FRANZ TSCHEIKNER-GRATL

INTEGRATED APPROACH FOR MULTI-UTILITY REHABILITATION PLANNING OF URBAN WATER INFRASTRUCTURE

Focus on small and medium sized municipalities

DISSERTATION

eingereicht an der

LEOPOLD-FRANZENS-UNIVERSITÄT INNSBRUCK
FAKULTÄT FÜR TECHNISCHE WISSENSCHAFTEN

zur Erlangung des akademischen Grades

DOKTOR DER TECHNISCHEN WISSENSCHAFTEN

Innsbruck, Oktober 2015

Erster Beurteiler:	Univ.-Prof. Dipl.-Ing. Dr. techn. Wolfgang Rauch Leopold-Franzens-Universität Innsbruck Institut für Infrastruktur Arbeitsbereich Umwelttechnik
Zweiter Beurteiler:	Univ.Prof. Dipl.-Ing. Dr.nat.techn. Thomas Ertl Universität für Bodenkultur Wien Institut für Siedlungswasserbau, Industriewasserwirtschaft und Gewässer- schutz

Hauptbetreuer: Univ.-Prof. Dipl.-Ing. Dr. techn.
Wolfgang Rauch
Leopold-Franzens-Universität Innsbruck
Institut für Infrastruktur
Arbeitsbereich Umwelttechnik

EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre hiermit an Eides statt durch meine eigenhändige Unterschrift, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe. Alle Stellen, die wörtlich oder inhaltlich den angegebenen Quellen entnommen wurden, sind als solche kenntlich gemacht. Die vorliegende Arbeit wurde bisher in gleicher oder ähnlicher Form noch nicht als Magister-/Master-/Diplomarbeit/Dissertation eingereicht.

Innsbruck, 27.10.2015

Franz Tscheikner-Gratl

ACKNOWLEDGEMENTS

These last four years doing my PhD were one of the most intensive and interesting times in my life. Therefore I would like to thank all those people who supported me during this period.
First of all I want to thank my supervisor Prof. Dr. Wolfgang Rauch who guided this work. He gave me the chance to participate in several interesting research projects, to attend different international conferences and took always time for questions and discussions. Further I want to especially thank Dr. Manfred Kleidorfer for his support in the different projects, the long discussions about research as well as the beers after work. I also want to thank Prof. Dr. Thomas Ertl for agreeing to review this thesis and for his input especially on the topic of sewer rehabilitation.
I would like to extend my gratitude to all my co-authors which supported the formation of this Thesis by giving good input for the herein implemented papers. Further I would like to thank my Bachelor and master students Tanja, Christina, Barbara, Eva, Ramona, Dawn and Patrick for the hard work and the inspired and interesting discussions, questions and insights on the topic. Further I want to thank Paul Fraiz Martinez for the proofreading of this work. I would also like to thank my colleagues, who accompanied me during my work on this thesis. Thanks for their motivating discussions, that helped me to stay focused and also for enduring me, when I got tired of writing my thesis and I had nothing better to do then to annoy them (especially Christian Mikovits and Günther Leonhardt). Also thanks to the great people I met on the various conferences and courses I attended for the good time and the interesting experiences.
Finally I would like to thank my family and friends for reminding me that there is a life outside the university. Especially I want to thank my girlfriend Marina for all the patience and support during these years. Muchisimas gracias mi amor.
Last but not least I want to thank all who I may have forgotten, it was not out of bad intent. Thanks to you all.

KURZFASSUNG

Diese Dissertation zeigt einen integrierten Ansatz für die Rehabilitierungsplanung urbaner Wasserinfrastruktur durch ganzheitliche Betrachtung der urbanen Infrastruktur, seine Möglichkeiten, Probleme und Herausforderungen sowie seine Anwendung auf verschiedene Fallstudien. Nach einer Einleitung, betreffend die Geschichte bzw. die aktuellen Herausforderungen der Siedlungswasserwirtschaft, werden die gesetzlichen und technischen Grundlagen und Leitlinien sowie der Begriff der integrierten Rehabilitationsplanung im Kontext des Standes der Technik in der Siedlungswasserwirtschaft erläutert. Im Folgendem wird der Datenproblematik, die den Einsatz verschiedenster Modelle be- bzw. verhindert, weiter Raum gegeben. Dabei wird sie anhand von drei Fallstudien von unterschiedlicher Größe und Qualität ausführlich behandelt. Weiters wird ein optimaler sowie ein mindestens notwendiger Datensatz definiert um die verschiedenen Modelle anwenden zu können. Abschließend werden die Probleme noch einmal zusammengefasst und Empfehlungen für zukünftiges Datenmanagement im Sinne des integrierten Ansatzes gegeben.

Mit diesen Grundlagen wird ein Ansatz zur Datenrekonstruktion anhand von Nachbarschaftsbeziehungen und zur Ermittlung der notwendigen Rehabilitierungsraten eines Netzes unter eingeschränkter Datenverfügbarkeit vorgestellt. Danach werden die vorhandenen Alterungs - sowie Entscheidungshilfemodelle, mittels ausführlicher Literaturrecherche betrachtet und erklärt, sowie ihre Vor- und Nachteile erläutert und einzelne Modellen auf die drei vorhandenen Fallstudien angewandt.

Es wird ein eigener dreiteiliger Ansatz zur integrierten Priorisierung von verschiedenen Infrastrukturnetzwerken vorgestellt und auf eine Fallstudie angewandt. Diese Methodik zielt darauf ab, über die Priorisierung und Reihung von verschiedenen Gebieten bzw. Straßenabschnitten, die Rehabilitierung von mehreren Netzwerken in diesen Abschnitten gleichzeitig durchzuführen, wenn dies technisch und ökonomisch sinnvoll ist. Sie ist an die bei kleinen und mittleren Betreibern oft auftretenden Probleme, wie z.B. schlechte bzw. mittelmäßige Datenqualität, angepasst und ermöglicht durch den modularen Aufbau die Implementierung weiterer Daten bzw. Netze ohne besondere Programmierkenntnisse. Abschließend wird anhand des Kanalsystems einer der Fallstudien die Möglichkeit eines Beitrags der notwendigen Rehabilitierungsplanung für die Anpassung unserer Netze an die sich ändernden Rahmenbedingungen gezeigt.

ABSTRACT

This dissertation and the included papers show the possibility of an integrated approach to rehabilitation management crossing the boundaries of individual networks, its problems and application on different case studies. After introducing the legal basis, the most important ideas and terminology of integrated rehabilitation management were discussed giving reference to the state of the art methods in this field. The data problematic, which hampers the application of models for small and medium sized municipalities, was highlighted using 3 case studies of different size and quality. Further optimal and minimal data requirements for the application of the mentioned models and recommendations for future data management were given.
This work used these inputs to develop approaches for data reconstruction and the estimation of the necessary rehabilitation rates using limited data availability. Furthermore, the available models regarding deterioration and decision support were introduced and the literature review on their application were given. The most used models were applied to the case studies and implemented in decision support models depending on the data quality and availability. These ranged from a simple weighted sum model, more sophisticated approaches to a novel methodology for the integrated prioritisation of different infrastructure networks used in a real case study.
This methodology for the integrated prioritisation of different infrastructure networks used in a real case studies aims to rank, and thereby prioritise, areas for rehabilitation of the different networks if economically viable or for single networks if not. It is an easy to use rehabilitation management procedure for small and medium sized municipalities. It is adjusted to the main problems for small operators - missing or have only recently begun data management and therefore bad or at best mediocre data quality. Moreover, the simple and modular setup of the methodology enables the addition of further information and networks into the model and it to be used without extensive programming skills. Finally by applying the established method for the sewer system of a case study, the possible contribution of the rehabilitation measures to the necessary adaptation to changing environmental conditions was estimated.

CONTENTS

I Thesis 1

1 INTRODUCTION 3
1.1 On the origins of urban water infrastructure 3
1.2 Challenges for modern urban water infrastructure . . . 4
1.3 Scope and structure of the thesis 6
1.3.1 Aim and scope 6
1.3.2 Structure of the dissertation 6
1.3.3 Contents of the papers of this dissertation . . . 7

2 INTEGRATED REHABILITATION MANAGEMENT 11
2.1 Legal basis and technical standards 11
2.1.1 Water distribution system 11
2.1.2 Sewer and drainage system 13
2.2 The idea of integrated rehabilitation management . . . 14

3 DATA MANAGEMENT 21
3.1 Data for rehabilitation management 21
3.2 Case studies and data quality 23
3.2.1 Case study 1 24
3.2.2 Case study 2 40
3.2.3 Case study 3 49
3.2.4 Characteristics of the case studies 62
3.3 Recapitulation of issues and recommendations for data management 66

4 DETERIORATION MODELING 71
4.1 Cohort survival model 74
4.2 Binary logistic regression model 78
4.3 Simplified approaches for the modeling of rehabilitation rates 81

5 MULTI-CRITERIA DECISION SUPPORT MODELS 87
5.1 Analytic Hierarchy Process 92
5.2 Weighted sum model 94
5.3 ELECTRE 95
5.4 PROMETHEE 97
5.5 VIKOR 98
5.6 Comparison of methods 100

6 ADAPTATION IN THE COURSE OF REHABILITATION 103

7 CONCLUSION, DISCUSSION AND OUTLOOK 107
7.1 Conclusion 107
7.2 Discussion and outlook 111

BIBLIOGRAPHY 117

II Publications 151

8 PAPER I 153

9 PAPER II 155

10 PAPER III 157

11 PAPER IV 159

12 PAPER V 161

13 PAPER VI 163

14 PAPER VII 165

15 PAPER VIII 167

16 PAPER IX 169

LIST OF FIGURES

Figure 1 Topics and used case studies for the included papers 10

Figure 2 Possibilities for coordinated rehabilitation for the networks of table 1: optimum for each network separately (upper left graph), exploitation of the full technical design life of the road network, while replacing the telecommunication and electric cables always at the same time (upper right graph), optimum for electric and telecommunication networks (lower left graph), global optimum for this example (lower right graph) 16

Figure 3 Standard cross section for sewer, water supply and gas supply 18

Figure 4 Construction years of the water distribution network of case study 1 before reconstruction . . 25

Figure 5 Construction years of the water distribution network of case study 1 after reconstruction . . . 26

