Sustainable Management of Wire-based Infrastructure
On the Multifaceted Challenges of Infrastructure Management in the Swedish Context

Eman Hegazy
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 conclusion emphasized the need for 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.
Acknowledgement

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.

This period was all about pure learning and growth on every level. Even though I had to master many lessons on my own, there are people to whom I owe gratitude. They have helped me immensely in my growth, both academically and personally.

Stefan, I am immensely thankful to you for your support and encouragement since my first day of studies. Every meeting, comment, and discussion, I learned something new from you. Your ideas, observations, and guidance have always illuminated my path and given me a push forward. You have been, and still are, the reliable and patient supervisor who never once abandoned me, despite any challenges that arose. Through it all, you made it possible to finish a Licentiate. Your steadfast presence has been an invaluable asset on this journey. Thank you very much!

Joakim, I owe you a special thanks for your continuous support, thorough explanations, and patience throughout this journey. Although I didn't have the privilege of your supervision until the end, your contributions are always acknowledged. Through your great intellect and patience, you supported developing my understanding of infrastructure management, as well as my own intellectual development in general. The influence of your supervision will continue to resonate throughout my career life. You are a trusted role model to me, and I look up to you.

Niclas, thank you for being the best leader I've known. Much of the guidance and support you provided helped me overcome many obstacles, inside and outside of work. You were consistently there to provide genuine assistance. Your great skills of leadership and patience have supported developing my understanding of the work environment, as well as my own social development in general. However, you have planted the seeds, and it falls upon me to carry on the process of learning and growth.

Helena, thank you for your constant presence in the toughest moments and for your encouraging words and dedication in guiding me. I can’t thank you enough for assisting me in this learning experience.

Lastly, my heartfelt gratitude to Renee. Renee, thank you for believing in me. Without you, my studies wouldn't have been possible. You have always been a primary motivator for me to become the best version of myself. I promised you that I wouldn't let you down, and I have done my best to fulfill that promise. The journey continues. I still have a lot to learn.

Eman Hegazy
List of appended papers:


1. INTRODUCTION ................................................................. 1

2. RESEARCH APPROACH AND CONTEXT ........................ 3

3. BACKGROUND .............................................................. 6

4. RESEARCH METHODOLOGY ........................................ 12

5. RESEARCH METHODS .................................................. 14

6. RESULTS ................................................................. 18

7. DISCUSSION ............................................................ 23

8. CONCLUSIONS .......................................................... 25

REFERENCES ................................................................ 27
1. INTRODUCTION

The urban utility management (UWI) is the largest and oldest WBIS. The provision of clean drinking water and taking responsible care of wastewater is a cornerstone of many cities in different parts of the world have witnessed an increasing malfunctioning and breakdowns due to decades of neglected maintenance and renewal needs. At the same time, as cities grow and networks age, a growing need for drivers for opportunities to change current management practice to become more sustainable (Krook et al., 2015). The sustainability challenges of urban utility management (UWI) are not just a matter of their physical structure and subsurface location but also related to current policy and managerial practices (Berglund, 2009). The sustainability consequences related to excavation work entail massive costs, large costs, and significant increase in environmental impacts related to the use of equipment, transportation, treatment of excavated dirt, and cause huge disturbance to the life in the city. In Sweden, important parts of these systems are already old and will have to be renewed within few decades (Skarendahl et al., 2016). Excavation operations for renewal and maintenance entail huge costs, left in the ground, despite that they contain valuable base metals and environmentally hazardous materials. High costs for excavation is an important reason for why discarded system parts are usually asphalting. High costs for excavation is an important reason for why discarded system parts are usually asphalting. Potential synergies in terms of reduced costs, environmental impacts and city interferences through coordinated excavation and maintenance are the example of the challenges and complexities of the world’s urban utility management (UWI) "are the infrastructure systems (WBIS) “ that are the infrastructure systems (WBIS) “ that are the infrastructure systems (WBIS) “ that are the infrastructure systems (WBIS) “
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

but due to time constraints, the focus was narrowed down to management of WBIS. The goal was to explore management to a wider range of infrastructure networks, With project funding from Formas, I got the opportunity to continue research in the sustainable environments, I got the chance to start with a PhD position in IEI, Linköping University.

sustainability specialization, looking into sustainable management of heating systems in residential way of my second master's degree in Linköping Univers

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 Linköping, a utility company fully owned by the municipality.

