as well as collection and refinement of UWI and validation of previous findings and hypotheses derived from literature analysis and interviews. Subsequent workshops involved an ongoing dialogue with staff members, facilitating a continuous data collection process while fostering in-depth discussions on different issues related to

management. This allowed for seeking clarifications and provided opportunities to address further issues.

The data collection spanned a wide array of data on the water and sewerage networks, particularly on the physical conditions of urban water infrastructure networks, but also information about the budget process with budgets and budget outcomes. Detailed data on installation and renewal dates, dimensions, and material of different parts of the networks as well as leakage incidents, were retrieved from TV's database *Trimble*. This allowed assessment of the status of the networks and their development in different parts of the city. TV also provided different documents related to the planning and management of the water services and networks, and workshops addressed the processes related planning and executing maintenance and renewal work, and their challenges. Among the most addressed issues during the workshops were water leakage incidents and pipeline damages, their causes and the structure and allocation of the budget between emergency interventions, new construction, renewal projects, and preventive measures. Additionally, the evolution of maintenance and renewal practices over time was explored.

5.2. Data Analysis

The analysis started by organizing and evaluating the gathered quantitative and qualitative data, developing an overview of the current state of UWI and their management. The collected data during workshops were transcribed and summarized for subsequent analysis. This involved scrutiny of the compiled information. Recurring themes, discernible patterns, and relevant observations were identified and systematically categorized for further examination and interpretation. Interviews were recorded and transcribed manually and automatically using Trint software. Interviews data was organized, analyzed, and processed using NVivo 12[2] software. This software enables extracting relevant statements through coding. Coding and themes were manually generated. The main theme created concerned WBIS management practices while subthemes included actors' responsibilities, management priorities, strategies, policies and regulations, resources, organizational capacity, and technical issues. In practice, participants' statements were translated into specific coding categories, linked to themes. Sometimes codes overlapped, and one statement could be linked to several themes. This made it easy to make links between stakeholders. Since categories develops during the research, one phrase may be coded to several themes, suggesting relationships between them, and revealing the common influencing factors (Mayring, 2015). All statements connected to different themes, were summarized in tables, and grouped for the analysis of management practices, their challenges and what influences them.

The quantitative analysis focused on the current status of the three UWI, renewal, renewal needs, and budgeting. The analyses of network data extracted from the supplied databases were performed with a recognition that some records are incomplete and have errors. Therefore, the city level results should be perceived as "best" approximations.

The analysis of the current status covered an analysis of the age and material of the drinking water, the stormwater and wastewater networks, as well as interruptions and leakages in recent years. The evaluation of the interruptions focused on types of interruptions, affected network types to identify which interruptions were typical for the different networks and areas, and the development of interruptions over years and months.

The renewal analysis spanned all the three networks and focused on the age, areas, types, and examined the involved materials, that were replaced and used for the renewal. The development of renewal debt was analyzed based on the current and assumed future renewal needs for each network, along with financial requirements for the renewal. This involved quantifying current renewal needs based on age and network lengths and estimated costs for the replacement. These estimates were based on the lengths of lines exceeding eighty years and the replacement cost of 20,000 kronor per meter, which was provided by TV[3]. Scenarios that are projecting the renewal debt for the years 2020, 2030

[2] "Used with permission from Lumivero".

[3] Renewal needs calculations are approximate. Lines lengths were first calculated based on the given total lengths of each type of UWI. An average of lengths was calculated by dividing the total lengths by the number of lines recorded in the database Trimble. Giving the average lengths of lines that are more than eighty years old, as well as the estimated replacement cost according to TV; 20,000 kronor per meter, the replacement cost was calculated.

and 2100, if the renewal rates stay at the current levels, were calculated based on estimated aging of the networks based on current renewal rates[4] and replacement costs, and assumed inflation and discount rates. Further details are available in Appendix 5, Paper 1. Fig. 1 illustrates the analytical framework for identifying renewal needs of UWI.

The analysis of the water management budget focused on developing an understanding of the budget process and its impact on resource allocation on different activities with a particular emphasis on maintenance and renewal. This analysis was based on information on budgets and the budget process as well as interviews and workshops with managers and politicians. For this analysis we had access to the budgets and their outcome 2014-2022 as well the preliminary budget planning 2022-2027. This analysis made it possible to better understand how TV water management navigates within the given frames and how different tasks and priorities may compete and which factors influence maintenance and renewal activities.

