THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Aspects of historical data and health criteria for drinking water network replacement strategies

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ABSTRACT

The drinking water distribution network represents a major proportion of the investments and capital assets of a water utility. Consequently, qualified insight into future replacement needs provides water utilities with a foundation for financial planning. This insight would allow responsible engineers to choose the right projects (pipes and pipe systems) for replacement. Currently, support for the correct project choice is through sophisticated methods and models. However, utilities (especially smaller) need simpler procedures as they often lack both input data and competence for advanced infrastructure asset management models, as well as the experience of using such models. The aim of this thesis has been to provide new knowledge and useful, simple and transparent tools for the assessment and evaluation of long-term needs and prioritization of drinking water pipe replacement.

An assessment of the future long-term replacement needs for drinking water distribution networks can be made through a combination of lifetime distribution functions and current network age data. Reliable lifetime predictions are limited by a lack of understanding of deterioration processes for different pipe materials under varying conditions. However, in this thesis a method was applied to calculate national investment needs and the results provided a basis for estimates for Swedish utilities where there is a scarcity of data. An alternative approach, employed successfully in this thesis, was the use of real historical data for replacement over an extended time series. The verified data provided a good fit to commonly used lifetime distribution curves. Further, reasonable projections of replacement needs into an uncertain future could be made.

CBA (Cost-benefit analysis) can be used to evaluate the replacement strategy for utilities' water distribution networks. CBA was applied to evaluate how first, pipe failure data and second, leakage strategies, might be used in pipe prioritization strategies. CBA was applied to pipe failure data replacement priorities, and here the cost of replacement was compared to the benefits of fewer pipe failures. The method enabled the selection of prioritised pipe sections for replacement without the need for a range of parameters and advanced methods that are difficult to interpret. Scenario analysis showed that health aspects have a significant impact on the result, and a method for evaluating the health risk was developed. For the CBA application to leakage management, the benefits of leakage reduction were compared to the cost of alternative management options to determine which was the most cost-effective. In the case study distribution system it was demonstrated that it is significantly more cost-effective to reduce leakage volumes by reactively repairing broken pipes than to proactively replace them, despite large leakage losses.

Key words: Pipe replacement, pipe rehabilitation, strategic planning, water distribution network, lifetime distribution, asset management, cost-benefit analysis, leakage control, health risk, pipe failure.

LIST OF PAPERS

This thesis is based on research in the following papers. Each paper is referred to in the text through Roman numerals:

I. **Malm, A**., Ljunggren, O., Bergstedt, O., Pettersson, T.J.R., Morrison, G.M., 2012. Replacement predictions for drinking water networks through historical data, Water Research, 46 (7), 2149–2158.

II. **Malm, A.**, Svensson, G., Bäckman, H., 2013. Prediction of water and wastewater networks rehabilitation based current age and material distribution. Water Science and Technology: Water Supply 13.2, 277-237.

III. **Malm, A**., Moberg. F., Rosén, L., Pettersson, T.J.R., 2015. Cost-benefit analysis and uncertainty analysis of water loss reduction measures: Case study of the Gothenburg drinking water distribution system. Water Resources Management 29 (15), 5451-5468.

IV. **Malm, A**., Bergstedt, O., Rosén, L., Pettersson, T.J.R., 2015. Cost-benefit analysis, incorporating health consequences of prioritizing measures in drinking water distribution networks. (Submitted to Water Resources Management).

V. **Malm, A**., Axelsson, G., Barregård, L., Ljungqvist, J., Forsberg, B., Bergstedt, O., Pettersson, T. J.R., 2013. The association of drinking water treatment and distribution network disturbances with Health Call Centre contacts for gastrointestinal illness symptoms. Water Research 47 (13), 4474-4484.

A number of other publications have been published and are relevant, although they are not included in this thesis:

- **Malm, A**., Pettersson, T.J.R. and Bergstedt, O., 2009. Förnyelseplanering av vatten- och avloppsförsörjningsnät i 18 svenska kommuner. In proceedings of the 11th Nordic Wastewater Conference, Odense, November 10-12. pp. 140-148
- **Malm, A**., Pettersson, T.J.R. and Bergstedt, O., 2010. Health effects of quality disturbances in Swedish water distribution networks (In Swedish). In proceedings of the 7th Nordic Drinking Water Conference, Copenhagen, June 7-9. pp.97-101
- Salehpour, Z., Pettersson, T.J.R., Rosén, L., **Malm, A.**, Lindhe, A., 2010. Risk-based asset management of potable water distribution systems: case study. In proceedings of the 7th Nordic Drinking Water Conference, Copenhagen, June 7-9, pp.187-190.
- **Malm, A**., Svensson, G. and Bäckman, H., 2011. Strategic asset management in water and wastewater networks using present conditions. In proceedings of LESAM 2011, Strategic Asset Management of Water and Wastewater Infrastructure, Mülheim an der Ruhr, Germany, September 27-30.
- **Malm, A**., Horstmark, A., Jansson, E. Larsson, G., Meyer, A., Uusijärvi, J., 2011. Asset management of water and wastewater networks. In proceedings of the 12th Nordic Wastewater Conference, Helsinki, November 14-16.
- **Malm, A**., Bergstedt, O., Pettersson, T.J.R., 2014. Microbiological risks in the distribution system. In proceedings of the 9th Nordic Drinking Water Conference, Helsinki, June 2-4.

To Gunnar and Ebba

Small engines can do big things!

ACKNOWLEDGEMENTS

My journey towards a PhD has been long, inspirational and usually delightful. My daughter Ebba was just a few weeks old when I began. She has now celebrated her eighth birthday. Her older brother Gunnar was two years old at the time and now he is ten.

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Gothenburg, on a lovely evening in late summer 2015.

Annika Malm

ABBREVIATIONS AND DEFINITIONS

AM	Asset Management
CARL	Current annual real losses; leakage on transmission and/or distribution mains, at utility storage tanks and on service connections up to point of costumer metering
CBA	Cost-Benefit Analysis
IAM	Infrastructure Asset Management
ILI	Infrastructure leakage index, representing the ratio of CARL and UARL (Lambert et al. 1999)
GI	Gastrointestinal
HCC	Health Call Centre
MCA	Multi-Criteria Analysis
NPV	Net Present Value
QMRA	Quantitative Microbial Risk Assessment
SAM	Strategic Asset Management
TAM	Tactical Asset Management
UARL	Unavoidable annual real losses is the lowest technically achievable real losses and depend on service connection density, system pressure and the average length of the service connection pipes between the water mains and the consumer’s water meters.
Pipe replacement	Substitution of a new pipe for an existing pipe when the latter is no longer used for its former objective.
Pipe rehabilitation	All methods for restoring or upgrading the performance of an existing pipeline system.
Pipe renovation	Methods of rehabilitation in which all or part of the original fabric of a pipeline are incorporated and its current performance improved.
Pipe renewal	Construction of a new pipe, on or off the line of an existing pipe. The basic function and capacity of the new pipe being similar to the original.
Pipe break	A fault in a pipe section when the pipe is completely broken.

Pipe leak	A fault in a pipe section causing leakage where the pipe may still be in function
Pipe failure	Detected pipe breaks and pipe leaks in need of repair

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1. INTRODUCTION

1.1. Background

An ageing drinking water distribution network implies a need for replacement strategies and prediction of asset lifetime. The drinking water distribution network represents a major proportion of the investments and capital assets of a water utility. Knowledge of future replacement needs can provide water utilities with a basis for financial planning.