Figure 6 Pipe diameter for the water distribution network of case study 1 26

Figure 7 Pipe length partitioned by construction year and pipe diameter for the water distribution network of case study 1 27

Figure 8 Pipe material for the water distribution network of case study 1 28

Figure 9 Pipe length partitioned by construction year and pipe material for the water distribution network of case study 1 28

Figure 10 Failure rates for the water distribution network of case study 1 30

Figure 11 Number of failures depending on the affected pipe age for the water distribution network of case study 1 31

Figure 12 Clustering of failures in street sections for the water distribution network of case study 1 . . 31

Figure 13 Construction years of the sewer network of case study 1 before reconstruction 32

Figure 14 Construction years of the sewer network of case study 1 after reconstruction 34

Figure 15 Pipe material for the sewer network of case study 1 . . . 35
Figure 16 Pipe length partitioned by construction year and pipe material for the sewer network of case study 1 . . . 35
Figure 17 Pipe diameter for the sewer network of case study 1 . . . 37
Figure 18 Condition states of the sewer network of case study 1 . . . 37
Figure 19 Pipe length partitioned by construction year and condition states of the sewer network of case study 1 . . . 38
Figure 20 Condition of the sewers per inspected pipe of case study 1 observed at a certain pipe age depending on the visual inspection date . . . 40
Figure 21 Construction years of the water distribution network of case study 2 before reconstruction . . . 41
Figure 22 Pipe diameters of the water distribution network of case study 2 after reconstruction . . . 42
Figure 23 Pipe material for the water distribution network of case study 2 . . . 44
Figure 24 Observed failure mechanisms in water distribution network of case study 2 . . . 45
Figure 25 Number of failures depending on the affected pipe age and type for the water distribution network of case study 2 . . . 47
Figure 26 Boxplot of the age of failure occurrence for cascading failures on house connections (left) and distribution pipes (right) in case study 2 . . . 47
Figure 27 Failure rates for the water distribution pipes of case study 2 . . . 48
Figure 28 Failure rates for the house connections of case study 2 . . . 48
Figure 29 Construction years of the water distribution network of case study 3 . . . 50
Figure 30 Pipe diameters of the water distribution network of case study 3 . . . 51
Figure 31 Pipe material of the water distribution network of case study 3 . . . 52
Figure 32 Pipe length of the water distribution network of case study 3 divided by material . . . 52
Figure 33 Number of failures of the water distribution network of case study 3 depending on construction depth . . . 53

Figure 34 Failure rates for the house connections of case study 3 . . . 55
Figure 35 Failure rates for the water distribution pipes of case study 3 . . . 55
Figure 36 Construction years of the urban drainage network of case study 3 . . . 56
Figure 37 Pipe diameters of the urban drainage network of case study 3 . . . 57
Figure 38 Hydraulic capacity utilisation of the urban drainage network of case study 3 . . . 58
Figure 39 Condition states using DWA-M 149-3 (2007) of the urban drainage network of case study 3 . . . 58
Figure 40 Construction years of the gas distribution network of case study 3 . . . 59
Figure 41 Pipe material of the gas distribution network of case study 3 . . . 60
Figure 42 Constructed pipe length of the gas distribution network of case study 3 divided by material and construction year . . . 60
Figure 43 Failure rates for distribution pipes and house connections of the gas distribution network of case study 3 . . . 62
Figure 44 Distribution of condition states of the sewer networks in case study 1 (classified into condition states using the methodology following ISYBAU (Arbeitshilfen Abwasser 2004/242/D, 2012)) and case study 3 (divided into 6 condition states using DWA-M 149-3 (2007)) . . . 66
Figure 45 Results of the cohort survival model for the water distribution network of case study 2 . . . 76
Figure 46 Results of the cohort survival model for the sewer system of case study 1 . . . 77
Figure 47 Result of the binary logistic regression model for the sewer network of case study 1 . . . 79
Figure 48 ROC-curves (left) and sensitivity/specificity plot (right) for the water distribution network of case study 1 . . . 80
Figure 49 Result of the binary logistic regression model for the water distribution network of case study 1 . . . 80
Figure 50 Simplified approach using average life expectancies and normal failure distribution for the water distribution pipes of case study 3 . . . 83

Figure 51 Comparison of the different approaches for the water distribution pipes of case study 3 84
Figure 52 Comparison of the different approaches for the sewer system of case study 1 85
Figure 53 Total ranking of street sections using the integrated approach with a VIKOR decision support system for case study 3 using the data of PAPER II 100
Figure 54 Total ranking of street sections using the integrated approach with a various decision support systems for case study 3 using the data of Egger (2015) 101
Figure 55 Hydraulic condition states following ÖWAV-RB 22 (2015) for the sewer system of case study 1 104
Figure 56 Yearly total costs of the different rehabilitation methods for different rehabilitation rates (Tscheikner-Gratl et al., 2014b) 105
Figure 57 Costs of the different rehabilitation methods for different rehabilitation rates applied for different depreciation times (Tscheikner-Gratl et al., 2014b) 106
Figure 58 Methodology of this work - in the colored topics methods were developed or enhanced . . . 109

LIST OF TABLES

Table 1 Expected service life taken from LAWA (2005) 15
Table 2 Information about the case studies 24
Table 3 Comparison construction period for the water distribution network in case study 1 between the original data and the reconstructed data . 27
Table 4 Comparison of material distribution in the water supply network of case study 1 between original data and reconstructed data 29
Table 5 Comparison of the material distribution in the water supply network of case study 1 between original data and reconstructed data 34
Table 6 Comparison of material distribution in the water supply network of case study 2 between original data and reconstructed data 43
Table 7 Characteristics of the water distribution system of the case studies 64
Table 8 Significant factors of the binary logistic regression model for the water distribution network of case study 1 81
Table 9 Comparison of the criteria according to the AHP scale (Egger, 2015) 93

LIST OF PAPERS

The following papers are an integral part of this thesis. They are annexed to this thesis starting on page 151 in the printed version, but not in the online version due to copyright issues. Copies of the papers may be obtained from journal publishers.

1. Integrated rehabilitation planning of urban infrastructure systems using a street section priority model
   Franz Tscheikner-Gratl, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer (2015)
   Published in Urban Water Journal, Published online: 16.07.2015,
   DOI: 10.1080/1573062X.2015.1057174
   Reproduced with permission from the copyright holders, Taylor & Francis

2. Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities
   Franz Tscheikner-Gratl, Robert Sitzenfrei, Christina Stibernitz, Wolfgang Rauch and Manfred Kleidorfer (2015)
   Published in Proceedings of the World Environmental and Water Resources Congress 2015, pp. 2045-2057
   DOI: 10.1061/9780784479162.201
   Reuse with permission from American Society of Civil Engineers (ASCE)

3. Prioritization of Rehabilitation Areas for Urban Water Infrastructure. A Case Study
   Franz Tscheikner-Gratl, Robert Sitzenfrei, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer (2014)
   Published in Procedia Engineering 89, pp. 811-816,
   DOI: 10.1016/j.proeng.2014.11.511

4. Integrated planning of rehabilitation strategies for sewers
   Manfred Kleidorfer, Michael Möderl, **Franz Tscheikner-Gratl**, Max Hammerer, Heiko Kinzel and Wolfgang Rauch (2013)
   Published in Water Science and Technology **68** (1), pp. 176-183,
   DOI: 10.2166/wst.2013.223
   Reproduced with permission from the copyright holders, IWA Publishing

5. Integrated Rehabilitation Management for Different Infrastructure Sectors (2013)
   Franz Tscheikner-Gratl, Max Hammerer, Wolfgang Rauch, Christian Mikovits and Manfred Kleidorfer
   Published in gwf Wasser-Abwasser **154**, International Issue 2013, pp. 50-56,
   ISSN: 0016-3651
   Reuse with permission from Deutscher Industrieverlag (DIV)

6. Enhancement of limited water supply network data for deterioration modelling and determination of rehabilitation rate
   Franz Tscheikner-Gratl, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer (2015)
   Published in Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, Published online: 06.03.2015,
   DOI: 10.1080/15732479.2015.1017730
   Reproduced with permission from the copyright holders, Taylor & Francis

7. Verwendete Materialien in der Wasserversorgung bei Betreibern von Versorgungsnetzen kleinerer und mittlerer Größe (in German)
   Franz Tscheikner-Gratl, Tanja Vonach, Wolfgang Rauch and Manfred Kleidorfer (2015)
   Published in Bauingenieur **90** (02-2015), pp. 81-87,
   ISSN: 0005-6650
   Reproduced with permission from the copyright holders, Springer-VDI-Verlag

8. What can we learn from historical water network transition?
   Robert Sitzenfrei, Michael Mair, **Franz Tscheikner-Gratl**, Bernhard Hupfauf and Wolfgang Rauch (2015)
   Published in Proceedings of the World Environmental and Water Resources Congress 2015, pp. 907-916
   DOI: 10.1061/9780784479162.086
   Reuse with permission from American Society of Civil Engineers (ASCE)

9. Adaptation of sewer networks using integrated rehabilitation management
   Franz Tscheikner-Gratl, Christian Mikovits, Wolfgang Rauch and Manfred Kleidorfer (2014)
   Published in Water Science and Technology **70** (11), pp. 1847-1856,
   DOI: 10.2166/wst.2014.353
   Reproduced with permission from the copyright holders, IWA Publishing

The following additional publications also resulted from the work during the PhD study. Although they are not part of this thesis, their content is also related to the topics presented here and could be of interest to the readers. Some publications are not that closely related to the topic, but demonstrate the broad range of research done during the PhD study. Copies of the papers may be obtained from the journal publishers or conference organisers.