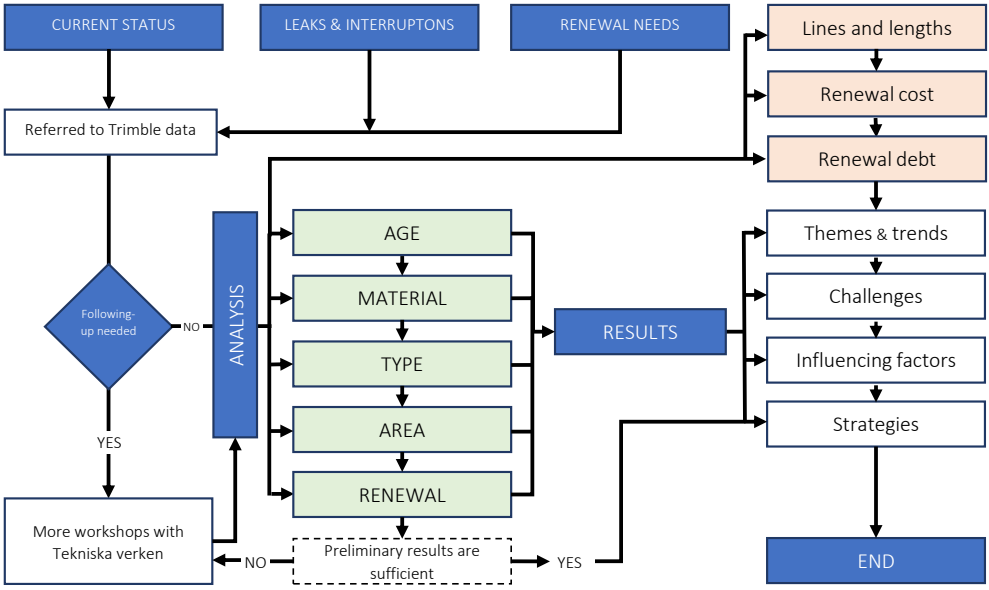

Fig. 1 Analytical Framework for Identifying Renewal Needs of UWI.

5.2.1. The Analysis in the Appended Papers

While all the papers were built on the same case and data collection process, they have different focus and rely on different types of analysis. The focus of the analysis in the papers was as follows:

Paper I: Assessing Renewal Needs of Urban Water Infrastructure Systems: Case Study of Linköping in Sweden, assessed the current status of the urban water infrastructure systems and their renewal needs. A crucial aspect of this analysis lies in unraveling the rate of renewal, how it had developed over time, and whether it is adequate. The network current state, interruptions occurrence, renewal state, as well as renewal needs, and renewal debt were identified. The collected data was examined to pinpoint the city's specific needs of renewal, and challenges that limit initiatives towards renewing its UWI.

Paper II: Systems Lens: Towards Sustainable Management of Maintenance and Renewal of Wire-based Infrastructure: The Case of UWI in the City of Linköping, Sweden, explored the management practices

[4] Renewal rates were calculated as the renovation of pipes counted in kilometers, in relation to the total line length.

in relation to Linköping's UWI. The analysis built further on the analysis in Paper I but was mainly based on qualitative data from interviews and documents and sought to understand the management processes, priorities, strategies, policies, resources, technical methods, and the factors influencing processes of management. The analysis bolstered the paper's findings with insights from stakeholders, providing a multifaceted perspective on the practices and challenges of water infrastructure management. By utilizing systemic lens as an interpretive tool, the dependencies, and interconnections between different elements of the management were explored.

Paper III: Enhancing Infrastructure Renewal: Analysis of Water System Budget, aimed at attaining an understanding of budgetary frameworks and financial strategies, and how immediate and long-term requirements are addressed. The assessment encompassed an investigation of the budget processes and their outcome in terms of proactive management, maintenance and renewal, and distribution, as well as the multifaceted dimensions of UWI management, ranging from processes and policies to resources and management priorities, which form the foundation of the quantitative analysis.

Budgeting analysis unfolded across a 14-year timeframe, spanning from 2014 to 2027. This examination dissects allocations for diverse categories, including emergency response, infrastructure renewal, and proactive spendings. This analysis sought insights into current management and the alignment of budgetary considerations with the need of maintaining a resilient and sustainable UWI.