General estimates of replacement investments on a national level have been made for various countries. In Canada, the need for replacement of the drinking water infrastructure (including waterworks, reservoirs and pumping stations) that is below standard is CAD 2,082 (€1,500) per Canadian household (Canadian infrastructure, 2012). In the USA, the need for rehabilitation in the water and wastewater network, including to some extent new developments, is estimated at USD 10,000 million per year (about €28 per person per year) for the period 2007–2026 (EPA, 2009). The investment need in Canada and the USA was based on an extensive survey (questionnaire study) conducted among water and wastewater utilities. In Sweden, it is estimated that the rehabilitation rate for the wastewater network, currently corresponding to €100 million per year, needs to triple in the next 25 years, from about €10 to €31 per person per year. This estimate is based on an assumption of an increased need to rehabilitate the pipe network resulting from major investments which were made in the 1960s and 1970s (SWWA, 2007). No such estimate was made for the drinking water network. The assessments made in the USA, Canada and Sweden provide an estimate of future rehabilitation needs. However, while estimates based purely on the current situation can provide reasonable trends for the near future, long-term forecasts are more difficult.

Good asset management implies that replacement investment needs should be estimated not only at a national level but also at a water utility level. The extent of the replacement needs provides an overall economic framework for a water utility although the right projects (pipes) need to be chosen. The choice of projects depends on utility goals, such as low frequency of consumer disruption, safe drinking water and minimization of traffic and environmental disruptions. Whilst there are sophisticated methods and models available that have been developed, some utilities lack the staff and knowledge to manage advanced infrastructure asset management (IAM) models and experience of using such models. Consequently, there is a need in many municipalities for simpler methods and tools to prioritize between replacement projects (Malm et al., 2009; Alegre, 2010).

In IAM models, cost-benefit analysis (CBA) is often included. CBA used alone is also a useful tool for asset management of drinking water pipes. The CBA can include both the direct costs and the benefit to a water utility, as well as externalities such as social and environmental costs and benefits. As pipe breaks and leakages reflect the status of the drinking water network, these parameters should be included in a CBA since increasing rehabilitation of the most exposed pipes will lower the need for pipe failure repairs.

Safe drinking water is the main goal for a drinking water utility (WHO, 2011). Leakage can increase the risk of contamination, especially in systems with frequent and/or sudden pressure losses (Besner et al. 2011). Occasionally, the pressure in the pipes falls as low as, or even lower than, the pressure on the outside, which may lead to (possibly contaminated) soil water intrusion (Besner et al., 2011). Each pipe failure repair then constitutes a risk of soil water intrusion and thus a risk to consumers' health. Depending on the size of the risk, the incentive to decrease the number of repairs will be affected. If the risk is significant, the cost of the risk should be included in asset management strategies.

1.2. Aim and objectives

The overall aim of this thesis is to provide new knowledge for replacement strategy providing guidance for water utilities through tools for the assessment and evaluation of long-term needs as well as prioritization of replacement of drinking water pipes.

In addition to the overall aim, the thesis has the following research objectives:

a. To develop a method for forecasting future strategic replacement needs using historical data.
b. To show how limited local pipe data can predict future replacement needs for a whole water utility or region.
c. To develop a transparent CBA method for decision support in pipe replacement prioritization using a limited amount of available data.
d. To evaluate which criteria should be included in the CBA with a specific focus on pipe failures, leakage and health risks.
e. To present a method for evaluating the health risk arising from pipe failure repairs.

The aims and objectives are shown in Figure 1.

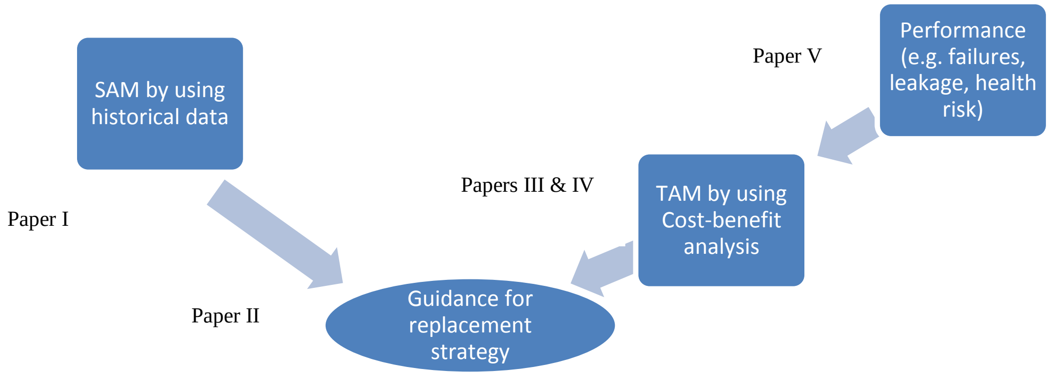

Figure 1 *Aims and objectives of this thesis, including both strategic asset management (SAM), and tactical asset management (TAM).*

1.3. Limitations

This thesis provides input for a utility's replacement strategies, although for a full strategy a multi-criteria analysis should be used, based on a variety of data and including the results from this thesis.

1.4. Overview of the thesis and included papers

Sophisticated tools are not widely employed by Swedish drinking water providers (Malm et al. 2009). The main reasons that are normally voiced are lack of data, time and competence. Decisions are therefore usually based on recent pipe breaks, coordination with ongoing road construction and experiential knowledge (Malm et al. 2009). For the purpose of this thesis three alternative paths can be identified.

1. Continue to base decisions on experiential knowledge of the drinking water system in question.
2. Build up the competence and data required for the introduction of sophisticated tools.
3. Make use of the knowledge that is the basis of the sophisticated tools and focus on the most critical factors for simpler models which can then be used to underpin decisions made on experiential knowledge.

It is proposed that path 3 will be the best option for utilities with a pressing need to refine replacement strategies. Path 3 may also be a feasible step for utilities that wish to approach path 2.

Pipe age itself does not have a decisive influence on the optimal point in time to renew a single pipe (Sægrov et al., 2005) but age or remaining asset lifetime is a useful criterion for strategic asset management when the intention is to predict the rehabilitation needs for an entire drinking water distribution network (Burn et al., 2010). Historical data was used to predict future pipe replacement needs for a water utility (Paper I).

Local (historical) data is not always available, but reliable estimates can be made using societal development and recent replacement data. Data from other utilities with similar presumptions can also be used to predict future replacement needs. A prediction of this nature has been made for an entire nation, in this case Sweden, with reliable results (Paper II).

When a water utility has established a framework for its overall replacement needs (Paper I), replacement must be prioritized. CBA is a useful tool to prioritize pipe sections (Papers III and IV). Leakage management is an important part of water distribution network management but is not an effective criterion for replacement prioritization (Paper III) although pipe failure is (Paper IV).

A pipe failure always generates a risk of the intrusion of contaminants before, during and after pipe failure repair and health risk costs should therefore be included in the CBA (Papers IV and V).

2. THEORETICAL BACKGROUND

2.1. Replacement predictions for drinking water networks

The current water distribution system has been developed over a long period of time and construction decisions always need to take previous decisions into account when all the pipes are connected to the same system. When decisions are dependent on past decisions, they can be defined as path-dependent (Kaivo-oja et al., 2004). The impact of path dependence is reliant on the binding, limiting or postponing of alternative options (Kaivo-oja et al., 2004), see Figure 2. The postponing option is to do nothing at all. For the water industry, the binding decision to develop a drinking water distribution pipe system for the transport of water from source to tap is an example of strong path dependence. When the distribution system is in place and only small parts at a time are rehabilitated, the system remains unchallenged, despite concern about rehabilitation rates.