1. GIS Anwendung in der integrierten Rehabilitierungsplanung von urbaner Wasserinfrastruktur (in German)
   Franz Tscheikner-Gratl, Christian Mikovits, Sitzenfrei Robert, Wolfgang Rauch and Manfred Kleidorfer (2015)
   Published in Angewandte Geoinformatik. Beiträge zur AGIT 2015, pp. 308-313
   DOI: 10.14627/537557043

2. Integrierte Rehabilitationsplanung für kleine und mittlere Gemeinden durch Priorisierung von Straßenabschnitten (in German)
   Franz Tscheikner-Gratl, Robert Sitzenfrei, Christina Stibernitz, Wolfgang Rauch and Manfred Kleidorfer (2015)
   Published in Wiener Mitteilungen 233, pp. E1-E15
   ISBN: 978-3-85234-127-9

3. Optimizing a series of rainfall events to reduce the computation time of hydrodynamic simulations
   Johannes Leimgruber, David Steffelbauer, Matthias Kaschutnig, **Franz Tscheikner-Gratl** and Dirk Muschalla (2015)
   Published in Proceedings of the 10th International Conference on Urban Drainage Modelling, Mont-Sainte-Anne, Quebec, Canada, Vol. III, pp. 39-44

4. How much detail is too much detail - A modelling perspective
   Peter Zeisl, **Franz Tscheikner-Gratl** Manfred Kleidorfer and Wolfgang Rauch (2015)
   Published in Proceedings of the 10th International Conference on Urban Drainage Modelling, Mont-Sainte-Anne, Quebec, Canada, Vol. III, pp. 45-53

5. Von den Daten zum Modell: Anforderungen an hydraulische Entwässerungsmodelle in kleinen und mittleren Gemeinden (in German)
Manfred Kleidorfer, Ulrich Tschiesche, **Franz Tscheikner-Gratl**, Robert Sitzenfrei, Florian Kretschmer, Dirk Muschalla, Thomas Ertl and Wolfgang Rauch (2014)
Published in Wiener Mitteilungen 231, pp. J1-J14
ISBN: 978-3-85234-125-5

6. Dealing with limited data in rehabilitation management of water supply networks
Franz Tscheikner-Gratl, Wolfgang Rauch, Max Hammerer and Manfred Kleidorfer (2014)
Published in Proceedings of the IWA Water Loss Conference 2014

7. Integrierte Betrachtung von Anpassungsmaßnahmen und Rehabilitierung (in German)
Christian Mikovits, **Franz Tscheikner-Gratl**, Wolfgang Rauch and Manfred Kleidorfer (2013)
Published in ÖWAV- Tagungsband: Sanierung und Anpassung von Entwässerungsmaßnahmen - Alternde Infrastrukur, Landnutzungsänderungen und Klimawandel, pp. J1-J11
ISBN: 978-3-902810-66-3

8. Chancen und Herausforderungen für eine ganzheitliche Sanierungsplanung von Kanalisationen (in German)
Franz Tscheikner-Gratl, Christian Mikovits, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer (2013)
Published in Wiener Mitteilungen 229, pp. C1-C26
ISBN: 978-3-85234-122-4

9. Potenziale und Problemstellungen bei der Verwertung von Klär- und Biogas (in German)
Franz Tscheikner-Gratl, Irene Schneider and Anke Bockreis (2012)
Published in ÖWAV- Tagungsband: Biogasanlagen und Co-Vergärung - Potenziale, Chancen und Risiken
ISBN: 978-3-902810-32-8

10. Siloxane im Klärgas - Untersuchungen an österreichischen Anlagen (in German)
Franz Tscheikner-Gratl, Julika Knapp and Anke Bockreis (2011)
Published in Beiträge zu Abfallwirtschaft/Altlasten 80, pp. 57-64
ISBN: 978-3-902810-32-8

11. Siloxane im Biogas (in German)
Franz Tscheikner-Gratl, Julika Knapp, Irene Schneider and Anke Bockreis (2011)
Published in Schriftenreihe IWAR 216, pp. 133 - 143
ISBN: 978-3-940897-13-8

The results of the scientific work were also presented at various conferences. These, hereby listed conferences are part of the scientific exchange of ideas and experience and form an invaluable part of the formation of this PhD thesis. The presentations were given by the author of this thesis during his PhD study.

1. GIS Anwendung in der integrierten Rehabilitierungsplanung von urbaner Wasserinfrastruktur (in German)
   Symposium und EXPO für Angewandte Geoinformatik (AGIT), Salzburg/Austria, 08.-10.07.2015

2. Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities
   World Environmental and Water Resources Congress 2015, Austin/Texas, 17.-21.05.2015

3. Integrierte Rehabilitationsplanung für kleinere und mittlere Gemeinden durch Priorisierung von Straßenabschnitten (in German)
   Kanalmanagement 2015, Vienna/Austria, 21.04.2015

4. Adaptation of Sewer Networks Using Integrated Rehabilitation Management
   13th International Conference on Urban Drainage (ICUD 2014), Kuching/Malaysia, 07.-12.09.2014

5. Prioritization of rehabilitation areas for urban water infrastructure - a case study
   Water Distribution Systems Analysis Conference (WDSA 2014), Bari/Italy, 14.-17.07.2014

6. Dealing with limited data in rehabilitation management of water supply networks
   IWA Water Loss Conference 2014, Vienna/Austria, 30.03.-02.04.2014

7. Integrated planning of rehabilitation strategies of urban infrastructure systems
   21st European Junior Scientist Workshop on Sewer Asset Management, Delft/Netherlands, 20.-22.11.2013

8. Integrated Rehabilitation management for different infrastructure sectors
   International Congress and Technical Exhibition: CeoCor 2013 "Drinking Water, Waste Water, Gas and Oil", Florence/Italy, 04.-07.06.2013

9. Chancen und Herausforderungen für eine ganzheitliche Sanierungsplanung von Kanalisationen (in German)
   Kanalmanagement 2013, Vienna/Austria, 09.04.2013

During the PhD study I worked on different scientific research projects, from which the herein mentioned or included publications derive.

- Project REHAB - Integrated planning of rehabilitation strategies of urban infrastructure systems funded by the Austrian Research Promotion Agency (FFG project number 832148)
- Project INSIDE - Integrated solutions for the landfill leachate problem funded by the technology promotion of the region of Tyrol
- Project DATMOD - An efficient way from data to model - rehabilitation and adaptation planning for small and medium size sewer networks funded by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management

Furthermore I co-supervised numerous bachelor thesis and one master thesis:

- Wachter, Barbara (2012) - Schadensklassifizierung und Rehabilitierungsplanung in der Abwasserentsorgung (in German); Bachelor thesis
- Pollhammer, Eva (2013) - Rehabilitationsplanung von Wasserversorgungsnetzen in der Siedlungswasserwirtschaft (in German); Bachelor thesis
- Bitsche, Ramona (2013) - Ausgewählte Kanalinspektions- und Kanalsanierungmethoden (in German); Bachelor thesis
- Vonach, Tanja (2013) - Verwendete Materialien in der Wasserversorgung (in German); Bachelor thesis
- Stibernitz, Christina (2014) - Rehabilitierungsplanung alternder Infrastruktur anhand eines konkreten Fallbeispiels (in German); Bachelor thesis
- Summer, Dawn (2015) - Einfluss von Unsicherheiten auf Modellergebnisse in der Siedlungsentwässerung (in German); Bachelor thesis
- Egger, Patrick (2015) - Comparison of multi-criteria decision support methods for integrated rehabilitation management of urban infrastructure networks; Master thesis

Part I

Thesis

1 INTRODUCTION

> And you shall have a trowel with your tools, and when you sit down outside, you shall dig a hole with it and turn back and cover up your excrement.
>
> — Deuteronomy 23:13

1.1 ON THE ORIGINS OF URBAN WATER INFRASTRUCTURE

The challenge of adequate fresh water supply and its disposal after usage (as already mentioned in the bible) is an old one. Early civilisations were built on complex systems of water management and hydraulic engineering (Mithen, 2010). It is no coincidence that the oldest advanced civilisations emerged near rivers, which enabled a permanent supply of fresh water. The main examples are the cultures at the banks of the rivers Nile, Euphrates, Tigris, Indus, Yangtze and Huang He. An impressive example of the technical knowledge of ancient cultures is the so-called Indus Valley or Harappan civilisation (ca. 3200-1900 BC) (Garbrecht, 1988). Although not the oldest example of urban water infrastructure - urban drainage pipes for rainwater were already in use in Ur, Babylon and Habuba Kabira (ca. 4000 BC) (De Feo et al., 2014; Strommenger, 1980) - it is together with the Minoan Culture (who used 1500 BC the first water distribution pipes (Walski et al., 2003)) the oldest example of a well organized and structured water infrastructure. Water supply was achieved by wells inside most of the houses, some of the houses had also flushing toilets (Büker, 2000; Garbrecht, 1988). Surprisingly, the largest city of the Harappan civilisation, Dholavira, depended solely on decentralised solutions (e.g. soak pits) and had no centralised sewer system (De Feo et al., 2014).
For areas with no great rivers as a water resource, as in the plateaus of the Middle East, other solutions had to be found using groundwater for drinking and irrigation. This was accomplished by Qanats

(the oldest ones dating to 1200 BC), where groundwater is brought to the surface without mechanical means, relying upon gravity alone (Jomehpour, 2009). From these ancient techniques (which are partly still in use) a bridge can be forged to modern systems of urban water infrastructure. De Feo et al. (2014) give a good overview on the historical development of sanitation over the centuries. Walski et al. (2003) does the same in brief for water distribution, Garbrecht (1988) in more detail for the ancient world, while Grewe (1991) focuses on medieval times.

A bridge from the past to present times.

1.2 CHALLENGES FOR MODERN URBAN WATER INFRASTRUCTURE

The public has certain expectations concerning the functionality of the urban water infrastructure. The European Standard EN 752 (2008) defines that the wastewater system should provide to the community

- removal of wastewater from premises for public health and hygienic reasons;
- prevention of flooding in urbanized areas;
- protection of the environment.

The national guideline for drinking water ÖVGW W 100 (2007) requires, that drinking water should be provided by the operating company in sufficient

- quality;
- quantity;
- and pressure.

These are the justified expectations of the community, but the modern urban infrastructure faces two major challenges while fulfilling these duties:

- Maintenance and rehabilitation of the aging networks;
- Adaptation to a changing environment (e.g. Climate change and/or urban development in the context of population increase/decrease).