6. RESULTS

6.1. Current Status of UWI

The water pipelines of the networks of drinking water, wastewater, and stormwater stretch in total approximately 1982 kilometers (2022). The water infrastructure also consists of sewage pumping stations, overflow sites, overflow pumping stations, and sewage storage tanks that ensure efficient operations. A significant portion of the networks are more than 50 years old, and consist of different materials. While plastics and iron dominate the drinking water system, Concrete pipes are prevalent in wastewater and stormwater networks. Recent decades have witnessed a shift towards utilization of plastic materials. Table 4 summarizes current status of age and material for UWI (Paper 1).

Table 4 Summary of Current Age and Material Distribution in the UWI

Networks	Drinking Water	Wastewater	Stormwater
Materials	25% PEM[5] 20% PE 18% Ductile Iron 15% Cast Iron 22% Other	54% Concrete 21% PVC 12% POLY[6] & PE 13% Other	75% Concrete 18% PVC 7% Other
Age	40% (50-80) Years 39% (20) Years	43% (50-80) Years 36% (20) Years	48% (50-60) Years 29% (20) Years

6.1.1. Drinking Water

The majority of Linköping's drinking water pipelines were established during the 1960s to 1980s. Materials such as Cast Iron, Ductile Iron, and PVCT were predominantly used until the 1980s. However, PE and PEM have emerged as dominant materials, collectively constituting 45% of the drinking water network. It's worth noting that Cast Iron and Ductile Iron pipes continue to comprise approximately one-third of the network (Paper 1).

6.1.2. Wastewater

A significant portion of Linköping's wastewater network was established between the 1950s and the 1980s. Prior to the year 2000, Concrete was the predominant material for wastewater pipes. Subsequently, plastic materials, especially PVC, POLY, and PE, have gained prominence, making up around one-third of the network. However, Concrete remains the predominant material in the wastewater pipe network (Paper 1).

6.1.3. Stormwater

The majority of Linköping's stormwater pipes were installed during the 1960s to 1980s, with Concrete being the predominant material until the early 2000s. In recent decades, there has been an adoption of PVC and PP[7]. However, Concrete continues to dominate the stormwater pipe network, constituting 75% of it, while PVC accounts for approximately one-fifth of the network (Paper 1).

6.1.4. Leakages and Interruptions

In 2020, the water leakage rate in Linköping was estimated at 5.5%, which increased to 6.7% in 2021. Over the years since 2000, the frequency of interruptions has displayed considerable variability, with a trend of increasing interruptions during the last decade. Six out of the seven years with the highest number of interruptions occurred after 2013. Interruptions are most frequent during winter and spring months, attributed to the susceptibility of water pipes to freezing and breaking in colder weather. However, factors such as inadequate maintenance, aging infrastructure, and insufficient renewal of UWI may also contribute. Water leakage, supply cuts, and pipe breaks are the most prevalent types of disruptions, with the highest number of interruptions concentrated in central city areas housing the oldest network sections (Paper 1).

[5] PEM (Polyethene).
[6] POLY (Polyethylene).
[7] PP (Polypropen).

6.1.5. Network Renewal

Documentation of network renewals extends back in time, with records for the drinking water network tracing as far back as 1900. Renewal efforts have intensified over recent decades, primarily utilizing plastic materials such as POLY for renewals across all UWI since the 2000s. For instance, wastewater network renewal averaged around 200 km per year post-2005, with 89% of these renewals comprising POLY. Stormwater network renewal has been less consistent, with fewer instances of renewing over 50 km in a single year since 2000. For stormwater, renewal primarily utilized POLY, accounting for 94%, alongside some instances of PEH[8], contributing 5%. Drinking water renewal has intensified particularly over the last two decades, driven by factors such as the end of lifespan or the necessity to upgrade to more efficient materials (Paper 1).

6.1.6. Adequacy of Renewal Rates

Since 2000, approximately 25% of the networks have undergone renewal, yet numerous pipes aged 80 years or more remain in the networks. According to TV, exceeding 80 years of network pipe age is undesirable. Table 5 represents average renewal rates for 2020/2021 for each network and in total. If the current renewal rates remain constant, the length of lines exceeding 80 years would grow from 48 km (1%) in 2020 to 590 km (8%) by 2050, and almost 2000 km (25%) by 2100. Such a trajectory would lead to escalating renewal costs and substantial renewal debt over time. These findings highlight the insufficiency of current renewal rates and the need for a more proactive approach (Paper 1).