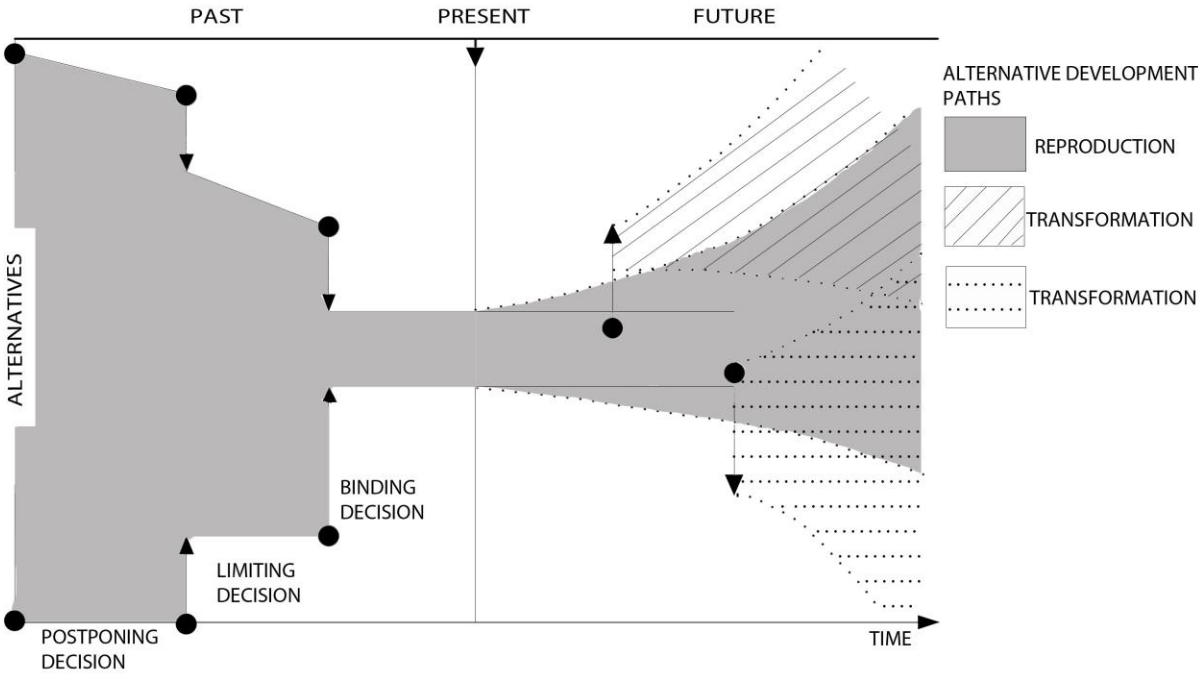

Figure 2 *Path dependence and related decision-making. The arrow indicates the effect of a societal or water utility decision. If the past is known and well described but the future is uncertain, the potential development paths with required decisions can be anticipated based on historical experience and data (figure adapted from Kaivo-oja et al., 2004 with permission).*

Fundamental change processes can occur in the sociotechnical drinking water distribution networks, which in turn affect rehabilitation needs. Three types of change processes in a sociotechnical system have been identified by Geels and Kemp (2007): reproduction, transformation and transition. Reproduction includes changes along defined paths, such as the use of new pipe materials. Transformation includes changes at the regime and landscape level, including changes to visions, goals or guiding principles. Transition is an expression of a major shift in a sociotechnical system, an example being a change from individuals carrying water from an outdoor stand pipe to home water delivery through a pipe system.

Asset condition is the most commonly used criterion for rehabilitation, whereas water losses, water quality and reliability are secondary causes (Sægrov, 2007, Malm et al, 2009). External factors such as change in water demand, large infrastructure projects and street or sewer pipe replacement, can significantly affect drinking water network rehabilitation (Malm et al., 2009; Sægrov, 2007; Torterotot et al., 2005).

Future rehabilitation needs depend on asset lifetime for the present pipe networks. While most methods for determining asset lifetime require failure event data or the physical characteristics of the pipes, the statistical cohort survival approach uses present age and lifetime for cohorts of pipes to predict future rehabilitation needs (Burn et al., 2010). In the latter study, the cohorts were defined as groups of pipes with similar deterioration processes. Software based on the cohort survival approach, Long Term Planning (LTP), was developed within the Care-W project (Sægrov, 2005; Herz and Lipkow, 2003). This software is an extended version of the original KANEW software (Deb et al., 1998). Two disadvantages of the cohort survival approach, presented by Burn et al. (2010), are the need for homogeneous cohorts or groups of pipes and the fact that data are often not available.

In Sweden, the water utilities are publicly owned and the majority (82%) are operated within the municipal administration system, where 35% of the utilities serve less than 10,000 consumers (SWWA, 2013; SWWA, 2015). The present trend is to merge utilities into larger, inter-municipal cooperatives or multi-utility solutions (Thomasson, 2013), normally in urban areas (SWWA, 2015). Nevertheless, one-third of inter-municipal cooperative utilities are small, with less than 30,000 consumers (SWWA, 2013; SWWA, 2015). The smaller utilities often lack the staff and knowledge to handle advanced IAM models and they have no experience of using such models. There is therefore a need, especially within many smaller municipal authorities, for simpler methods and tools for prioritizing between replacement projects and for prioritizing replacement in the right projects (Malm et al., 2009; Alegre, 2010). In Sweden, current prioritization of pipe replacement is not systematic and is based largely on experience from pipe failure data, professional judgement and coordination with ongoing road construction (Malm et al., 2009). International experience from 14 water utilities in eight European countries reveals that pipe failure data and road construction work are the main parameters when deciding which pipe sections to replace (Torterotot et al., 2005).

Strategic decision-making affects both the need for rehabilitation and the actual rehabilitation. This need is affected by the rehabilitation necessary in the light of external decision factors, such as major infrastructure projects, or internal decision factors, such as targets for acceptable failure rates. The actual rehabilitation can be affected by the economic preferences of the water utility, such as investment plans where less (or possibly more) money than required has been allocated. In an interview study of 18 Swedish water utilities, the limitation on rehabilitation was as much a lack of human resources as it was a restriction on economic resources (Malm et al., 2009).

Asset management or replacement strategies can be divided into a strategic asset management (SAM) level, a tactical asset management (TAM) level, and an operational and maintenance level (Marlow and Burn, 2008). The strategic level has a long-term view and should answer questions such as “How much?” or “What replacement rate is needed for a water distribution network as a whole?” The tactical level should provide the tools for prioritization and answer questions such as “Which criteria should we use to decide which pipe sections should be prioritized first?” The operational and maintenance level is the day-to-day work.

Asset lifetime of drinking water pipes can be described as the breakpoint in time when it is no longer socially and/or economically acceptable to choose acute spot repair, the alternative being to rehabilitate the pipe using renovation or replacement techniques. Marlow et al. (2010) describe several approaches for modelling remaining asset lifetime, making a distinction between deterministic models, statistical models, physical probabilistic models and soft computing or artificial intelligence models. The statistical models are based on historical failure rate or service lifetime and sometimes condition data. One of the statistical models is a service lifetime approach where asset properties that influence ageing behaviour are the basis for dividing assets into groups. Age itself does not have a decisive influence on the optimal point in time to renew a single pipe. Pipe failure rate, which includes pipe breaks and leakage, is shown to be the best criterion for optimal individual pipe rehabilitation (Herz, 1998). However, age or remaining asset life is a useful criterion for strategic asset management (Burn et al., 2010) when the intention is to predict the rehabilitation needs of an entire drinking water distribution network.