Linköping is located in the province of Östergötland and an area of 1,428 square kilometers. It has a population of Linköping, approximately 200 kilometers southwest of Stockholm. It is the capital of Östergötland County and the fifth largest municipality in Sweden. 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 indispensable components of a sustainable infrastructure management.

The management of its UWI.

TV’s management of critical infrastructure is relatively larger Swedish cities and its diverse UWI networks that span generations. Notably, a substantial portion of Linköping’s infrastructure is entrusted by the Municipal Board. Decision-making authority lies with the Municipal Board, while the Municipal Board governs municipal affairs encompassing 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. 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 components to ensure they continue to function optimally.

2.1. The Case: UWI Management in Linköping City

TV’s structure, streamlined data collection processes, and facilitated subsequent analysis. The management of its UWI.

TV’s role these elements play in ensuring the longevity, reliability, and overall sustainability of urban infrastructure management, the focus on maintenance and renewal in central sustainable infrastructure management is driven by the particular focus on the potential for enhanced sustainability. In the context of central sustainable infrastructure management, the focus on maintenance and renewal in central sustainable infrastructure management is driven by the particular focus on the potential for enhanced sustainability.

2.2. Research Journey

This study contribute technologies, rather than considering the broader system dynamics. This study contributed to the development of systemic knowledge that can serve as a basis for fostering sustainability transition in the infrastructure area will not be possible through individual efforts without coordinated technical, organizational, and regulatory changes. Sustainability transition in the infrastructure area will not be possible through individual efforts without coordinated technical, organizational, and regulatory changes (Little, 2005; Little, 2005). Developing long-term sustainable management of WBIS requires a combination of different measures and changes in management cannot rely solely on isolated efforts.

Pathirana et al., 2021; Von der Tann et al., 2020; Little, 2005; Xue et al., 2018. 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. A significant interruption to the provision of services can result from even the slightest deviation from the optimal state of infrastructure elements.

In this context, the identification of a suitable case is critical. Yin, 2003; Yin, 2003; Yin, 2003. Making authority lies with the Municipal Board with TV’s activities being simplified the identification of a suitable case is critical. Yin, 2003; Yin, 2003; Yin, 2003. Making authority lies with the Municipal Board with TV’s activities being simplified the identification of a suitable case is critical. Yin, 2003; Yin, 2003; Yin, 2003. Making authority lies with the Municipal Board with TV’s activities being simplified the identification of a suitable case is critical.

2.1. The Case: UWI Management in Linköping City

TV’s role these elements play in ensuring the longevity, reliability, and overall sustainability of urban infrastructure management, the focus on maintenance and renewal in central sustainable infrastructure management is driven by the particular focus on the potential for enhanced sustainability. In the context of central sustainable infrastructure management, the focus on maintenance and renewal in central sustainable infrastructure management is driven by the particular focus on the potential for enhanced sustainability.

2.2. Research Journey

This study contribute technologies, rather than considering the broader system dynamics. This study contributed to the development of systemic knowledge that can serve as a basis for fostering sustainability transition in the infrastructure area will not be possible through individual efforts without coordinated technical, organizational, and regulatory changes (Little, 2005; Little, 2005). Developing long-term sustainable management of WBIS requires a combination of different measures and changes in management cannot rely solely on isolated efforts.

Pathirana et al., 2021; Von der Tann et al., 2020; Little, 2005; Xue et al., 2018. 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. A significant interruption to the provision of services can result from even the slightest deviation from the optimal state of infrastructure elements.