Table 5 Current Renewal Rates for Different UWI (Average % 2020/21)

Water Networks	2020/21
Drinking Water	0.13
Wastewater	0.05
Storm water	0.04
Overall	0.22

6.2. The Management of UWI in Linköping

The municipality has delegated the water services, including the ownership and management of the UWI to TV. However, the municipality maintains control via setting the budget and user tariffs, and the board of the utility company consists of municipal politicians (Paper 2). The responsibilities of TV include maintenance and renewal of the UWI, as well as repairs and emergency preparedness. TV is also responsible for the expansion of the networks in connection with city development projects. Continuous communication and collaboration with different municipal departments involved in city planning and construction are therefore required (Linköpings Kommun, 2017).

At TV, three departments are involved in the management of the water systems. The customer department handles issues related to customers, such as maintenance work or new connections related to water and sewerage. The planning and projects department handles network monitoring and the construction and operational work in connection with city development. The operation and business unit handles the maintenance and renewal and establishes a plan for investment needs (Paper 2).

In alignment with The Public Water Services Act (Lagen om Allmänna Vattentjänster LAV) (Linköpings Kommun, 2017), TV prioritizes delivery reliability as its overarching objective. Prompt resolution of detected malfunctions is therefore the highest priority and swift action is taken to immediately repair malfunctions aiming to avert any significant repercussions. Urgent maintenance and renewal to secure functionality are also of high priority. Acute maintenance and renewal operations are also immediately carried out to restore the functionality. Since 2012, TV has installed real-time online monitoring systems. The monitoring of the drinking water network is based on 18 flow zones, each encompassing designated flow meter regions for flow and pressure oversight. To ensure precision, the system is calibrated using data from around 200 real-time pressure sensors (Svenskt Vatten Utveckling, 2018). These data are processed and analyzed using tools provided by Svenskt Vatten. Network

[8] PEH (Polyethene).

expansion projects in connection with city development projects are the second priority, mostly because delays have far-reaching consequences for whole construction projects (Paper 2).

The planned proactive maintenance and renewal activities targeting sustained network efficiency over the long term has lower priority. The planning and prioritization of maintenance and renewal is based on factors such as pipeline importance, age, and material composition. This approach also incorporates considerations of risks and potential impacts linked to climate change adaptation. "High-risk pipelines," characterized by age-related vulnerability and potential severe consequences, receive the primary attention (Paper 2). Furthermore, the age of the network pipes should not exceed 80 years. To facilitate the maintenance and renewal planning TV employs a self-produced application called Trimble. Trimble offers a systematic prioritization based on the probability of malfunctions and associated consequences for each major pipeline (Paper 1).

The planning of maintenance and renewal operates with a timeframe of 3 to 5 years, but the ambition is to establish a more consistent, and long-term strategic assessment procedure. TV focuses thus mostly on improvements in a short-term perspective. However, while the strategic long-term planning is still in its initial stages, the objective is to institute a recurring strategic assessment process, ensuring effective management over the long run (Paper 2).

6.2.1. Network Maintenance and Renewal Spending

Understanding how the budget is allocated and utilized for the management of TV's UWI provides valuable insights into the competition among various tasks and the factors that influence network renewal efforts. The budget plays a central role, encompassing a range of operational activities such as expansion, maintenance, repair, and renewal initiatives, all of which collectively ensure a continuous water supply. However, a closer examination of the budget distribution reveals the competitive nature of different tasks, sheds light on factors that limit the focus on network renewal, and underscores the complexities within the management process (Paper 3).

KF, responsible for adjusting user fees, plays a crucial role in shaping the financial framework for the existing infrastructure's operations. They also approve the annual operating budget for water infrastructure management, in line with special owner instructions (Linköpings Kommun, 2017). These decisions are based on TV's suggestions and preparatory work, as well as long-term planning and analysis of urgent renewal needs and ongoing projects (Paper 3). Since 2014, there have been only modest increases in user fees. However, in 2023, a 14% increase in user fees was announced due to high inflation in recent years (Tekniska Verken, 2023).

The budget for water infrastructure management encompasses various operations for different networks, including expansion, maintenance, repair, and renewal (Paper 3). It is divided into three categories:

- Improvements: This category focuses on planned investments to enhance and secure the functionality of the three UWI. It also includes new pipe installations to connect smaller town wastewater networks to the main wastewater plant and expand the stormwater network in critical areas.
- Renewal, Emergency, and Preventive Operations: This category covers a broad spectrum of activities, including emergency repairs, renewal projects, and proactive initiatives to prevent future interruptions.
- Expansion: This category involves new pipe networks connected to city development projects.