An interview study of 18 Swedish water utilities conducted by Malm et al. (2009) showed that there is a need for tools to assess the appropriate present and future replacement rate. The water utilities had replacement plans, but these were rarely developed systematically and in some cases they were not even recorded. The water utilities had a feeling that the replacement rate should be higher but they need tools to make a more well-founded prediction. Only some of the interviewed utilities had sufficient data to conclude that they should increase their replacement rate. Most of the interviewed utilities felt that their drinking water network is in good condition but they would nevertheless like to increase the replacement rate. For them, replacement management is based more on feeling than on real facts (Malm et al., 2009).

2.2. Replacement strategies and prioritization using cost-benefit analysis

CBA is intended to provide guidance for a water utility in asset management of drinking water pipes. The CBA can include both the direct costs and benefits for a water utility, such as leakage or failure repair costs versus replacement costs, but also externalities such as social and environmental costs (Marlow et al. 2011).

CBA is used in several studies for pipe replacement prioritization. Davis et al. (2008) used CBA to evaluate the economic lifetime of asbestos pipes. Kleiner and Rajani (2004) used CBA to evaluate the effectiveness of cathodic corrosion protection of the pipe.

A large number of tools and methods have been developed to help utilities with replacement strategies, using software models such as Pirem, AWARE-P, PARMS, WILCO, I-WARP/D-WARP and Siroco (Fuchs-Hanusch et al. 2008; Cardoso et al. 2012; Burn 2003; Engelhart et al. 2003; Kleiner et al. 2010; Renaud et al. 2007). Common to most of the models is that they are based on economic CBA and analysis of pipe failure (i.e. pipe break or leakage). These CBAs take into account failure repair costs, including future increasing failure rates, possible maintenance rates, replacements and pipe failure repair costs in a new pipe section, and in some cases externalities such as environmental and social costs, see Table 1.

Table 1 *Tactical asset management tools and methods, what is included? CBA is cost-benefit analysis, MCA is multi-criteria analysis (Y=yes, N=no, N/A= not available).*

Programme	Source	CBA	Consequence of failure	Environmental costs	Social cost	Increased failure rate over time	Remark
Pirem	Fuchs-Hanusch et al. 2008	Y	N	N/A	N	Y	Savings from roadwork coordination can be included. Social costs are specified (traffic jam).
AWARE-P	Cardoso et al. 2012; Coelho 2015	Y	Y	N	N	Y	MCA model. The environmental and social aspects can be included in the MCA.
PARMS	Burn 2003; Marlow et al. 2011	Y	Y	Y	Y	Y	Social and environmental costs are specified.
WILCO	Engelhart et al. 2003	Y	Y	Y	Y	Y	Social and environmental costs can be included but are not specified.
I-WARP/D-WARP	Kleiner et al. 2010	Y	N	N	Y	Y	Savings from roadwork coordination and pipe replacement nearby can be included.
Siroco	Renaud et al. 2007; Renaud et al. 2012	Y	Y	N	Y	Y	MCA model. Specified social costs. Savings from roadwork coordination and pipe replacement nearby can be included.

A CBA can also be used to compare the cost of mitigating leakages with the variable cost of lost water (Lambert and Lalonde, 2005). The costs and effort of identifying leaks can preferably be balanced against the benefits with, including lower costs for treatment and delivery of water, avoidance of costly alternative water supplies in case of water scarcity, more stable water quality with lower risk of contamination, and reduced costs caused by sudden delivery interruptions. The latter affect consumer confidence and, when leaks have to be repaired outside normal working hours, generate extra costs. The greater the value of drinking water, and the higher the level of leakage, the more there is to gain from leakage mitigation. In Sweden, saving water is motivated by political rather than economic factors (Malm et al. 2009). Methods for implementing CBAs for a drinking water distribution system vary. Lambert and Lalonde (2005) suggest the application of a CBA for direct costs and benefits, including a rate of (future) leakage increase, if no action is taken. When more water has to be produced as a result of leakage, more chemicals are used for treatment and more energy is consumed, which means that not only the direct costs to the utility, but also the external, environmental and social, costs should be included, as suggested by e.g. Ofwat (2008), Ashton and Hope (2001) and Kanakoudis et al. (2011).

Environmental costs include for example changes in ecosystems and carbon emission costs Ofwat (2008). Most of the environmental costs (such as recreation, biodiversity, fisheries) are due to impacts on the water cycle, which are close to zero when water is abundant. Social costs include for example disruption in delivery, traffic delays due to repair work and health costs caused by impaired water quality during repairs. A lower frequency of leaks may also reduce the cost of health risks, as each pipe failure repair may involve a risk.

When external costs are included, it is often done in a general way because of difficulty acquiring adequate data. Marlow et al. (2011) have introduced a typology of urban externalities and suggested potential for significance. According to Marlow et al. (2011), the externalities that should be considered for water supply are pollution from greenhouse gas emissions, environmental impact due to disruption to heritage sites, public health and safety, social disruptions and non-compensated financial loss (e.g. opportunity cost of water). In conditions where water is abundant, the environmental impact and financial loss are low (Ofwat, 2008).

An external cost is the benefit of lower social health risk cost due to a lower frequency of pipe failure repairs when pipes are replaced. During pipe failure repair, the water pressure is reduced or turned off completely and may lead to contaminant migration into the pipe (Besner et al. 2011).

2.3. How do health risks affect replacement?

Waterborne disease outbreaks due to microbial contamination of water supply systems are predominantly caused by quality impairment in the raw water and/or waterworks but can also be caused by quality impairment in the distribution networks (Craun et al., 2006; Risebro et al., 2007). In the Nordic countries, 14 out of 59 outbreaks in municipal waterworks systems were found to be directly attributable to the distribution network (Guzman-Herrador et al., 2015). Swedish municipalities are bound by the obligation to report quality impairment in water quality to the Swedish National Food Agency (SNFA). Quality impairment reported to the SNFA for the period 1980-2009 show that 44 (56%) of the 79 outbreaks were caused by quality impairment in the raw water and/or the treatment process, 27 (34%) were due to quality impairment in the distribution network and the remaining eight (10%) had unknown causes. For the number of people who became sick, 69% could be attributed to quality impairment in the raw water/treatment and 25% to the distribution network. Over the 30 years, 1,800 people per year became ill, corresponding to a risk of 2.0 per 10,000 inhabitants per year for the whole drinking water system from source to tap (Lindberg and Lindqvist, 2005; Malm et al., 2010).

Outbreak data reported to the Swedish National Food Administration were compiled and analysed (with permission). The causes of contamination for the 27 registered outbreaks in Sweden during the period 1980-2009 that are attributable to quality impairment in the distribution network were compiled and divided according to cause, as shown in Figure 3. The most common cause is various types of cross-connections.