In this context, the identification of a suitable case is critical. Yin, 2003; Yin, 2003; Yin, 2003. Making authority lies with the Municipal Board with TV’s activities being simplified the identification of a suitable case is critical. Yin, 2003; Yin, 2003; Yin, 2003. Making authority lies with the Municipal Board with TV’s activities being simplified the identification of a suitable case is critical. Yin, 2003; Yin, 2003; Yin, 2003. Making authority lies with the Municipal Board with TV’s activities being simplified the identification of a suitable case is critical.
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 II

Paper III
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.

Table 1: Papers' Contributions to the Thesis Research Questions.

<table>
<thead>
<tr>
<th>Papers/ RQs</th>
<th>RQ1</th>
<th>RQ2</th>
<th>RQ3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper 1</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper 2</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Paper 3</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 2: Overview of the Appended Papers.

<table>
<thead>
<tr>
<th>Papers</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrib</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. BACKGROUND

3.1. Urban Infrastructure Management

Calls for more sustainable management of underground space and subsurface infrastructure, including urban environments, have been reiterated, aligning with a broader trend toward viewing cities as complex systems of innovation combining institutional theory to socio-technical systems. The increasing volume of subsurface work within strategic spatial planning, policy emphasis and the capacity of administrative management systems to drive transformative changes in urban planning and management. However, due to the diversity of legal and institutional settings, practices, and their influencing factors, previous research has often been limited in scope, focusing on specific tasks or project levels, neglecting dependencies between urban planning objectives and the subsurface. Initiatives in the urban systems research have been acknowledged in the broader context of 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 Swedish case study.

The study by Admiraal and Cornaro (2018) based on interviews and document analysis, also underscored the interplay between subsurface infrastructure and urban development, emphasizing its influence on urban development, stability, and sustainability. With the risk of water pipe bursts and other infrastructure failures, professionals have contributed to the discourse on regional contexts. While these investigations have identified important management challenges from the perspective of subsurface infrastructure, they have not fully addressed the need for systemic knowledge concerning the linkages between technological and urban studies. Previous research in the field of urban infrastructure management has focused on achieving infrastructure characteristics and the interrelations between system components. However, systemic principles have often been grounded in technical knowledge rather than addressing social aspects, often examined specific technologies, systems, or infrastructure configurations rather than suggesting pathways for the future. These studies have provided valuable insights into existing management practices and the policy emphasis and the capacity of administrative management systems to drive transformative changes in urban planning and management. However, due to the diversity of legal and institutional settings, practices, and their influencing factors, previous research has often been limited in scope, focusing on specific tasks or project levels, neglecting dependencies between urban planning objectives and the subsurface.

The study by Admiraal and Cornaro (2018) based on interviews and document analysis, also underscored the interplay between subsurface infrastructure and urban development, emphasizing its influence on urban development, stability, and sustainability. With the risk of water pipe bursts and other infrastructure failures, professionals have contributed to the discourse on regional contexts. While these investigations have identified important management challenges from the perspective of subsurface infrastructure, they have not fully addressed the need for systemic knowledge concerning the linkages between technological and urban studies. Previous research in the field of urban infrastructure management has focused on achieving infrastructure characteristics and the interrelations between system components. However, systemic principles have often been grounded in technical knowledge rather than addressing social aspects, often examined specific technologies, systems, or infrastructure configurations rather than suggesting pathways for the future. These studies have provided valuable insights into existing management practices and the policy emphasis and the capacity of administrative management systems to drive transformative changes in urban planning and management. However, due to the diversity of legal and institutional settings, practices, and their influencing factors, previous research has often been limited in scope, focusing on specific tasks or project levels, neglecting dependencies between urban planning objectives and the subsurface.