The focus of operating companies in developed countries is moving away from construction of new networks to the maintenance and repair and sometimes even reduction of the existing ones, if made necessary by decreasing population (Großmann et al., 2013). In Austria for example with 94.9% connection rate to the sewer system and 91.8% to the water distribution network (KPC, 2013) the potential for further growth is limited. Furthermore, the existing 96,200 km of sewer and drainage as well as the 76,700 km water distribution pipes (Neunteufel et al., 2012), not including the house connections, are aging and will sooner or later reach the end of their technical design life. In Tyrol Willi et al. (1992) estimated that 2.5% of the existing sewer and drainage network had to be rehabilitated, when only 5% of the network was more than 40 years old. In 2015 8% of the network is more than 50 years old (Wildt, 2013). Therefore, the rehabilitation of these networks is also an important economic factor, due to the fact that rehabilitation also means major investments in infrastructure. KPC (2013) expect an investment volume in rehabilitation works in Austria until 2021 in water supply, sewer and drainage of 3.83 billion €. Cashman and Ashley (2008) however estimated a necessary investment to provide the current level of service of 2-3 billion € per year whilst the more conservative estimation of Neunteufel et al. (2012) still assumes that 8.4 - 13.2 billion € are required in the period until 2021.

On the other hand the urban drainage and sewer system is influenced by climate change due to the expected increase in rainfall intensities (Ashley et al., 2005; Kleidorfer et al., 2009), which leads to a temporarily higher runoff. The same effect is caused by surface sealing, which can be linked with urban development (Mikovits et al., 2015). Higher runoffs lead to a higher risk of urban flooding and decrease the performance of storm water treatment as well (Langeveld et al., 2013; Semadeni-Davies et al., 2008), due to the more frequent and intensive combined sewer overflows contaminated with pollutants from different surfaces.

The water supply system is driven by the demand and is therefore influenced by urbanisation (population in- and decrease). The impact of climate change is very case specific, ranging from severe pressure to water resource management in some areas to having an insignificant effect in other parts of the world. Nevertheless it can have an impact on water consumption (Ruth et al., 2007). Furthermore, maintaining a network for a decreasing population can be problematical in terms of water quality due to the increased retention time in the network, as well as for economic reasons.

These two influences - the need for rehabilitation and adaptation - form the Scylla and Charybdis of the operating companies of urban water networks today. They have to find a course in between which avoids neglecting one by focusing solely on the other. At the same time they have to provide the aforementioned services and be economically viable.

Scylla and Charybdis of the operating companies of urban water networks: the need for rehabilitation and adaptation.

1.3 SCOPE AND STRUCTURE OF THE THESIS

1.3.1 Aim and scope

The aim of this thesis is to provide a new perspective on rehabilitation management by using an integrated approach and at the same time to avoid creating an "Integronster" (Voinov and Shugart, 2013). The focus of this work are the sewer and drainage systems as well as the water supply network. The goal is to increase the efficiency of rehabilitation works by an integrated view of all the available networks together with the transportation network, by minimising costs through better coordination. To achieve this goal different influencing factors are taken into account:

- Deterioration models to estimate the probability of failures;
- Vulnerability of the networks to occurring failures;
- Environmental factors ranging from public transport to urban development;
- Economic view (e.g. deterioration and savings through the coordination of different networks).

These factors are implemented into a decision support framework. All of these parts depend of course on the availability and quality of the data. Due to the difficulties in obtaining and to the varying quality of the available data another focus of this work is the processing of and working with limited data. This is of further importance for the third focus of this work, on smaller and medium sized municipalities, because large municipalities (more than 50,000 inhabitants) typically have better asset management practices and data sets (Younis and Knight, 2010a). In Austria 68% of the overall population lives in such small municipalities (Statistik Austria, 2015) and the vast majority of water utilities in the world serve populations of less than 100,000 inhabitants (Alegre and Coelho, 2012). Therefore three case studies were used ranging from 13,000 and 95,000 up to 130,000 inhabitants to represent municipalities of different sizes where 54%, 71% and 76% of the Austrian population respectively live in municipalities that are smaller or of the same size. Although two of the case studies are not considered small by Austrian standards, they are on an international scale.

An integrated perspective on rehabilitation management for smaller and medium sized municipalities.

1.3.2 Structure of the dissertation

The first part of this thesis (chapter 2) introduces the terminology, legal aspects and standards of rehabilitation and asset management.

Finally it explains the ideas and concept of integrated rehabilitation management in greater depth.
Chapter 3 is mainly concerned with the data problematic. It introduces the case studies used, highlights the encountered difficulties regarding data quality, consistency and availability and shows the chosen path of dealing with these shortcomings. Furthermore, it shows the differences in the networks of the three case studies in materials used, diameters and so on.
Chapter 4 gives a brief overview of the state-of-the-art in deterioration modeling, discussing shortcomings and advantages of different approaches with the focus on the methods used in the publications, which constitute the main part of this dissertation. Chapter 5 does the same regarding decision support approaches, including the findings of a supervised Masters Thesis, that it is currently ongoing (Egger, 2015).
Chapter 6 elaborates on the approach, described in PAPER IX, of using necessary rehabilitation works for adaptation measures to a changing environment. Finally, in chapter 7, some conclusions are drawn on the hereby presented work and an outlook given on future research questions.

Introduction, terminology, data, deterioration modeling, decision support, adaptation, conclusion, outlook.

1.3.3 Contents of the papers of this dissertation

The 9 included papers use the data of three different case studies (elaborated in chapter 3) applying different approaches for different topics including decision support (chapter 5), deterioration modeling and the prediction of a necessary rehabilitation rate (chapter 4), data management and reconstruction (chapter 3) and adaptation by using rehabilitation management (chapter 6). The distribution of the included papers on these topics can be seen in figure 1.

PAPER I, PAPER II and PAPER III show the process of establishing a prioritisation model and its application on different case studies, with adaptions depending on the available data.
PAPER I (Tscheikner-Gratl et al., 2015d) shows a methodology for the integrated prioritisation of different infrastructure networks used in a real case study with a water and wastewater network. Its main aim was to rank, and thereby prioritise, economically viable areas for rehabilitation of the different networks or for individual networks if not. This is achieved by implementing factors of structural resiliency, vulnerability of the network, capital value and other network components (e.g. manholes, house connections). This model is applied to a medium sized case study in which the rehabilitation areas identified by the developed model are compared to the actual rehabilitation

Prioritisation models and their application on different case studies.

plans of the water and sewage companies. Results also show the application of the estimated ranking for rehabilitation planning with a fixed budget.
PAPER II (Tscheikner-Gratl et al., 2015c) shows a simplified approach for the integrated prioritisation method. This work presents the methodology and results of a case study, including water, wastewater and gas networks, for an easy to use rehabilitation management procedure for small and medium sized municipalities. It is adjusted to the main problems small operators face - missing or only recently begun data management and therefore bad or at best mediocre data quality. Furthermore, the simple setup of the methodology enables it to be used without extensive programming skills. Due to its modular setup it can be extended, additional information or even whole networks such as electrical grids or telecommunication networks can be easily included.
PAPER III (Tscheikner-Gratl et al., 2014c) shows the application of a priority model for the rehabilitation management of water distribution systems. The methodology provides a comprehensible and replicable approach in ranking and prioritising rehabilitation areas. Its main use is the investigation of different future scenarios and how these scenarios can be evaluated to aid in the decision making process.

The idea of integrated rehabilitation management.

PAPER IV and PAPER V form the foundation of the idea of integrated rehabilitation management and the research project "REHAB", funded by the Austrian Research Promotion Agency FFG (FFG project number 832148). The ideas and results of this research project form the major part of this dissertation.
PAPER IV (Kleidorfer et al., 2013) introduces the idea of the integrated approach for rehabilitation management and the research project "REHAB". In this study the scope and participating partners of the project are described as well as the first results regarding sewer pipe conditions. Moreover, future developments and vulnerability assessments are discussed.
PAPER V (Tscheikner-Gratl et al., 2013b) elaborates on the idea of integrated rehabilitation and prioritisation of street sections, adding the momentum of data management and quality as a main factor. It also shows the application of deterioration models and models to estimate the necessary rehabilitation rates. These models depend strongly on the quality and accuracy of the available data. Data is seldom available in high quality due to the fact that the operating companies have only recently started information management. Therefore, a good data validation and reconstruction of the available data is essential for rehabilitation planning. Moreover, an example for the consider-

ation of future scenarios is shown and the phenomenon of failure clustering in water distribution networks as well as the higher failure rates on house connections is discussed.

PAPER VI, PAPER VII and PAPER VIII show the possibilities of dealing with data problems: reconstruction, expert knowledge and historical research.

Approaches for dealing with data problems.

PAPER VI (Tscheikner-Gratl et al., 2015a) presents a methodology for the enhancement of the available data of the water supply networks and the prognosis of the necessary rehabilitation rates under limited data availability. Results indicate that the presented data reconstruction technique has advantages compared to traditional data extrapolation. It also allows the reconstruction of fragmentary data about existing water supply and wastewater collection systems for the operating utilities. However, it cannot be used for reconstructing failure types as well as for the whole information on pipes.
PAPER VII (Tscheikner-Gratl et al., 2015e) shows the results of a survey in ten small to medium sized municipalities in Tyrol and in Vorarlberg, which was carried out to investigate not only the operator characteristics (e.g. water loss, failure rate and active leakage control) but also the operating company's assessment of the qualities and life expectancies of the pipe materials used. These findings were then compared to values of literature review. The results show the diversity of the influencing factors but also of the experiences of the operators concerning the behaviour of different materials in the construction phase, in maintenance and rehabilitation. Moreover, the visible differences between the operators' assessments and the available models were discussed.
PAPER VIII (Sitzenfrei et al., 2015) explores the historical development of a case study over a period of over 100 years. For that, all the available historic data was collected. Missing data was reconstructed and hydraulic Epanet2 models were assembled in a 10 year time step starting from 1910 up to the present date. With that data base of network models, the technical performance over time is analysed and discussed with regard to significant events that occurred and their impact on the technical performance. Furthermore, how this information helps in addressing current challenges is outlined.

PAPER IX (Tscheikner-Gratl et al., 2014a) investigates if it is possible to combine rehabilitation and adaptation measures. To do so, an urban development model, an urban drainage model and a rehabilitation model were combined. A case study was used to develop and apply this method. A priority model to pinpoint the structures in need of replacement was used. This model considered a deterioration

The possibility of combining rehabilitation and adaptation for the urban drainage system.

model, vulnerability estimation and other influences. Additionally, different rehabilitation rates and methods were examined. The urban development model used is a simplistic approach specifically tailored for the field of urban infrastructure management. Climate change is considered in terms of climate change factors. All of these different influences together create scenarios for which the construction costs and the flooding volume are estimated and compared. Consequently the aim of this paper was to test to which degree it is possible to reduce urban flooding by adapting those parts of the network which require rehabilitation anyway. In our case study this could be reduced by 5%. These results are elaborated in chapter 7.