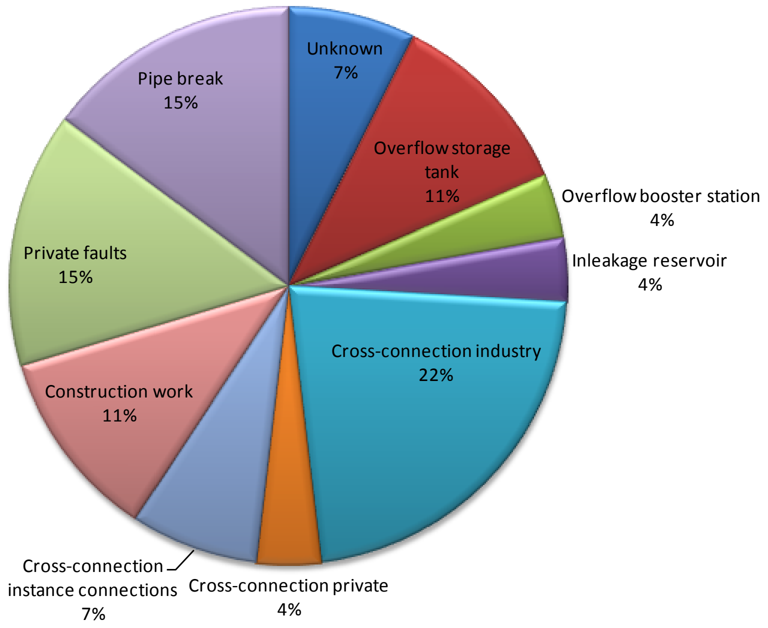

Figure 3 *Subdivision of the outbreaks reported to the Swedish National Food Administration, 1980-2009.*

Far from all symptoms of waterborne gastrointestinal (GI) illness are reported officially or even discovered locally. To be classified as a waterborne outbreak, the people who become ill must seek medical care and the medical centre must recognize a link between the patients' symptoms and the drinking water. Of course, not all persons with GI symptoms contact a physician, not all patients are tested, common waterborne contaminants are not normally analysed, and waterborne infections are not required to be reported by law (SMI, 2012). There is thus a lack of information in the national statistics. However, studies have shown that drinking water can cause GI symptoms in non-outbreak situations. A Canadian study showed that 14-35% of all GI symptoms were caused by drinking water outside an outbreak (Payment, 1991; 1997). On the other hand, studies in the US and Australia did not show any correlation between GI symptoms and drinking water quality (Colford et al., 2005; Hellard et al., 2001). An epidemiological study in Norway showed an increased risk of GI illness in areas with total loss of water pressure due to repair of pipe failures or maintenance work (Nygård et al., 2007). The risk of GI illness was significantly higher in the exposed households (RR 1.58), which means 4% of households suffered from GI illness during unpressurized incidents due to the event. A questionnaire survey in the UK showed that up to 15% of self-reported diarrhoea was related to low water pressure in the drinking water distribution network (Hunter et al., 2005). One risk cost is the risk of waterborne disease outbreaks. Between 1981 and 2010 in the USA, 57 outbreaks were associated with distribution system faults, and about 31% of these were due to mains breaks, mains repairs and leaching (WHO, 2014).

When estimating the extent of GI illness caused by insufficient drinking water quality, the frequency of contact with Health Call Centres (HCC) can be used. The HCC in Sweden is a national network where nurses evaluate, provide advice, inform and direct persons by telephone (Wahlberg, 2004). The Swedish HCCs receive about 4.5 million calls each year (Inera, 2011). Specific information, such as cause, geographical information and age of the person concerned, are recorded for each call. An analysis of incoming phone calls to HCCs in Sweden over a one-week period showed that approximately 31% of the calls involved infection symptoms such as influenza and diarrhoea (Wahlberg and Wredling, 1999).

Each pipe failure repair constitutes a risk of intrusion (Besner et al., 2011). Depending on the size of the risk, the incentive to decrease the number of repairs will be affected. If the risk is negligible, the health aspects can be excluded in the prioritization. No methods or models for including the health aspects in renewal planning have been found in the published literature.

3. METHODS

In this chapter the methods used in this thesis are briefly summarized. For detailed descriptions reference has been made to the appended papers.

3.1. Study area

The case studies in this thesis were carried out in the city of Gothenburg in Sweden. The city has a population of 500,000 and is located in the Västra Götaland region of Western Sweden, which has a population of 1.5 million. The citizens of Gothenburg are supplied with drinking water from the Göta älv river via two waterworks and a 1,750 km distribution network, see Figure 4. The distribution network is connected.

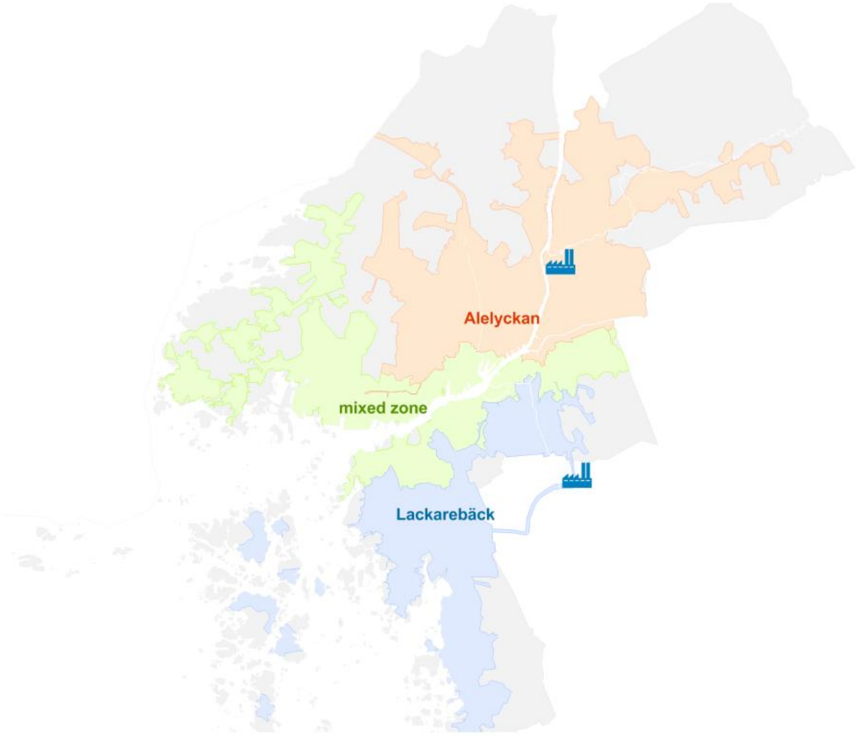

Figure 4 *Study area. The distribution network is not included due to safety restrictions.*

The two waterworks, Alelyckan and Lackarebäck, have similar treatment processes, including chemical flocculation, sedimentation, filtration (granulated active carbon) and disinfection (ClO_2/Cl_2). The microbial barriers are the same. The free chlorine residual level in the network is low.

The studied drinking water distribution network is dominated by three pipe materials: grey cast iron, ductile iron and polyethylene (PE). PE is the dominant material used for newly laid pipes and for replacement. Replacement of network pipes takes place continuously, prioritizing pipe sections with the highest failure rates. Over the past 10 years, the annual replacement rate in Gothenburg has averaged about 8 km or 0.5% per year of the total length. The replacement rate may sound low, however the average network age is still young (42 years in 2014). According to the long-term plan for City of Gothenburg, replacement is scheduled to increase steadily and to be double the present replacement rate in 20 years in order to maintain the pipe failure rate and robustness.

The status of a water distribution network can be measured using pipe failure rate and leakage as performance indicators. In Gothenburg the pipe failure rate has been decreasing rapidly from the late 1960s to the mid 1970s and has thereafter slowly decreased. Present pipe failure rate is 0.16 failures per kilometre per year (mean value 2009-2013) and includes both leak and pipe failure repairs (SWW, 2014). In comparison with national data the failure rate in Gothenburg is in the worst 20% group (SWWA, 2010) but compared to international data the failure rate is low (Sægrov, 2005). Gothenburg has adopted a high-priority target reducing the total leakage from 770 L per service connection per day in 2012 to 520 L per service connection per day in 2024 (SWW, 2006). The current Infrastructure leakage index (ILI), representing the ratio of Current annual real losses (CARL) and Unavoidable annual real losses (UARL), (Lambert et al. 1999), is 9 and the leakage represents approximately 20 % of the drinking water produced. The ILI of 9 is defined as ‘very bad’ according to the World Bank Institute Banding system (Seago et al. 2005).