The expenses for these categories are funded from different sources. Categories 1 and 2 are financed by user fees, while Category 3 is covered by the city's overall investment budget. The allocation of the budget among these categories varies each year, depending on the city's new construction activities. While the first two categories have had relatively stable budgets over the past decade, the renewal part in Category 2 was strengthened from 2017. The actual expenditures, particularly for Category 1, fluctuate from year to year (Paper 3).

Table 6 illustrates the distribution of total water infrastructure expenditures across these categories from 2014 to 2022. While the total expenditures during this period exceeded 600 million SEK, they fluctuated significantly from year to year, often favoring expansion operations at the expense of proactive

maintenance and improvement projects. This was due to capacity limitations, as the water management organization had difficulty adapting to the variations in their responsibilities. Emergency repairs and renewal projects in Category 2 were often prioritized, leading to competition for resources (Paper 3).

Table 6 The Distribution of the Total Water Infrastructure Expenditure on the Three Budget Categories (2014-2022)

%	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
Category 1	12	9	12	16	15	27	6	5	13	12
Category 2	33	34	50	52	46	35	36	45	30	39
Category 3	55	58	37	32	39	39	58	50	57	49

TV follows a long-term budget planning process that extends over the next five years. According to the 2022-27 long-term budget, Category 1's budget for proactive operations will increase substantially, while Category 2 will remain stable. Category 3 will decrease, reflecting the trend of reduced construction in Swedish society. Maintaining Category 2's budget at the same level as 2017-2022 does not signal a strong commitment to increasing and stabilizing the renewal rate. Strengthening Category 1's budget could enhance TV's water management capacity by expanding its workforce, a crucial factor for renewal activities. Increasing user fees and budgets for Categories 1 and 2 is a necessary step to ensure higher renewal rates, but challenges related to personnel recruitment may impede immediate results (Paper 3).

The dominance of Category 3 (expansion) in recent years is noteworthy, with almost as much expenditure as maintenance and renewal improvements. This emphasis on expansion may inadvertently delay broader development goals and essential infrastructure renewal. Achieving a balanced approach between maintenance, renewal, and risk-based operations with expansion efforts is essential for a resilient, adaptable, and sustainable water management framework in Linköping (Paper 3).

The budget analysis also prompts consideration of the optimal allocation of funds for Improvements (Category 1) to ensure the network's long-term sustainability. Embracing innovative technologies, such as Trimble application, reflects TV's commitment to efficient management. Implementing technologies that streamline maintenance and renewal planning can optimize resource utilization by prioritizing high risk areas and strategically directing budget allocations (Paper 3).

6.3. Summing up Case Observations

Water suppliers like TV operate under a legal obligation to provide safe and high-quality water to their customers. This obligation shapes the core focus of the water management, emphasizing the reduction of water supply disruptions and the preservation of water quality through a risk-based strategy. Consequently, acute operations and the enhancement of high-risk pipelines are prioritized. This approach may divert resources and attention from proactive maintenance and renewal, particularly when unforeseen emergencies arise or when there's a need to connect new customers to the water supply network.

Most of the budget is normally allocated to expansion operations, followed by addressing immediate acute cases. However, the prevalence of emergencies, which are often unpredictable, leads to competition that affects planned maintenance and renewal projects in terms of both time and capacity. Due to current capacity restrictions, it is difficult to significantly elevate the rate of renewal within the existing budget frames and the capacity of the water management. This situation contributes to an insufficient renewal rate within Linköping, accompanied by a growing number of water leaks and supply disruptions. However, an increase in the user fees would bring an increased budget and opportunities to increase the management capacity by recruiting more personnel.

The overarching issue of aging infrastructure significantly contributes to water supply leaks and disruptions. To address these challenges effectively, it becomes necessary to invest in maintenance and renewal projects that bolster the resilience of water pipelines. By giving precedence to these initiatives, the risks associated with aging infrastructure can be mitigated, and a dependable, uninterrupted water supply can be secured. Financial constraints have contributed to that TV follows a rather reactive maintenance and renewal strategy based on risk assessment.

However, the water management also has introduced some “innovative solutions”, such as online detection methods in the drinking water network to identify potential toxins early on. However, the digitalized monitoring system encounters technological hurdles, including errors, disconnections, data uncertainty, limited sensor sensitivity, and detection reliability issues. The introduction of digitalization into staff education requires comprehensive training programs, imposing financial commitments. Establishing a cohesive and accessible database faces challenges related to permissions and stakeholders. Improvement strategies involve exploring new tools for risk assessments and advocating for streamlined and accurate analysis methods, particularly in maintenance and renewal cost estimation. Interviews reveal a call for more efficient models that can estimate project costs in a simpler and more precise manner.