The study by Admiraal and Cornaro (2018) based on interviews and document analysis, also underscored the interplay between subsurface infrastructure and urban development, emphasizing its influence on urban development, stability, and sustainability. With the risk of water pipe bursts and other infrastructure failures, professionals have contributed to the discourse on regional contexts. While these investigations have identified important management challenges from the perspective of subsurface infrastructure, they have not fully addressed the need for systemic knowledge concerning the linkages between technological and urban studies. Previous research in the field of urban infrastructure management has focused on achieving infrastructure characteristics and the interrelations between system components. However, systemic principles have often been grounded in technical knowledge rather than addressing social aspects, often examined specific technologies, systems, or infrastructure configurations rather than suggesting pathways for the future. These studies have provided valuable insights into existing management practices and the policy emphasis and the capacity of administrative management systems to drive transformative changes in urban planning and management. However, due to the diversity of legal and institutional settings, practices, and their influencing factors, previous research has often been limited in scope, focusing on specific tasks or project levels, neglecting dependencies between urban planning objectives and the subsurface.
3.2. Management Challenges

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 urban infrastructure systems to accommodate rapid growth of populations and urban development (Ingram & Brandt, 2013). This urban growth highlights the urgency for maintenance, prioritizing maintenance and renewal using risk-based approaches. Responding to poor infrastructure maintenance, IAM emphasizes the importance of a systems perspective. However, despite that some recent studies have explored infrastructure resilience and explored their interconnectedness, demonstrating the importance of a systems approach (Krook et al., 2020).

Pathirana et al. (2021) have shown the necessity of an integrated modeling and multi-criteria framework for both PMPs and IS. The study developed conceptual frameworks for both PMPs and IS, establishing for IS, covering project, organizational, and macro levels. The study contributed to the understanding institutional interdependencies in social, ecological, and technological systems. This convergence is crucial for the resilience, efficiency, and sustainability of these foundational urban systems.

Recent research (Krook et al., 2020) discussed infrastructure resilience in the context of climate change, emphasizing the need for integrated modeling and multi-criteria indicators. It is argued for a shift in thinking from a focus on resilience engineering to resilience based infrastructure. Whyte et al. (2020) 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 service functions, prioritizing maintenance and renewal using risk-based criteria indicators. This study draws on concepts from resilience engineering and psychology. It identifies 18 system capacities and 23 human capacities based on a review of the literature.

It is evident that the complexity and interconnectedness of infrastructure systems demand a comprehensive approach that combines technical capacity with strategic foresight and collaborative engagement among a multitude of stakeholders. One pressing challenge stems from the continuing expansion of cities, which places heightened demands on urban infrastructure systems to accommodate rapid growth of populations and urban development. This urban growth highlights the urgency for maintenance, prioritizing maintenance and renewal using risk-based approaches. Responding to poor infrastructure maintenance, IAM emphasizes the importance of a systems perspective.
but stem from the impacts of these issues on the quality of drinking water and the environment also escalates the risk of technical issues and interruptions increased costs repercussions of this maintenance deficit.

Syssner & Jonsson 

reinvestments in the current infrastructure there ha

then a decline in investments in these networks can be observed (investments in water and sewerage maintenance have increasingly been addressed. As accomplished by

increased environmental requirements and climate change that notable advancements have been made, particularly in relation to sustainability. Firstly

During the recent decade, the urban infrastructure has increased and drive meaningful change. Challenges between sustainable development and urban infrastructure.

In an inventory of urban infrastructure research in Sweden, maintenance education and effective communication becomes necessitated to garner support for the essential sustainable infrastructure management policymakers, and stakeholders can hinder the necessary investments and initiatives required for renewing infrastructure (Xue et al., 2018).

Another underlying challenge is the lack of awareness regarding the importance of maintaining and waste during excavation, presents a multifaceted challenge that invites innovative and holistic solutions. Mitigating the ecological impact of these activities, including curtailing emissions and growth must confront the environmental footprint associated with infrastructure activities.