3.2. Replacement predictions from historical data

In effective planning of replacement of drinking water pipes, the first step is to determine the cost, financial framework and general needs. The method for calculating the need in the long term (SAM) must be transparent if it is to be reliable for a water utility. The data used must be accessible and relevant and output must be presented in a way that it can be easily understood. Methods based on data about present condition, age and material in the network, together with estimates of lifespan for different cohorts of pipes, are often transparent and use the relevant data.

Once the strategic needs are established, the pipes that would be the most effective to replace first must be chosen (TAM). The method should also be transparent, not complicated for water utility staff to understand or require data that are often missing at a water utility. An effective method often requires some form of multi-criteria analysis (MCA) (not included here), where part of the MCA consists of a CBA. A knowledge gap in the CBA is that the health risk costs of a disruption in water delivery are not included.

3.2.1. Lifetime curves

The survival rate of the distribution network can be the residual pipe length for each year, expressed as a percentage. Residual pipe length is the percentage of the original pipe length for a certain year that remains at a later (present) time period. During the first few years after the pipes are laid all pipes in the group survive, but with time an increasing number of pipes need replacement or renovation. The residual pipe length is calculated using the present residual pipe length and the annual pipe length laid for each year or decade. Since pipe lifetime can be more than one hundred years, one decade is assumed in this context to be a sufficient level of detail for expressing the ageing process.

Survival functions are used to determine the percentage of a group of pipes reaching a particular age (Sægrov, 2005). These functions are described in more detail in Paper I and are used to model the time until the pipes are replaced.

3.2.2. Predictions for the future

The historical replacement data was used to predict future replacement rates. In Paper I, predictions for the future were made for two alternatives: (1) Predictions from the calculated survival function based on an extended time series of historical data; (2) Predictions from the calculated survival function based on the replacement rate during the period 1991-2005.

Future replacement needs are discussed in the context of path-dependence theory. Strategic decisions in the future can affect both the need for replacement and actual replacement. Furthermore, fundamental changes in the sociotechnical sphere may affect renovation and replacement.

In Paper II, a case study of the whole of Sweden was carried out using the live time curve method to see if it was possible to make a prediction of future needs based on the present condition and not on historical data. In the study, current network age and material distribution were provided via a questionnaire sent to Swedish water and wastewater utilities and the data provided were extrapolated to cover the whole of Sweden. The material distribution was compared to previously reported data (SWWA, 1999). The data was then combined with lifetime distribution functions to provide predictions.

3.3. Cost-benefit analysis as a tool for prioritization

CBA can be used to evaluate the replacement strategy for utilities' water distribution networks. In Papers III and IV, CBA is used to evaluate how pipe failure data and leakage strategies should be used in pipe prioritization strategies. CBA measures both utility costs and benefits but can also include external costs and benefits. By discounting costs and benefits, the net present value can be calculated for a management option and a positive net present value (NPV) shows that the alternative is worth implementing. Moreover, the options with a positive NPV can be compared to find the most effective option. This study uses an objective function (Equation 1) that maximizes the present value of a stream of benefits minus costs over time, *t*, for each alternative, *i*, (see Hanley and Barbier 2009):

$$\Phi_i = \sum_{t=1}^{T} \frac{1}{(1+r)^t}(B_{it} - C_{it}) \qquad (1)$$

where Φ_i = net present value, B_{it} = the benefit of leakage reduction (expressed as a function), C_{it} = the costs for leakage reduction measures (expressed as a function), r = discount rate and T = time horizon in years.

When CBA is used for prioritizing replacement, the cost of replacement is compared to the benefits of having fewer pipe failures. The cost of replacement investment is expected to be safest by using data for a number of real replacement works and the unit costs for each cost driver. If this data are not available, a fixed unit price can be used. The benefit of having fewer pipe failure repairs depends on the average cost of pipe failure repair, which often depends on the pipe size and the location of the failure. Additional benefits are lower costs for water leakage. The volume of leaking water depends on the size of the leak and on how long the leak has existed before it is detected. The marginal cost to produce and pump the leaking water is made up of the chemical cost and the energy cost for the treatment process and pumping. In addition, some of the leaking water finds its way into sewers and consequently a marginal cost of wastewater treatment and management should also be included.

When CBA is used for leakage management, the costs and effort of identifying leaks must be balanced by the benefits. The costs for methods for locating leaks can include acoustic monitoring, inline inspection, gas injection or manual listening stick as well as district flow metering or pressure analysis. The benefits can include lower costs for treatment and delivery of water, avoidance of costly alternative water supplies in the event of water scarcity, more stable water quality with a lower contamination risk, and reduced cost due to sudden delivery disruptions. The latter affects consumer confidence and, when leaks need to be repaired in the middle of the night, it gives rise to extra costs. The greater the value of the drinking water and the higher the level of leakage, the higher the revenue resulting from leak mitigation.

3.4. Evaluation of health risk during leak repair

To estimate the extent of GI illness caused by insufficient drinking water quality, the frequency of contact with Health Call Centres (HCC) was used. By studying the number of persons seeking care and/or medical information regarding GI symptoms at HCCs, changes in the incidence of illness were evaluated.

For the pipe failure repair part of the study, information from the HCC was compared to pipe failure data (Paper V). All pipe failure repairs in Gothenburg over a three-year period were recorded. The included pipe failures were geocoded on the ‘small sub-area’ level. A comparison was then made by comparing the number of contacts before and after a leak repair in the specific small sub-area. The pipe failures were stratified into two types. Type A are easily repaired pipe failures, where the pipe break or leakage can be repaired by using a repair clamp fastened around the pipe and with the water pressure retained while the work is being carried out, Figure 5. Type B are pipe failures that are more difficult to repair, where a piece of new piping needs to be inserted and the pressure cannot be retained, Figure 6.

In addition to the analyses on the ‘sub-area’ level, a number of Type B pipe failures were assigned to the property level. The study was carried out using a quality analysis in a hydraulic modelling tool where the model indicated which properties would be affected by intrusion.

Figure 5 *Grey cast iron pipe failure Type A (left), easily repaired with a repair clamp (right). Photo Annika Malm.*