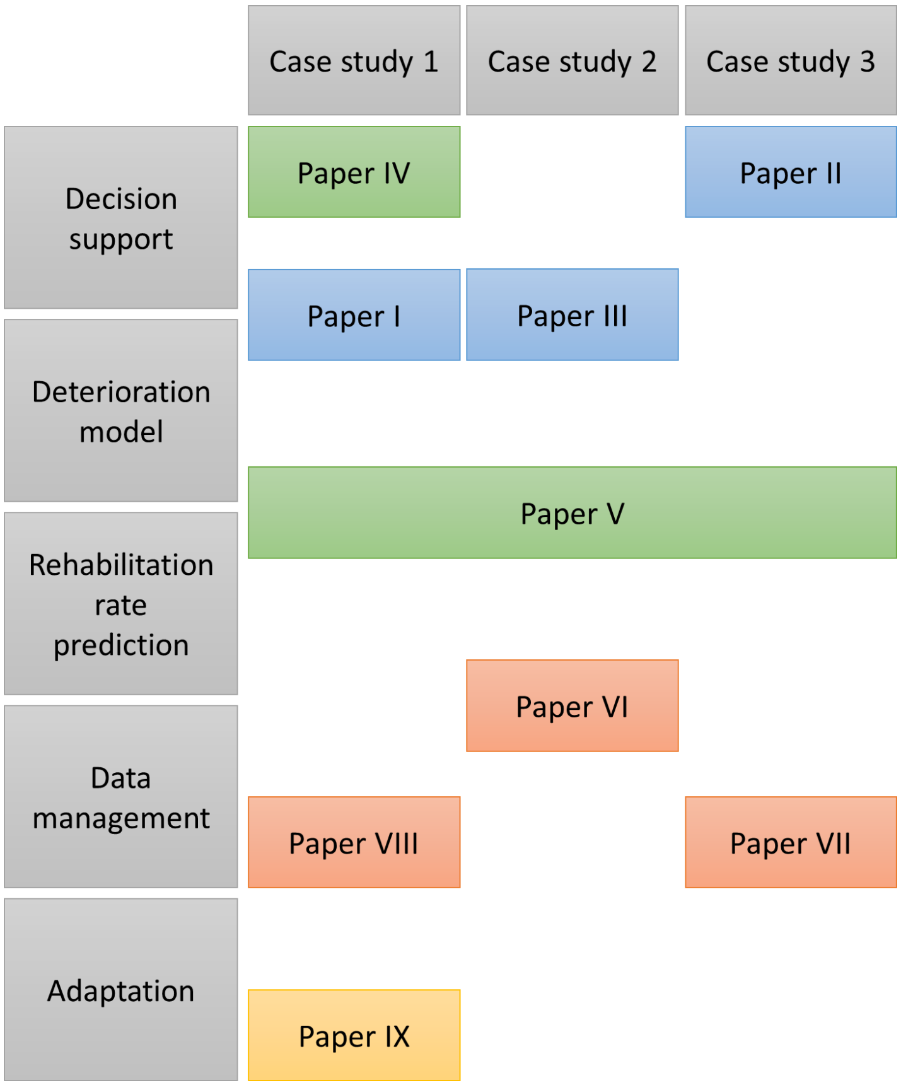

Figure 1: Topics and used case studies for the included papers

2 INTEGRATED REHABILITATION MANAGEMENT

> They tried to make me go to rehab, but I said no, no, no.
>
> Amy Winehouse

2.1 LEGAL BASIS AND TECHNICAL STANDARDS

The legal basis for the rehabilitation and adaptation of the urban water network has already been explained in detail for Austria by Weber and Obermeier (2012) in general, by Ertl (2007) for the sewer system in Austria and by Ochs (2012) and Wolf (2006) for the wastewater system in Germany. Gangl (2008) and Friedl (2014) made a good compendium for the water distribution network. Krainz (2003) shows the international guidelines, which apply for Austria. For the United States, this information can be obtained at the Environmental Protection Agency (EPA). The main legislation is 42 U.S.C. §300f et seq. (1974), which authorises the EPA to establish minimum standards for drinking water and 33 U.S.C. §1251 et seq. (1972), which regulates discharges of pollutants into surface waters and the quality standards of said waters. Therefore this part of the Thesis is confined to a small overview of the most important standards and laws for both networks with the focus on the region of Tyrol in Austria and to the definition of the most important terms and concepts.

Legal basis and technical standards with a focus on Austria.

2.1.1 Water distribution system

The main legal basis for water supply is the Austrian Water Rights Act (BGBl. I Nr. 54, 2014), which implements the European Water Framework Directive 2000/60/EC (2000) into Austrian legislation. It governs the rules for licensing, operating and the construction of water supply facilities. In Austria all facilities need, with very few exceptions (e.g. home use of private water), a license from the local water authorities. Furthermore, it provides extensive protection measures by stating the public interest in water supply and defining protective regulations so as to avoid the pollution of water bodies. Moreover, it includes regulations defining the operators responsibility for monitoring and maintaining their facilities. Monitoring means having the facility technically and hygienically tested by external experts every 5 years, if no shorter period is dictated by local authorities. BGBl. II Nr. 359 (2012) commits the operator to building the facilities using state-of-the-art techniques, maintain the functionality of the system and avoiding negative influences on the water quality. The necessary quality is also defined by BGBl. II Nr. 359 (2012), based on the claim of BGBl. II Nr. 88 (2015) that drinking water is regarded as food. In all regions of Austria regional legislation concerning the public water supply exists, except for the region of Tyrol. So all water pricing, which in Austria is the responsibility of the municipalities, can be considered as payment under private law (Weber and Obermeier, 2012). The state-of-the-art techniques are defined by standards (e.g. European standards) and guidelines (as complementary material), which are issued in Austria by the Austrian Association for Gas and Water. For the rehabilitation management EN 805 (2000) and ÖNORM B 2538 (2002) define the requirements that have to be met by newly constructed and rehabilitated pipes. ÖVGW W 100 (2007) defines rehabilitation as all measures to restore the full functionality of existing facilities or expand their remaining useful life, including replacement, renovation and cleaning. The differences between rehabilitation strategy, planning and measures are described in ÖVGW W 100 (2007). This is solely dependent on the time scale necessary. While a rehabilitation strategy focuses on a longer period, rehabilitation planning has a shorter decision horizon and rehabilitation measures are decided on short notice. Repairs are not included, due to the necessity of keeping the downtime of water supply as low as possible. Therefore rehabilitation measures can still be planned in the longer term, while repairs have to be managed immediately after occurring. Three rehabilitation strategies are therefore defined by ÖVGW W 100 (2007):

- Failure driven rehabilitation - e.g. Reacting on occurring failures;
- Preventive rehabilitation - e.g. using fixed time intervals;
- Condition driven rehabilitation - e.g. comparison of an actual observed condition to a an aspired one.

To this present day the failure driven rehabilitation strategy is the most widely used in Austria (Friedl, 2014). Other important guidelines include ÖVGW W 63 (2009), which deals with water losses and the estimation of indicators for leakage, ÖVGW W 62 (2013), which is a guideline for water pricing, and ÖVGW W 105 (2011), which structures the form and use of failure statistics.

For the entire urban water infrastructure in terms of financing of rehabilitation and adaptation works the most important law is BGBl. I Nr. 51 (2015) and the associated guidelines for project funding.

2.1.2 Sewer and drainage system

Sewer and drainage systems are also subject to the Austrian Water Rights Act (BGBl. I Nr. 54, 2014). It defines waste water as water whose qualities are changed by usage in a way that can affect and damage natural water bodies. The main focus is hereby on the water quality of natural water bodies and its preservation. Although it regulates the discharge into the water bodies as well as into the sewer system, the permitted concentrations of pollutants is specified by delegated legislation ordinances (BGBl. Nr. 186, 1996). BGBl. Nr. 186 (1996) also defines which water can be fed into combined and separated sewer systems. For certain dischargers specific ordinances exist, for example for municipal wastewater (BGBl. Nr. 186, 1996) or landfill leachates (BGBl. II Nr. 103, 2005) or for indirect dischargers, who are dischargers into the sewer system of another operator (BGBl. I Nr. 54, 2014) with wastewater that differs more than marginally from household wastewater (BGBl. II Nr. 523, 2006).
Transportation and the necessary pipe networks are subject of regional legislation, in Tyrol LGBl. Nr.130 (2013), although an obligation for maintenance of the system exists in BGBl. I Nr. 54 (2014). LGBl. Nr.130 (2013) defines the obligation of the municipalities to construct, operate and maintain a sewer and drainage network and the obligation to connect to this system (and the exceptions from this obligation).
The state-of-the-art of techniques is defined by standards (e.g. European standards) and guidelines (as complementary material), which are issued in Austria by the Austrian Water and Waste Management Association. Rehabilitation is defined by EN 752 (2008) as measures for restoring or upgrading the performance of existing drain and sewer systems. The assessment of the performance concerns four categories:

- Hydraulic;
- Environmental;
- Structural;
- Operational.

This assessment is elaborated by the guideline ÖWAV-RB 22 (2015). For hydraulic performance simulation models are defined as a state-of-the-art method for proving flood protection (ÖWAV-RB 11, 2009) and receiving water quality protection (ÖWAV-RB 19, 2007). For the environmental assessment the tightness of the pipe network (especially in ground water) is essential. ÖWAV-RB 22 (2015) implements an optical assessment of tightness if no ground water is affected. In the other case a leakage test, as defined in EN 1610 (1998) and ÖNORM B 2503 (2009), is compulsory. The environmental effects on receiving water bodies are covered by ÖWAV-RB 19 (2007) for combined and ÖWAV-RB 35 (2003) for rainwater. The structural and operational assessment of the drainage and sewer system is elaborated in ÖWAV-RB 43 (2013). The coding of this visual inspection is regulated by EN 13508-2 (2011). For this coding different assessment and classification methods are currently in use. The two most common are: ISYBAU (Arbeitshilfen Abwasser 2004/242/D, 2012) and DWA-M 149-3 (2007). Trenchless rehabilitation methods, in contrast to open cut, are described in ÖWAV-RB 28 (2007) for main sewers and in ÖWAV-RB 42 (2011) for lateral house connections. ÖWAV-RB 22 (2015) also mentions the three previously mentioned rehabilitation strategies corresponding to those in ÖVGW W 100 (2007). Of particular importantanve is the differentiation between condition (or necessity) driven and preventive strategy. If the first one is not applied, inspection intervals for the latter are defined (e.g. for sewers 10 years).