In the context of global interest of environmental sustainability, the ecological consequences of infrastructure management emerge as a challenge associated with urban infrastructure management.

Effective WBIS management necessitates collaborative efforts across governmental bodies, utility corporations, regulatory entities, and urban planners (Xue et al.; Von der Tann et al., 2020). Navigating differing interests, regulations, and operational strategies among these stakeholders often leads to a comprehensive lack of understanding among the general public, lack of sufficient research on the ecological, economic, and social impacts of neglected maintenance in Sweden, and the dynamics of population growth and the problems of outdated infrastructure and neglected policy and legislation.

Emphasizing this neglect not only diminishes the value of fixed assets but also diminishes public confidence in the government’s ability to deliver sustainable public services. The long-term lack of maintenance leads to insufficient research on the institutional configurations, including education and future research needs.

In Sweden, significant environmental improvements have been recorded in recent years, yet many of these improvements are not sustainable. This lack of understanding among the general public, policymakers, and stakeholders can hinder the necessary investments and initiatives required for renewing infrastructure and reducing the environmental footprint associated with infrastructure activities. Notable research gaps were observed, particularly in relation to sustainability. Firstly, lack of understanding regarding the connections between sustainable development and urban infrastructure. Secondly, insufficient research on the institutional configurations, including education and effective communication becomes necessitated to garner support for the essential sustainable infrastructure management.

3.3. Urban Infrastructure Challenges in Sweden

Pandit et al., 2017)

Carlsson et al., 2017

Paradigm shift of institutional and political governance needed for sustainable development and urban infrastructure management. Effective WBIS management necessitates collaborative efforts across governmental bodies, utility corporations, regulatory entities, and urban planners (Pathirana et al.; Xue et al., 2018). Navigating differing interests, regulations, and operational strategies among these stakeholders often leads to a comprehensive lack of understanding among the general public, lack of sufficient research on the ecological, economic, and social impacts of neglected maintenance in Sweden, and the dynamics of population growth and the problems of outdated infrastructure and neglected policy and legislation.

Emphasizing this neglect not only diminishes the value of fixed assets but also diminishes public confidence in the government’s ability to deliver sustainable public services. The long-term lack of maintenance leads to insufficient research on the institutional configurations, including education and future research needs. Notable research gaps were observed, particularly in relation to sustainability. Firstly, lack of understanding regarding the connections between sustainable development and urban infrastructure. Secondly, insufficient research on the institutional configurations, including education and effective communication becomes necessitated to garner support for the essential sustainable infrastructure management.
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).

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 an 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 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 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.

4.2. Assessing the Management of Urban Infrastructure

The lack of essential knowledge regarding the age, type, materials, geographic areas, and historical maintenance and renewal records, constitute essential considerations. These collective efforts aim to enhance the long-term durability of WBIS and facilitate system knowledge in this study. As such, the systems perspective serves as a means to examine current WBIS practices as well as the diverse factors influencing current WBIS maintenance and renewal, and the consideration of diverse viewpoints from multiple stakeholders and scientific disciplines.

The management of WBIS is acknowledged as a multifaceted and challenging, driven by the interplay of system elements. Described as the "holism principle," this perspective acknowledges that the sum of the parts of a system interacts on different levels, resulting in outcomes or functions that cannot be understood by merely focusing on individual components or sub-systems. Understanding the overall functionality of these systems, which encompass the infrastructure system and its elements, such as people, processes, and policies, requires an awareness of a multitude of perspectives and scales as well as the interdependencies between those and tools to examine them.

4.3. Long-term Asset Management

The age of the infrastructure system serves as a determinant for issue identification and the formulation of enhancement strategies. The operational efficiency of the infrastructure system is critically affected by the age of its components, as aging components are more prone to reaching their functional limits and necessitating renewal or replacement requisites. This process often entails the development of long-term asset management plans that outline schedules for renewing various elements.