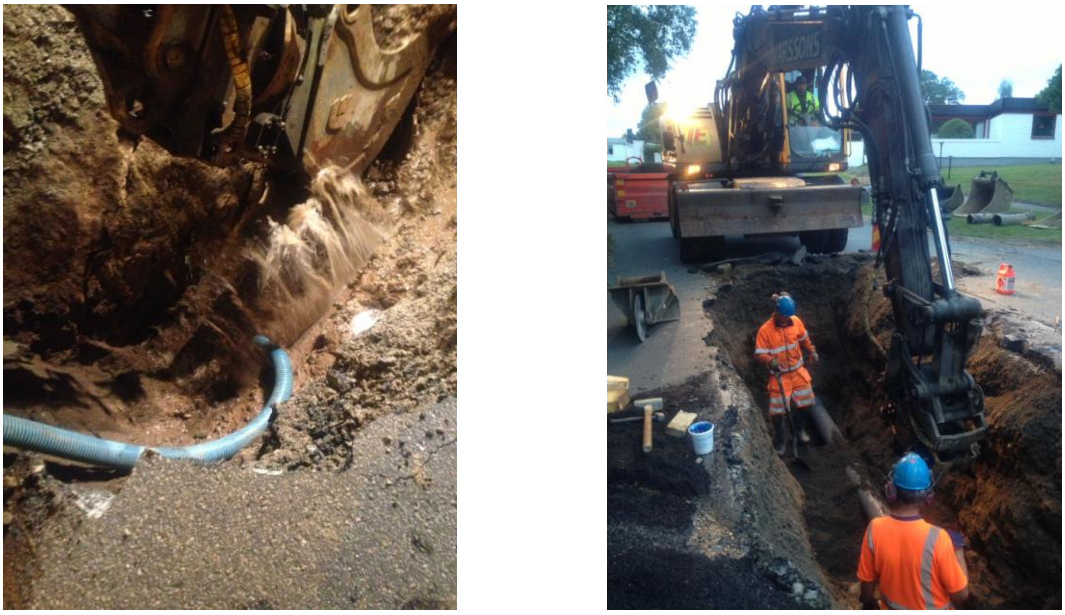

Figure 6 *PVC pipe failure Type B (left), with a new piece of pipe installed (right). Photo Jonas Wall.*

4. RESULTS AND DISCUSSION

In this Chapter, the results for long-term overall needs are presented, including prioritization of the most cost-effective replacement strategy for a water utility.

4.1. Long-term replacement predictions

The results in Paper I show that historical data provide a reliable prediction of future replacement needs on a water distribution network level. The method described is applicable and the crucial limitation is lack of data.

Documentation of data is important for strategic decisions affecting the future. If data about replaced pipes are archived, then data for predicting the future can be improved continuously. The method could increase the eagerness of water utilities to archive data and make use of the data they already have. The results in Paper I show that using the described method, the data requirements are:

- Annual or decade-based data related to pipe length laid
- Present pipe length for each year/decade
- Reasons for replacement (condition-based or non-condition-based)
- Replacement rate for a period of approximately 10 years (optional)
- Pipe failure statistics (optional)
- Future potential decision drivers (optional).

It is recommended that failure statistics are collected to provide a robust prediction of future replacement. Failure statistics provide an understanding of whether the speed of the pipe deterioration process is increasing or decreasing.

The results in Paper II show that, even though the data are incomplete, a reliable prognosis for the future rehabilitation rate can be produced. The method described has been applied to Swedish conditions, although the method can be used for all infrastructures irrespective of country. Expansive utilities, where new urban constructions are a significant part of the total pipe length, must take into account the decreasing effect the new network lengths have on the rehabilitation rate. The difference in the rehabilitation rate between expansive water utilities and utilities with few new urban constructions can be major even though the total pipe lengths in need of rehabilitation are the same.

In Sweden, replacement needs of water and wastewater networks equal approximately 300 million € (about 31 € per person and year) annually for the next 30 years, and thereafter slightly increase (Paper II). The estimate is lower than earlier estimates from SWWA (2007) but in the same range as estimates for the USA of about €28 per person per year (EPA, 2009). In Canada, the average household consist of 2.5 persons (Statistic Canada, 2015). If the Canadian needs of €1,500 per household (Canadian infrastructure, 2012) are calculated per person, the estimate can be expressed as €30 per person per year over 20 years.

Furthermore, consumer preferences, health aspects, change of pipe material, climate change and strategic decisions affect the rehabilitation needs (Paper I). The potential decision drivers described in Table 1 (Paper I) will increase the needs, although a change of pipe materials and consumer preferences can also decrease the needs due to better pipe material or if more delivery disruptions can be accepted.

4.2. Replacement strategies and prioritization through cost-benefit analysis

The results in Papers III and IV show that CBA is a useful tool in replacement strategies and when designing leakage control programmes for WDSs. A CBA can compare all the costs and benefits of different measures over the long term.

Generally, the cost to a utility for replacement has decreased since trenchless technologies have increased in use, at least in Sweden. At the same time, the costs for spot repair of failures have increased in line with the increase in the cost of labour. This means that nowadays more pipe sections can be replaced with a positive CBA. When it is mostly trenchless technologies that are used, the benefits of coordination with road construction work have less impact on the CBA. On the contrary, a good IAM method can better position the utility to decide which pipe sections to replace, and not follow road construction work.

In the case study scenarios, the parameters that affect the outcome the most are the health effect costs, the discount rate and future pipe failure rate predictions. Studies dealing with the health effects are still very few. The discount rate is not easy to predict, but most water utilities use a standard rate. The effect of the pipe failure rate is mostly based on an increased failure rate for the grey cast iron pipes. When the failure rate is that important, it should be investigated even more to ensure the right results are obtained.

4.3. Does a risk to health affect replacement strategies and prioritization?

The technique of using geocoded HCC data together with geocoded records of quality impairment in the drinking water network was found to be feasible for health risk evaluation (Paper V). For analysis on a small sub-area level there were no significant differences in GI contacts between the two-week periods before and after pipe failures, or for all pipe failures or Type B pipe failures. In the study on the single-property level there were slightly more frequent GI contacts with the HCCs after pipe failures but the difference was not statistically significant. However, the study on the single-property level was small, and more events need to be studied. The results from the method used can easily be included in the CBA model for pipe prioritization (Paper IV).

4.4. Driving forces for future replacement

A replacement strategy for a DWS is path-dependent and in the reproduction state the driving forces for replacement are as seen today. Pipe failure repair, the consequences of failure and utility goals (e.g. consumer preferences) are the driving forces for condition-based reasons as well as societal development and changes in demand for other reasons. Leakage is found to be more effective for spot repair and should not be a driving force for replacement.

Replacement needs are increasing in Sweden and in many other countries. It is important that the pipes in the worst condition are largely replaced, otherwise the replacement needs will be even higher. In reality, pipes are to some extent replaced too early according to their condition when this is done in conjunction with road construction work or based on human decisions. If prioritization for these reasons is found to be significant, the lifetime expectations for pipes should be shortened to correspond to the real lifetime.

As shown in Table 1, in Paper I, potential decision drivers can change the replacement needs. A transformation that is seen is inclusion of the health risk in the driving forces for replacement. Even if the results in this thesis did not identify a health risk, other studies have and the CBA in this thesis found that the health risk affects prioritization. If the health effects are significant, more pipes are cost-effective to replace; possibly more pipes than are calculated in the strategic replacement needs. The strategic needs can then be forecast with a cost-effective management effect for the utility.

A major transition is migration due to climate change. Southern Europe, for example, suffers from warmer drier summers with less opportunity to live a comfortable life. This can be a driving force behind migration and changes in water demand and the need for replacement for reasons other than pipe condition. Moreover, migration and the fact that people travel more nowadays affect the risk of infectious agents spreading via water. Climate change can also lead to a higher risk of drinking water-related outbreaks due to lower-quality raw drinking water and unadjusted waterworks. The increased risk can affect consumer trust and confidence if more outbreaks and other incidents occur in the future, which may lead to less use of tap water as drinking water. Consequently, there are fewer replacement needs when people are less affected by disruptions. If you always have drinking water at home in bottles or tanks, it is acceptable not to be able to take a shower for a couple of hours (see Figure 7).