2.2 THE IDEA OF INTEGRATED REHABILITATION MANAGEMENT

The idea of integrated rehabilitation management is simple: Instead of examining all public networks separately (all of them in an integrated way implementing all available influences), which are intertwined in our street networks, the road network is considered a container for all together and is used for prioritisation.

Instead of examining all public networks separately, the road network is considered a container for all together and is used for prioritisation.

To illustrate the idea, we will take a look at the urban infrastructure, that can be found in a street section and its expected service life (see table 1).

If we assume that all of them reach at least the lower threshold we can start to search for times, where coordinated rehabilitation could take place (see figure 2). If we furthermore assume that the lower threshold is the end of the economic depreciation and the higher threshold the end of the technical design life, we can define the period in between as the aim for the optimal rehabilitation time. Of course the optimal time should be nearer to the technical design life to obtain the maximum economic value from the system. A linear function

Table 1: Expected service life taken from LAWA (2005)

Network	Service life
Road	15 - 30
Electric/Telecommunication (ET)	30 - 40
Gas supply	40 - 60
District heating (DH)	40 - 60
Water supply (WS)	40 - 60
Sewer and urban drainage network (UD)	50 - 100

is applied to the time between the thresholds, ranging from 0 to 100, illustrating this assumption. For optimisation we therefore use:

$$\max \frac{\sum_{i=1}^{N} R_i(t = t_R)}{n_R}$$

where R_i represents value of the linear function at the time of the rehabilitation of that certain network N and n_R the total number of construction periods over the whole observation time.
If we examine each system separately the optimum for rehabilitation is the end of the technical design life (see figure 2 - the upper left graph). As such, for the 6 networks of the street section and an observation time of 100 years, we would need 6 construction periods. The following periods of the networks with shorter life expectancies (Road network and electric and telecommunication cables) of course depend on the first decision when to replace them. Therefore different scenarios are possible. If we exploit the full technical design life of the road network, while always replacing the telecommunication and electric cables at the same time, we can reduce the necessary construction periods to 3 (see figure 2 - the upper right graph). If we do not want to replace the cables that early we would need 4 (see figure 2 - the lower left graph). The optimal solution for this example under the assumptions taken can be seen at the lower right graph of figure 2. Of course this very simplified example does not fully represent the complexity of real systems but it does give a good reflection of the idea of integrated rehabilitation management. By maximising the service life of all network while minimising the necessary disturbances it strives to optimise the overall performance of rehabilitation works in urban infrastructure.

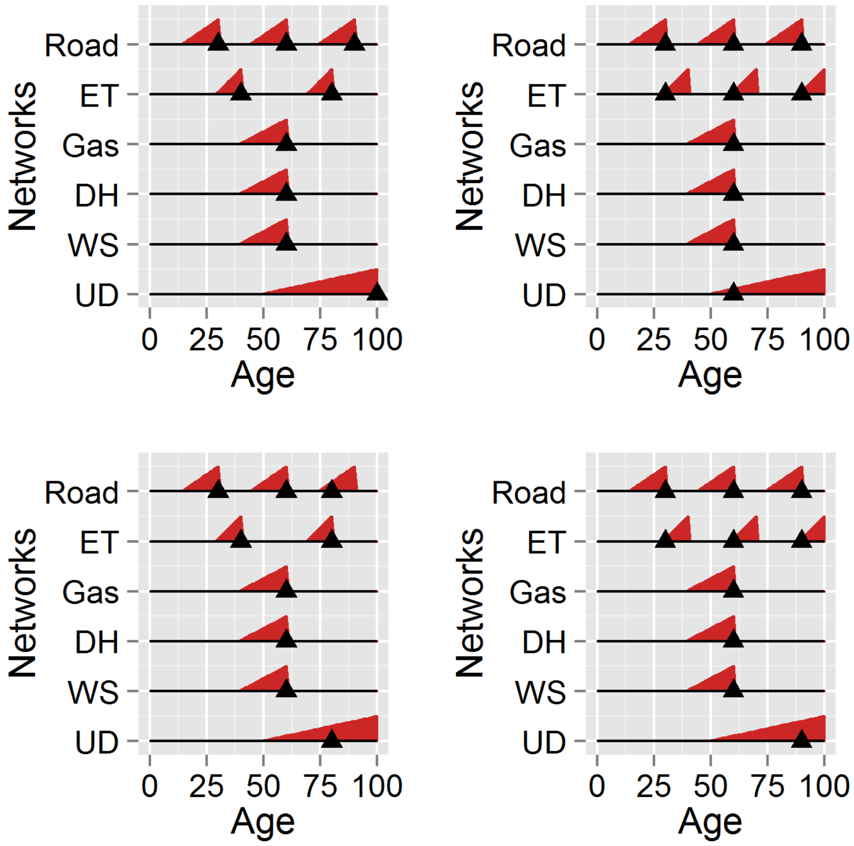

Figure 2: Possibilities for coordinated rehabilitation for the networks of table 1: optimum for each network separately (upper left graph), exploitation of the full technical design life of the road network, while replacing the telecommunication and electric cables always at the same time (upper right graph), optimum for electric and telecommunication networks (lower left graph), global optimum for this example (lower right graph)

For real systems the influencing factors multiply and further infrastructure interdependencies have to be taken into account.

For real systems the influencing factors multiply. The street sections which are chosen as a subdivision of an unitary urban body (Di Sivo and Ladiana, 2011), contain almost all (nearly 80% following Mair et al. (2012)) underground infrastructure but not entirely. Further infrastructure interdependencies have to be taken into account. Rinaldi et al. (2001) define four types of these interdependencies:

- Physical Interdependency: This means that one infrastructure depends on the output of the other and in consequence a failure in one infrastructure has effects on the other. For example a failure of the electricity network can have effects on the functionality of groundwater pumping stations and therefore on the water supply system itself.

- Cyber Interdependency: This means one infrastructure depends on the information output of another. Examples of this are SCADA systems that control high water pumping stations or penstocks.
- Geographic Interdependency: This interdependency is caused by geographic proximity. An event in one network can have effects on another. The proximity for geographic interdependency is not fixed and depends on the event, for example a gas explosion can have an effect over a wider area than a flooding sewer. This interdependency is important for rehabilitation management in terms of the effects of construction sites on neighbouring infrastructure as well as possible failure mechanisms caused by other infrastructures (e.g. stray currents from tram and railway causing corrosion of metal pipes).
- Logical Interdependency: These are interdependencies which are not caused by one of the afore mentioned mechanisms but rather by socio-economic effects. Human decisions may play the predominant role in logical interdependencies in particular. For example a public campaign to promote water saving could lead to problems in a combined sewer system due to less dry weather flow and therefore less tractive force in the sewer and higher sedimentation and sulfide formation.

Another difference to an existing system of infrastructure networks is of course the possibility of sudden failure occurrence before reaching any of the above-mentioned thresholds. It is also possible to expand the technical design life by renovation and repair methods. These techniques and methods offer further possibilities in optimisation. Furthermore, the determination of the mentioned thresholds can be difficult, depending on the available data. Especially when integrating several different networks a loss of information can occur, depending on the amount of information available. A difference in data quality between the networks can also cause problems, due to the fact that they can influence the outcome of the models drastically. A certain compensation effect between different networks can also occur when thresholds and weights are not carefully chosen and observed. Additionally, the economic profitability may not be the same for all the networks and although the infrastructure is often public property the distribution of the savings can be difficult. Kleiner et al. (2010) estimated these savings to be around 20% for water supply networks when coordinated with road networks, while Burger and Hochedlinger (2008) suggests that even 25% could be saved. Calculations from one of our case studies, using a standard cross section with the specifications of LB-SW05 (2005), Land Tirol (2014) and ÖNORM

B 2533 (2004) (see figure 3), showed overall average savings of 15.6% could be estimated. These savings however should not only include the reduced costs for excavation and resurfacing works but also the additional costs for the society by provoking time delays and detours, as quantified by Gangl (2008).

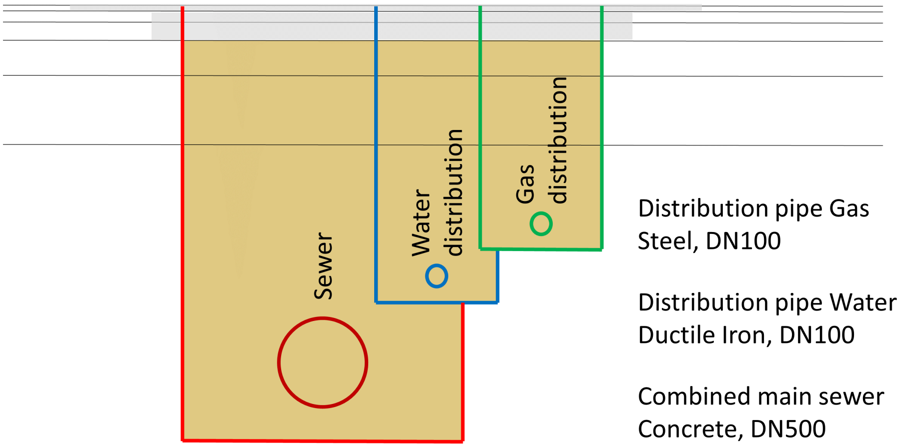

Figure 3: Standard cross section for sewer, water supply and gas supply

An integrated multi-utility approach is still seldom used. The state-of-the-art projects in rehabilitation decision making focus mainly on one network alone:

- CARE-S on sewer and storm water networks (Sægrov, 2006; Sægrov and Schilling, 2002);
- CARE-W on water distribution networks (Sægrov, 2005);
- Approaches using multi-objective genetic algorithm optimisation models for rehabilitation of either sewers (Berardi et al., 2009; Halfawy et al., 2008; Ward and Savić, 2012) or water mains (Dandy and Engelhardt, 2006; Giustolisi et al., 2006).