When it comes to selecting materials for pipeline renewal, TV relies on past performance and historical data. Plastic-based materials, such as POLY and PVC, have emerged as preferred choices due to their proven durability, resistance to corrosion, and cost-effectiveness. These materials are well-regarded for their ability to withstand harsh environmental conditions, offer excellent hydraulic performance, and simplify installation through trenchless methods. This approach minimizes the inconvenience caused by extensive excavation, thereby ensuring uninterrupted daily activities for residents and businesses.

Coordination between different infrastructure networks is encouraged in Linköping. However, this coordination is difficult to realize in practice. The complex decision-making structure and unclear division of responsibilities between the municipality and net owner, as well as within the net managing company, pose obstacles for effective management. Coordination with other infrastructure networks, such as district heating and traffic, is also essential to limit excavation and align with sustainability goals. However, practical coordination often leads to conflicts, delays, or cancellations due to organizational boundaries, differing laws, and regulations. To improve efficiency and reduce economic losses associated with project delays, there's a need for clearer and more aligned laws to facilitate collaboration and reduce conflicts of interest among various infrastructure networks.

7. DISCUSSION

7.1. The Water Infrastructure Challenges in Swedish cities

The challenges identified in the case of Linköping are also faced by other Swedish cities. While there is a recognized need for increased investment in the water and wastewater systems in Sweden, the water management in many municipalities is characterized by reactive maintenance and renewal strategies. Since LAV mandates self-financing through tariffs, it seems crucial to gradually increase water tariffs to meet maintenance and renewal needs.

If this is not done, it could result in sudden fee increases, as experienced by several municipalities (WSP-VA-Fakta, 2014). Investments directly impact water quality and quantity, especially considering the expansion of municipal water and sewerage systems.

To address these financial challenges, alternative funding sources like public-private partnerships, grants, or infrastructure financing methods might be explored to secure additional resources for renewal initiatives. Investing in skilled employees and technological capabilities is essential, even though it comes with financial implications. Technological challenges such as improving digital systems for monitoring and detecting leaks, along with data management and analysis, require additional resources for staff training and technology reliability.

Municipal guidelines express the need for strategic planning in UWI management, yet inadequate budgets hinder this approach. To achieve long-term sustainable solutions, municipalities must prioritize adequate funding for strategic planning. Political leadership plays a central role in establishing clear roles and responsibilities and making necessary investments to ensure the networks' long-term functionality.

However, the existing regulations primarily consider health and environmental performance, potentially leading to inconsistencies between areas where the municipality is responsible for water supply and housing development. Addressing these challenges requires broader factors to be considered, incorporating strategic management and sustainability principles into planning practices.

In navigating towards sustainable WBIS management, collaborative governance, organizational capacity enhancement, risk-based approaches, and embracing innovative solutions, are in line with the strategies suggested by Ansell & Gash (2008), Pathirana et al. (2021), and Little (2005). The importance of incorporating sustainability principles into policies and regulations resonates with the need for sustainable management in Swedish cities, emphasized by Gustafsson et al. (2019) as well. The challenges of aging infrastructure, financial constraints, and coordination among stakeholders align with findings by Haraldsson (2019) and Thomasson & Jonsson (2022). The gap in research regarding the connections between sustainable development and urban infrastructure in Swedish cities, identified by Anders & Mattsson (2011), corresponds with the need for systemic knowledge that is discussed internationally by e.g. Pathirana et al. (2021) and Von der Tann et al. (2020).

The need for ongoing development and updating of existing infrastructure to cope with changes in technology and knowledge as well as the importance of embracing innovative solutions, is emphasized by Thomasson & Jonsson (2022) in connection with Swedish cities, and related to cities abroad as discussed by e.g. Lemer (1996) and Pathirana et al. (2021). The importance of population dynamics highlighted by Haraldsson (2019) and Syssner & Jonsson (2020), reinforce the importance of adaptive infrastructure planning, as suggested by Lemer (1996), Little (2005), and Von der Tann et al. (2018, 2020).