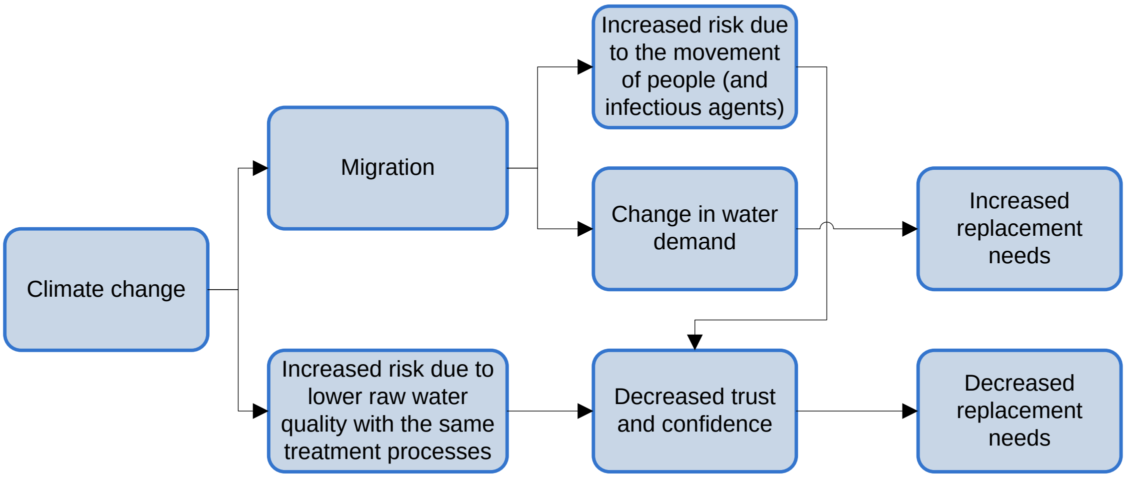

Figure 7 *The potential outcomes of a transformation change in a sociotechnical system: climate change (Paper I).*

4.5 Alternative paths for replacement strategies

A review on water pipe condition, deterioration and failure rate prediction models concludes that there is a multitude of parameters that influence the condition and performance of water pipe infrastructure and a lack of data collection (St. Clair and Sinha, 2012). One path is to make use of the knowledge that is the basis of the sophisticated tools and focus on the most critical factors which can then be used to underpin decisions made on experiential knowledge (path 3, section 1.4).

The age and material distribution presented in this study can be scaled down to a local water and wastewater utility when no local data are available for them to facilitate calculation of their own long-term rehabilitation needs.

The results from the CBA studies in this thesis can be used as a start for a utility with poorer data quality. However, accurate pipe failure data is essential.

5. CONCLUSIONS

The conclusions are presented in relation to the objectives and the overall aim of the thesis (as presented in section 1.2).

Objective a): To develop a method for forecasting future strategic replacement needs using historical data.

Replacement needs are strongly path-dependent and influenced by the reasons for replacement (condition based or non condition-based), postponing factors and decision drivers such as major reconstructions in the city and a (longer) expected lifetime of present pipe material. Historical data provide a reliable prediction, although the survival curve fits the data best when the reason for replacement is condition-based only. This thesis shows that a service life approach can be reliable when data is scarce. (Paper I)

Objective b): To show how limited local pipe data can predict future replacement needs for a whole water utility or region.

The results from the comprehensive questionnaire sent to Swedish municipalities show that even though the data are incomplete, a reliable prognosis for the future rehabilitation rate can be produced. The method described has been applied to Swedish conditions although the method can be used for all infrastructures irrespective of country. (Paper II)

Objective c): To develop a transparent CBA method for decision support in pipe replacement prioritization using a limited amount of available data.

Pipe failures are a good measure of management status and can be used as a force for replacement. By not looking purely at the pipe failure rate, but prioritizing actions based on CBA, economic efficiency increased significantly (Paper III and IV). To be complete, the CBA should also include external costs and risk costs.

Objective d): To evaluate which criteria should be included in the CBA with a specific focus on pipe failures, leakage and health risks.

To be complete, the CBA should also include external costs and risk costs. Health risk costs, for example, should be included as they affect the results. The case study in this thesis showed that health risk costs are low (Paper V), but when the results from other studies were included in the CBA used in this study, the health risk costs affected the results (Paper IV).

In the case study of the Gothenburg municipal water distribution system, reactively performing local repairs of water pipe leaks was significantly more economical to reduce leakage volumes than proactively replacing old pipes, despite a high overall leakage rate and abundant water resources (Paper III). However, CBA is a useful tool for comparing measures when designing leakage control programmes for water distribution systems.

Objective e): To present a method for evaluating the health risk arising from pipe failure repairs.

A novel method using geocoded HCC data on contacts together with geocoded records of disruptions was considered feasible and even if no statistically significant health risks were found in Gothenburg (Paper V), it should be included as it affects the result (Paper IV).

Conclusion of the overall aim: The overall aim of this thesis is to provide new knowledge for replacement strategy providing guidance for water utilities by tools for assessment and evaluation of the long-term needs as well as prioritization of replacement of drinking water pipes.

This thesis has provided some pieces in the puzzle of determining how to manage a drinking water network strategically. We have created a simple, transparent and easy to use approach for pipe replacement assessment where no specific software is needed.

6. FUTURE RESEARCH

There is a need to incorporate the CBA method used here into a Multi-Criteria Analysis. Pipe failure data in a CBA provides valuable input, but for total asset management of the drinking water network, risk aspects and effects for consumers must be included, and for that a MCA can be used. There are useful tools available, but more research is needed to transform the research into basic recommendations and to allow utilities with less data available to be better at asset management. The method used in this thesis enable this work. In a MCA, the order of priority is not strictly based on economic criteria. Instead, priority is given to aspects such as high-risk pipe sections and consumer preference. The utility can then reach a decision based on aims and goals, serious consequences, a positive NPV and/or high probability pipes with many consumers affected.

Moreover, if water utilities improve their IAM with the above mentioned basic recommendation, the implementation and the chance for improvement in effectiveness of the utilities can be studied. There is a need for research regarding health aspects. Studies in more cities and countries are needed which link drinking water treatment and distribution network quality impairment with Health Call Centre contacts for gastrointestinal illness symptoms.

A hypothesis worth testing is that the risk of intrusion during pipe failure repair depends on whether the pipe is laid bare (Type B, Figure 6) or not (Type A, Figure 5). When the pipe failure is small (Type A), the pipe can be repaired using a repair clamp that is fastened around the pipe and the pipe does not need to be opened. The points at which groundwater can intrude are potential leakiness on the unpressurized pipe section. Consequently, not very much contaminated groundwater can intrude during a normal unpressurized event as the number of small holes is too small and the difference in pressure from outside the pipe due to the groundwater level is also small (Malm et al., 2015). The risk of intrusion during unpressurized events is mainly at the repair spot. The risk is small if no sewerage occurs but it is significant if sewerage is present (Blokker et al., 2014). In the HCC study, there is an indication that Type B pipe events could represent a greater health risk, and during all these events the pipe was opened. The HCC offers potential for many future studies although it would require a certain size of area to obtain relevant data as well as model runs for each pipe break even though the focus should be on the broken pipe at the point at which the pipe is exposed.

Estimates of public health risks associated with intrusion are currently based on several untested assumptions. These risks have begun to be addressed in relation to epidemiological data from general public calls to the HCC and other sources but require validation with further sites studied over longer periods of time. Other risks, e.g. lack of backflow prevention devices, have never been studied from an epidemiological point of view. Calculation of microbial and chemical risks in the distribution network, combining data from surveys, interviews and hydraulic models as well as disease prevalence data, need to be carried out. The size of these risks (we know that there are risks from outbreak data) should be evaluated in order to make a quantitative microbial risk assessment (QMRA) for the entire drinking water system from source to tap.

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