The approach of the project AWARE-P (Alegre and Coelho, 2012; Carriço et al., 2012) can be used for an integrated approach, however mainly on a strategic level. The approach of Nafi and Kleiner (2010) and Kleiner et al. (2010) focuses mainly on water distribution networks, implementing other infrastructure mainly as source of cost savings due to coordination. Carey and Lueke (2013) considered three infrastructure networks (roads, sewers and water distribution) but focused mainly on the economic outcome and monetary savings. Another shortcoming is the usage of randomly generated conditions of the networks and not real existing ones. Marzouk and Osama, 2015 applied a fuzzy approach for optimum replacement time of different infrastructure networks (roads, sewers, water, gas and electric cables) but did not show the applicability on real data, instead using a hypothetical numerical example. Also the geographical component was not shown. Osman (2015) presents a temporal coordination algorithm applying it for the road, sewer and water distribution network of a real world case study. The comparison between the results of this method and a partially or uncoordinated project for rehabilitation is not shown however. This thesis and especially PAPER I and PAPER II want to add further input to this promising approach by providing an outlook on the possibilities for asset management.

An integrated multi-utility approach is still seldom used.

3 DATA MANAGEMENT

You can have data without information, but you cannot have information without data.

Daniel Keys Moran

3.1 DATA FOR REHABILITATION MANAGEMENT

Reliable data are the foundation of every successful rehabilitation and asset management approach (Alegre and Coelho, 2012). Especially for the implementation of deterioration and decision support models, because the outcome of these models depends on the quality of the input or in other words - you cannot implement what you don't know. PAPER V defines the optimal data set for an integrated approach including three pipe networks (sewer, water, gas) and the adjacent infrastructure (roads, public transport,...). One important piece of data, that should be highlighted, is the recording of construction sites. All rehabilitation works of the considered networks should be of course recorded and saved (and localised), but also other construction sites as well. This could be important due to the geographical interdependency (Rinaldi et al., 2001) - the possible effects on the surrounding networks. This optimal data set can be subdivided into three data types (Tscheikner-Gratl et al., 2015b):

Reliable data are the foundation of every successful rehabilitation and asset management approach.

- Network data: These include all of the physical properties (material, diameter, construction year) of the examined networks and the connected structures (e.g. manholes, pumping stations). For sewers and water distribution networks these properties are shown in the Austrian guideline ÖWAV-RB 40 (2010).

- Condition data: These are derived for sewers mainly from condition assessment (Arbeitshilfen Abwasser 2004/242/D, 2012; DWA-M 149-3, 2007) of visual inspection data (ÖWAV-RB 43, 2013), although this assessment is flawed with uncertainties (Dirksen et al., 2013). For water supply networks internal optical inspections are difficult to apply. Other inspection techniques (an overview is given by Marlow et al. (2007)) are available, but expensive. An often applied strategy is the estimation of a daily consumption statistics and if irregularities appear searches for failures by acoustic measures are carried out. A thorough failure recording with the exact localisation is an extremely useful piece of information for risk assessment and deterioration modeling if it includes all of the relevant information as defined in ÖVGW W 100 (2007) and DVGW W 402 (2010).

- Data of surrounding influences: These data summarise all the information, which are not part of the examined networks but can have a massive influence on them. This includes urban development, soil properties, ground water levels and so on.

- Model data: Models derive from the other data types and measurements for validation and calibration. They produce output data as well as they are data themselves. Examples are the hydrodynamic models for sewers, which are used for proving flood protection (ÖWAV-RB 11, 2009) and receiving water quality protection (ÖWAV-RB 19, 2007). Furthermore, they can be used for vulnerability assessment (Möderl, 2009; Möderl et al., 2009) and hydraulic condition assessment (ÖWAV-RB 22, 2015; Wolf et al., 2005). The same is true for the water distribution networks, where models can be used for the hydraulic assessment of the network (ÖVGW W 100, 2007; ÖVGW W 63, 2009) as well as vulnerability (Friedl et al., 2012; Fuchs-Hanusch et al., 2015; Möderl, 2009; Möderl et al., 2009).

Another approach to classifying data (more driven by an GIS background) for integrated management is offered by Di Sivo and Ladiana (2011):

- Network structures: It includes all network shaped infrastructures such as sewers, roads, railways and similar.

- Widespread structures: It consists of all those widespread elements over the town territory that have a relevant impact on the town image and its functioning.

- Punctual structures: It consists of structures whose malfunctioning do not generate negative effects on other subsystems.

The optimum data demand is often not available. Therefore a minimum data demand is defined for further deterioration modeling and decision making. This data has to be included as attributes of a GIS-system with geographical information. For the water distribution network this was first the identification attributes for the pipe, valve and street section and if available for the house connections. Moreover, the pipe qualities are necessary including pipe type (house connection, distribution pipe, etc.), material, diameter, pressure (preferably from a hydraulic model or else maximum values) and pipe length (can also be calculated from the GIS data). Additionally, the construction year of the pipe is necessary. For every pipe section the information about the failures that have occurred on that section also have to be recorded (from $1 - n$ where n is the maximum sum of the occurred failures on one pipe section). The failures need a unique ID for connecting them with further information. The most important information is of course the year the failure occurs. If this year dates before or the same year as the construction year a replacement of the pipe has to be assumed. If this is the case (which has to be checked) also the diameter, material and construction year of the replaced pipe has to be recorded.

For the sewer system the same information was defined. The first part is again the ID to uniquely define the pipe section as well as to connect it to a manhole section and a street section and if the data is available to a house connection. Then, the data about the pipe properties are needed. First the pipe type (house connection, main sewer, etc.) and the sewer type (combined, stormwater, sewage) and then Material, diameter, shape and the construction year. The pipe length can also be calculated from the GIS data although the possibility of underestimation cannot be ruled out this way. To enable a deterioration model the data of an inspection is necessary, at least a condition state and the year of inspection.

The optimum data demand is often not available, therefore a minimum data demand is defined for deterioration modeling and decision making.

3.2 CASE STUDIES AND DATA QUALITY

For this thesis the above mentioned data was partly available from three case studies, which were also used in the publications. Following the wish of the operating companies all of the data are anonymised. For the three case studies of different size different types of data were available (see table 2).

In case study 1 data about the water distribution network (with the exception of a small area) and the urban drainage system (mainly combined sewer) was available. However, this was without the data about the house connections for the water distribution network and a little for the sewer system (535 house connections were available of an estimated 12,366). Case study 2 had the data for all of the house connections but this data was only about the water distribution network and case study 3 included data for three networks. Failure recordings started very early in case study 1 (1976) and quite late in case study

Case study 1 - sewer and water distribution. Case study 2 - water distribution. Case study 3 - sewer, gas and water distribution.

3 (2002). The visual inspection of the sewers in case study 1 was quite extensive while in case study 3 less than half of the network was inspected. The data were of varying quality. Missing data was reconstructed using the methodology shown in PAPER VI.

Table 2: Information about the case studies

Data		Case study 1	Case study 2	Case study 3
Population (2013)		124,386	96,531	12,855
WD	Network length [km]	225.98	851.27	192.08
WD	House connections	-	17,263	3,665
WD	Failure records since	1976	1983	2002
UD	Network length [km]	253.50	-	92.29
UD	House connections	-	-	-
UD	Network inspected [%]	72.43	-	46.22
GD	Network length [km]	-	-	134.24
GD	House connections	-	-	3,093
GD	Failure records since	-	-	2002

WD...Water distribution, UD...Urban drainage, GD...Gas distribution

3.2.1 Case study 1

Water distribution network data

The available network information consists of a main trunk loop and attached water mains but no house connections and have a total length of 225.98km. Of the total network the information about the following qualities were available in the original data:

- 84.96% of the construction years (figure 4),
- 99.02% of the pipe materials,
- 99.98% of the pipe diameters.

Therefore a reconstruction of the data (especially construction years) was necessary to enable further modeling. Using the methodology in PAPER VI the gaps could be filled. The original data of the construction period of the network (figure 4) shows that mainly the short hydrant pipes had no construction year. After reconstruction we see that the construction year distribution corresponds with the historical growth of the network (PAPER VIII).

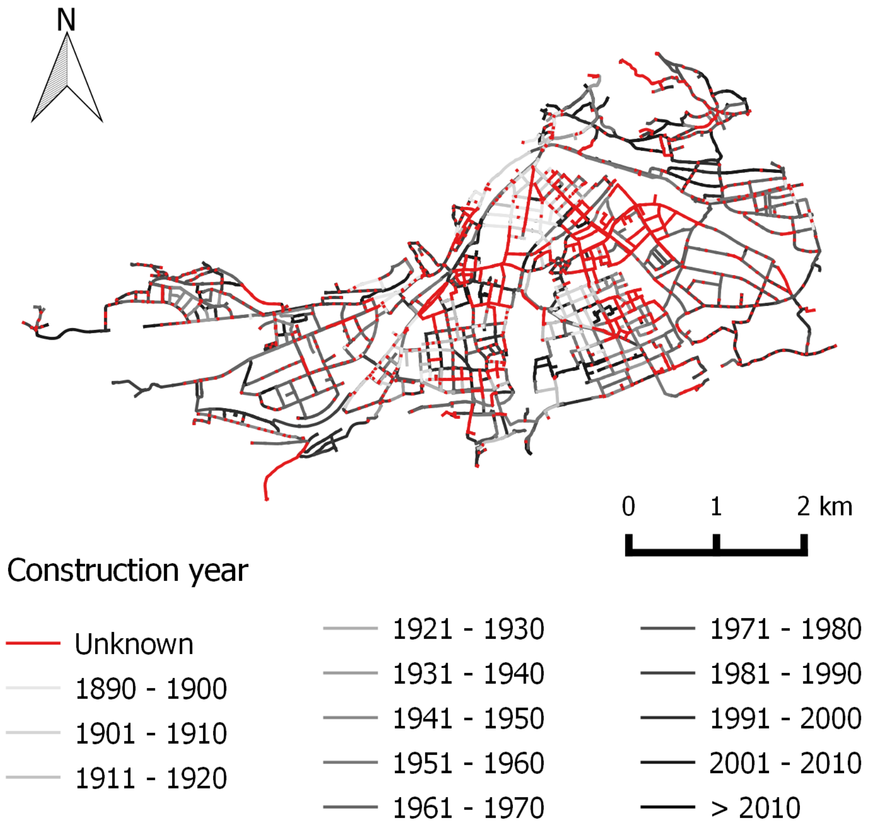

Figure 4: Construction years of the water distribution network of case study 1 before reconstruction

Table 3 shows the lengths and percentages of the network for the construction periods before and after reconstruction. It shows one of the advantages of the method in comparison to simple extrapolation: it can not only reconstruct the pipe length for every construction year and material but also reconstruct the geographic information for each individual pipe of the network (compare Figure 4 with Figure 5). Furthermore, the extrapolation tends to generate more data from newer pipes - simply because there is more information available. This possible error in the data is avoided as the comparison (table 3) shows that the older periods are more represented in our reconstructed data than in the extrapolation.
If we examine the pipe diameters (figure 6), the water main trunk loop with a higher diameter (>400mm) is the most visible structure. The rest of the network consists of pipes mainly with a diameter between 100 and 300mm (figure 7).