7.2. An Issue of Increasing Concern of Climate Change

Climate change poses significant challenges for water supply systems, impacting both water quality and quantity. The effects of climate change include increased risks of flooding, erosion, and groundwater decrease, which can damage infrastructure and affect water supply. In some areas of Linköping, heavy rainfall events may lead to flooding, highlighting the importance of a stormwater system capable of handling such scenarios to prevent damage. However, increasing stormwater diversion to prevent flooding can have unintended consequences, such as reduced groundwater storage and increased operational costs during flood events. TV currently adopts a risk-based approach to stormwater

management, focusing on mitigating consequences rather than implementing strategic solutions. This approach is largely driven by financial limitations, and the existing legislation mandates dimensioning the stormwater system up to a reasonable level. To address these climate-related challenges effectively, proactive planning is essential. The need for proactive planning, collaborative governance, strengthening organizational capacity, and embracing innovative solutions aligns with strategies suggested in the literature (Ansell & Gash, 2008; Lemer, 1996; Little, 2000). Municipalities must ensure safe drainage routes, multifunctional surfaces, and proper stormwater management at all stages of spatial development, from planning to implementation and assessment. Furthermore, there is a need for further clarification of responsibilities and procedures regarding climate-related water issues within spatial planning and infrastructure management. The emphasis on climate-resilient strategies aligns with the broader focus on climate change in Swedish cities, as discussed by Thomasson & Jonsson (2022).

7.3. Is There a Lack of Knowledge, Awareness, and Motivation?

It is essential to recognize that the ability to drive infrastructure renewal is influenced by more than just a lack of knowledge. Political, economic, and social factors also play important roles in shaping infrastructure management. The incentive for effective renewal often hinges on the availability of key resources such as funding, expertise, and public support. The research findings highlight varying levels of awareness and motivation among different stakeholders. Those directly involved in water systems, such as Svenskt Vatten, water managers, and researchers, generally possess a strong understanding of the challenges and perceive them as important. However, there is a divergence in the knowledge and grasp of maintenance and renewal needs among politicians. Individuals with a deeper understanding of these issues tend to recognize their importance and are more inclined to invest resources in addressing them. It is also evident that a more systemic understanding of infrastructure management practices is needed to facilitate decision-makers' understanding of infrastructure conditions and performance, enabling them to allocate resources for maintenance and renewal over time. The specific challenge of the lack of knowledge and awareness among decision-makers aligns with the findings of previous research in Urban Infrastructure (Little, 2005; Pathirana et al., 2021).

Addressing this multifaceted challenge requires a systems approach (Xue et al., 2018; Von der Tann et al., 2020). When dealing with infrastructure maintenance and renewal, adopting a well-balanced, long-term strategic perspective can contribute to the well-being of present and future generations. Systems approach involves engaging a diverse range of stakeholders, including engineers, planners, policymakers, and community members (Little, 2005). The predominant focus on technology in previous studies has left gaps in understanding management settings, practices, and influencing factors (Xue et al., 2018; Von der Tann et al., 2020). While technical and quantitative assessments are valuable, they should not be the sole basis for decision-making (Lemer, 1996). The lack of systemic knowledge concerning the diverse factors influencing management practices within subsurface infrastructure systems is a common gap (Pathirana et al., 2021; Xue et al., 2018). Collaborative efforts allow for the inclusion of the entire community's needs and priorities in renewal plans, ensuring that infrastructure systems are effectively maintained and capable of meeting the community's long-term needs (Ansell & Gash, 2008; Pathirana et al., 2021).

8. CONCLUSIONS

This study aims to contribute to an enhanced understanding of the challenges associated with the management of WBIS in urban areas. Focusing on the case of Linköping, Sweden, the primary objective is to address three research questions, namely (1) What is the current status of the UWI and their management in terms of repair, maintenance, and renewal? (2) Which are the key challenges for increasing renewal and improving maintenance? and (3) How can these challenges be met?

The investigation into the current state of Linköping's UWI and its management assessed the current conditions and revealed a management dynamic encompassing drinking water, wastewater, and stormwater networks. The networks, predominantly aged over 50 years, present a combination of materials, with recent shifts towards plastic-based materials. TV deals with networks displaying signs of aging and financial constraints. However, although UWI is currently in a reasonable state, there is a risk of accumulating future renewal debt, if renewal rates remain at current levels.

In response to RQ2, several challenges were synthesized, including an aging UWI, suboptimal renewal rates, and budgetary constraints. The allocation of financial resources tends to favor expansion, fostering competition for funds and impacting proactive maintenance and renewal endeavors.