Within this framework, the systems perspective facilitates a comprehensive understanding of the existing conditions of WBIS management and explores their joint maintenance and renewal outcomes of various intertwined factors and conditions that influence at different levels. The age of the infrastructure system serves as a critical determinant for issue identification and the formulation of enhancement strategies.
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

5.1. Data Collection

The continuous data collection process while fostering workshops involved interviews. Subsequent workshops were designed to encourage participants to share their viewpoints, unveil challenges and their management prospects. The intr-workshops were interactive presentations and discussions on diverse issues related to the water infrastructure. An overview of these workshops and their main focus is presented in Table 3.

Six workshops were held at the premises of TV with members of its water management team. An introductory workshop focused on introducing the water management network and Trimble support. This methodology facilitates the collection of local data, which is central for the collection of documents and water system data. The case study is based on a mixed methods approach, characterized by predefined question categories coupled with the flexibility to resequence or modify questions as needed.

The interviews started with semi-structured questions, tailed to each respondent’s perspective. This methodology ensures that the interview remains tailored to each position in the organizational management processes, challenges, maintenance and documents. The complete interview guide consisted of themes such as organizational management processes, challenges, maintenance and documents. This methodology facilitates the collection of local data, which is central for the collection of documents and water system data.

The data collection encompasses documents and validation of previous findings and hypotheses derived from literature analysis. These sessions also served as platforms for the exchange of valuable insights and practices and organizational management processes. By gathering insights from these individuals, the study gained valuable perspectives on network management, renewal considerations, and proposed measures.

The interviews were video calls and planned question categories coupled with the flexibility to ensure that the interview remains tailored to each respondent. The interview guide consisted of themes such as organizational management processes, challenges, maintenance and documents. This methodology ensures that the interview remains tailored to each position in the organizational management processes, challenges, maintenance and documents.

Table 3 Information About the Respondents.

<table>
<thead>
<tr>
<th>No.</th>
<th>Respondents’ Position</th>
<th>Date</th>
<th>Time-min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int.1</td>
<td>Head of Planning &amp; Projects, water and sewage, Tekniska verken, Linköping</td>
<td>01/12/2020</td>
<td>60</td>
</tr>
<tr>
<td>Int.2</td>
<td>Group Manager, Nordvästra Skånes organisation, AB, Malmö</td>
<td>06/10/2020</td>
<td>60</td>
</tr>
<tr>
<td>Int.3</td>
<td>Group leader project, water and sewage networks AB, Malmö</td>
<td>07/10/2020</td>
<td>60</td>
</tr>
<tr>
<td>Int.4</td>
<td>Respondent of the board of Tekniska verken, and for the municipality</td>
<td>13/01/2023</td>
<td>60</td>
</tr>
<tr>
<td>Int.5</td>
<td>Acting CEO, electricity network, Tekniska verken, Linköping</td>
<td>17/11/2020</td>
<td>60</td>
</tr>
<tr>
<td>Int.6</td>
<td>Deputy Business Unit Manager Management Network, Tekniska verken, Linköping</td>
<td>26/10/2020</td>
<td>60</td>
</tr>
<tr>
<td>Int.7</td>
<td>CEO, water network, Tekniska verken, Linköping</td>
<td>04/10/2022</td>
<td>60</td>
</tr>
</tbody>
</table>

5.1.1. Interviews

The complete interview guide consisted of themes such as organizational management processes, challenges, maintenance and documents. This methodology ensures that the interview remains tailored to each position in the organizational management processes, challenges, maintenance and documents. By gathering insights from these individuals, the study gained valuable perspectives on network management, renewal considerations, and proposed measures.

5.1.2. Workshops and Collection of Network Data and Documents
The renewal analysis spanned all the three parts of the city. TV also provided different documents related to the planning and management processes with budgets and budget outcomes. Detailed data on the physical conditions of urban water infrastructure networks, but also information about the budget allocations of the emergency interventions, new construction, renewal projects, and preventive measures allocation of the budget between emergency interventions, new construction, renewal projects, and maintenance work, and their challenges.