In addressing these challenges in RQ3, potential solutions come to the forefront. Proposals include a strategic increase in user fees, exploration of alternative funding sources, and advocacy for comprehensive strategic planning. The study highlights the need for a more proactive and strategic approach in UWI management to ensure sustained functionality and address the evolving needs of the infrastructure.

To advance sustainable development and management of UWI, it is important to gain a profound understanding of existing management practices and the intertwined array of factors that shape them. Existing research has predominantly concentrated on engineering-centric inquiries into specific technologies, largely neglecting the need for a holistic understanding of contemporary management strategies. Consequently, there exists a research gap surrounding the relationship between sustainable development, urban infrastructure, and the multifaceted challenges inherent to maintenance and renewal management. The prevailing regulatory framework, primarily oriented towards cost considerations, may not facilitate the cultivation of long-term, efficient, and sustainable management practices. It is crucial to increase understanding of the management of systems, their lifecycles, and their reliability, especially within the realm of maintenance and renewal management. This mandates a reevaluation of policy boundaries to enable increased investments and the accommodation of ongoing maintenance and renewal needs within the scope of organizational capacity, policies, and regulations. The establishment of a well-defined management structure that fosters enhanced collaboration with diverse stakeholders across various networks is crucial for augmenting the sustainability of current networks management. Effective leadership and clearly defined responsibilities are essential in driving decisions pertaining to critical maintenance and renewal requirements. Ultimately, a transition towards long-term thinking and a holistic perspective is important towards sustainable management of WBIS.

In conclusion, while a lack of knowledge can indeed pose a barrier to driving renewal efforts, it is just one component within a broader array of challenges facing Linköping and other Swedish cities. In the recent decades, Sweden has established commendable initiatives in innovations and sustainability, such as its commitment to recyclability and renewable energy sources. However, like any nation, there is always room for improvement. As technology and sustainability knowledge continue to advance, Sweden must continually update its efforts to maintain its leadership in these areas. While addressing leaking pipelines is important, data suggests that renewal efforts have predominantly concentrated on critical parts of the network rather than the entire system, possibly due to resource constraints or a limited awareness of the need for renewal. To effectively tackle leakages, prioritizing renewal for the entire system, particularly the high-risk main lines, is essential.

8.1. Contributions of the Thesis

The Linköping case study contributes new knowledge by providing a context-specific, in-depth analysis of water and sewerage network management, providing a detailed analysis of the current status of water and sewerage networks, with a specific focus on the risks associated with increasing renewal debt.

This study connects to earlier research related to aging urban infrastructure, the need for sustainable renewal strategies, and the challenges associated with balancing competing demands in water management. However, it differs from previous studies in its exploration of the challenges in water and sewerage network management, emphasizing the impact on renewal debt and addressing the particular complications of budgeting processes, technological challenges, and organizational capacity constraints. It particularly contributes to the existing body of literature by the analysis of long-term renewal needs and the barriers of proactive maintenance, particularly related to the interconnections between financial frames and organizational capacity.

Strategically, the study highlights the importance of strategic planning to address long-term renewal needs and of organizational capacity by identifying how technical, technological, and staff capabilities play a central role in addressing these challenges. It demonstrates how limited organizational capacity and prioritization may lead to limited proactive maintenance and renewal.

8.2. Future Research

Linköping's water infrastructure management presents opportunities for future research. Potential areas include leveraging advanced technologies for proactive maintenance, investigating sustainable pipeline materials, fostering interdisciplinary collaboration, enhancing resilience towards climate change, evaluating governing management effectiveness, engaging communities in water conservation, developing innovative financing models, and learning from international comparisons. These avenues offer exploration of challenges and solutions in sustaining WBIS:

- **Technological Innovations:** Future research opportunities include leveraging advanced technologies for proactive maintenance, such as improved digital systems for monitoring and detecting leaks, data management, and analysis.
- **Sustainable Pipeline Materials:** Exploring sustainable pipeline materials aligning with environmental goals and long-term resilience is suggested for future investigation.
- **Interdisciplinary Collaboration:** The study proposes exploring avenues for interdisciplinary collaboration, engaging communities in water conservation, and evaluating the effectiveness of governing management.
- **Climate Change Resilience:** Research avenues could include enhancing resilience towards climate change, evaluating the impact of climate-related water issues on spatial planning, and developing strategies for sustainable stormwater management.
- **Innovative Financing Models:** The study suggests exploring innovative financing models, such as public-private partnerships or grants, to address financial challenges in water infrastructure renewal.

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