Data on installation and renewal dates, dimensions, involved materials, that exceeded the age of eighty years and the replacement cost was calculated. The renewal needs were replaced and used for the renewal. The development of preventive measures, their challenges and what influences them were perceived as “best” approximations.

5.2. Data Analysis

The collected data during the workshops were transcribed and processed using NVivo 12 software. This software enables extracting relevant statements through coding. Coding and themes were manually generated. The main theme created concerned WBIS management practices, their challenges and what influences them. Among the most addressed issues during the workshops were water leakage incidents and pipeline damages, their causes and the physical conditions of urban water infrastructure networks, as well as interruptions and leakages in recent years. The analysis of management interruptions focused on types of interruptions, affected network types to identify the stormwater and wastewater networks, as well as the estimated costs for the replacement. These calculations are based on the number of lines recorded in the database and divided by the average of lengths was estimated based on the ages exceeding eighty years and the replacement needs for the renewal. This involved quantifying current renewal needs based on the age and material of the drinking water, sewerage, and network data extracted from TV's supplied databases were performed. This allowed assessment of the status of the networks and their development in scenarios that are projecting the renewal debt for the years 2020, 2030, and network development over years and months. The development of maintenance and renewal practices over time spanned all types of interruptions, affected network types to identify

....
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 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 as 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.

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 achieving 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, 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>
<thead>
<tr>
<th>Networks</th>
<th>Drinking Water</th>
<th>Wastewater</th>
<th>Stormwater</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PE, PEM</td>
<td>5%</td>
<td>20%</td>
<td>18%</td>
</tr>
<tr>
<td>PE, POLY</td>
<td>20%</td>
<td>54%</td>
<td>12%</td>
</tr>
<tr>
<td>Cast Iron, Ductile Iron</td>
<td>15%</td>
<td>21%</td>
<td>7%</td>
</tr>
<tr>
<td>Concrete</td>
<td>22%</td>
<td>5%</td>
<td>75%</td>
</tr>
<tr>
<td>Other</td>
<td>13%</td>
<td>7%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(50-80) Years</td>
<td>40%</td>
<td>39%</td>
<td>43%</td>
</tr>
<tr>
<td>(20) Years</td>
<td>20%</td>
<td>36%</td>
<td>29%</td>
</tr>
<tr>
<td>Other</td>
<td>36%</td>
<td>11%</td>
<td>2%</td>
</tr>
</tbody>
</table>

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 PVC 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. 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. Leaks 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, 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>
<thead>
<tr>
<th>Water Networks</th>
<th>2020/21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking Water</td>
<td>0.13</td>
</tr>
<tr>
<td>Wastewater</td>
<td>0.05</td>
</tr>
<tr>
<td>Storm water</td>
<td>0.04</td>
</tr>
<tr>
<td>Overall</td>
<td>0.22</td>
</tr>
</tbody>
</table>

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 (Linköping’s 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) (Linköping’s 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
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 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:

1. **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.

2. **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.

3. **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).
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)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>12</td>
<td>9</td>
<td>12</td>
<td>16</td>
<td>15</td>
<td>27</td>
<td>6</td>
<td>5</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Category 2</td>
<td>33</td>
<td>34</td>
<td>50</td>
<td>52</td>
<td>46</td>
<td>35</td>
<td>36</td>
<td>45</td>
<td>30</td>
<td>39</td>
</tr>
<tr>
<td>Category 3</td>
<td>55</td>
<td>58</td>
<td>37</td>
<td>32</td>
<td>39</td>
<td>39</td>
<td>58</td>
<td>50</td>
<td>57</td>
<td>49</td>
</tr>
</tbody>
</table>

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 Improvement (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 TV following 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 clear 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.
REFERENCES


Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789180754699