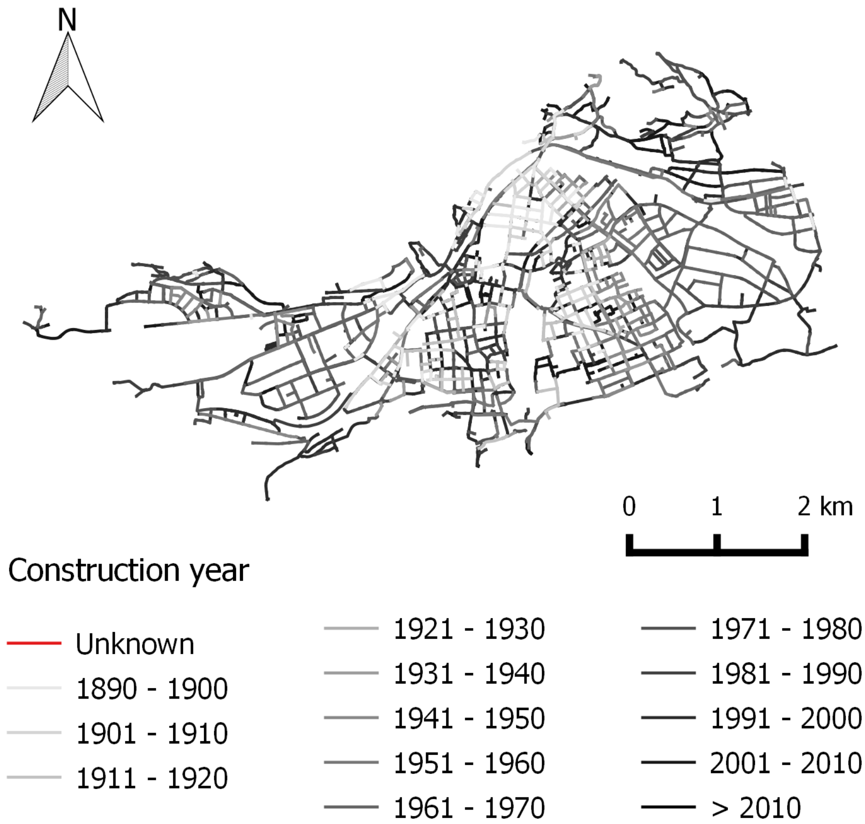

Figure 5: Construction years of the water distribution network of case study 1 after reconstruction

Figure 6: Pipe diameter for the water distribution network of case study 1

Table 3: Comparison construction period for the water distribution network in case study 1 between the original data and the reconstructed data

Construction period	Original data Length [m]	Original data Percentage [%]	Reconstructed data Length [m]	Reconstructed data Percentage [%]
1890 - 1900	7,648.71	3.38	9,121.05	4.04
1901 - 1910	8,298.42	3.67	9,876.53	4.37
1911 - 1920	6,056.09	2.68	7,118.56	3.15
1921 - 1930	1,680.73	0.74	2,775.44	1.23
1931 - 1940	5,245.44	2.32	6,419.31	2.84
1941 - 1950	7,310.59	3.24	8,638.41	3.82
1951 - 1960	22,830.21	10.10	28,890.98	12,78
1961 - 1970	34,751.12	15.38	40,685.59	18.00
1971 - 1980	22,545.74	9.98	26,143.56	11.57
1981 - 1990	23,016.25	10.19	25,597.29	11.33
1991 - 2000	29,958.02	13.26	34,668.61	15.34
2001 - 2010	22,648.92	10.02	26,047.07	11.53
2011 - 2014	0.00	0.00	0.00	0.00
Unknown	33,992.17	15.04	0.00	0.00
Total	225,982.40	100.00	225,982.40	100.00

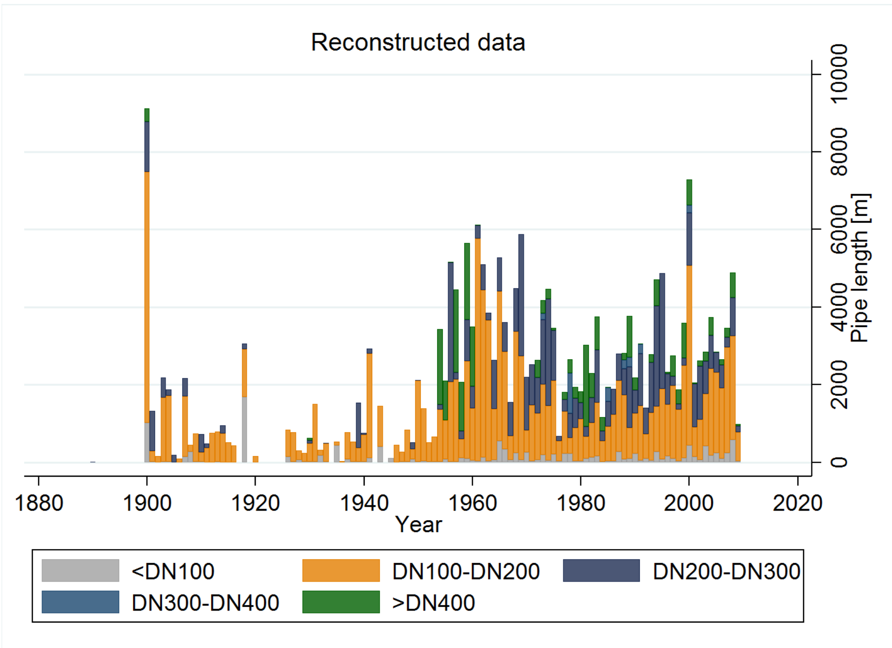

Figure 7: Pipe length partitioned by construction year and pipe diameter for the water distribution network of case study 1

The network consists mainly of cast (CI) and ductile iron (DI) pipes and only smaller amount of steel (ST) and Polyethylene (PE) (see figure 8 and 9).

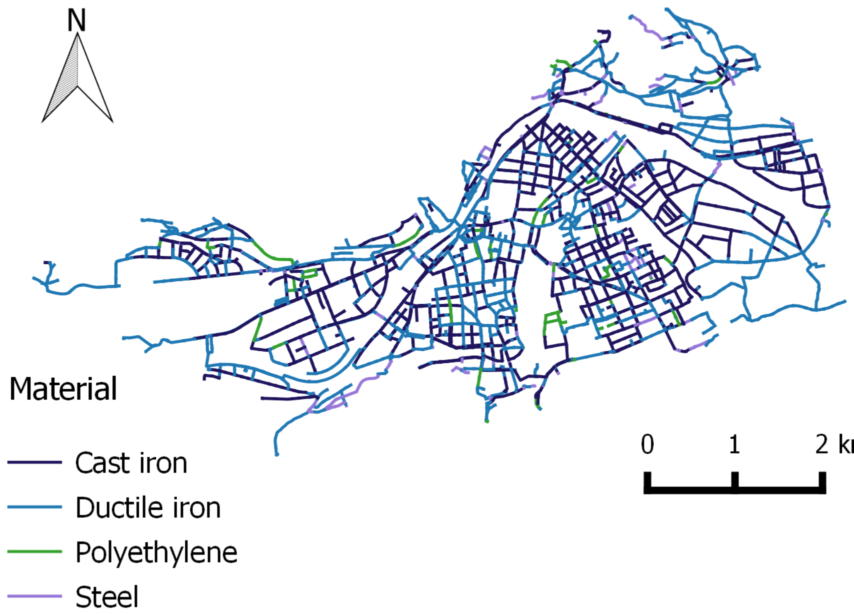

Figure 8: Pipe material for the water distribution network of case study 1

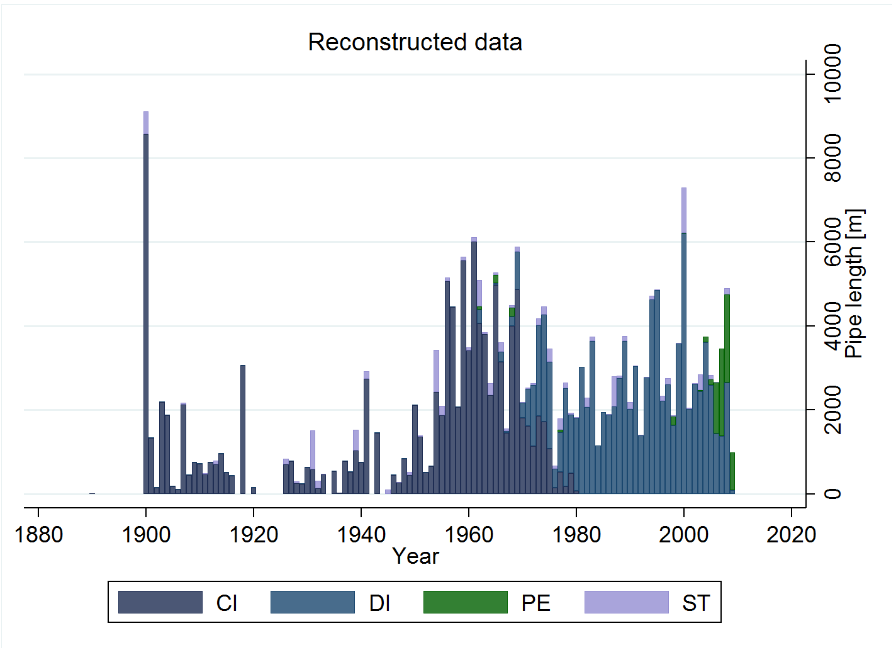

Figure 9: Pipe length partitioned by construction year and pipe material for the water distribution network of case study 1

The main change between original and reconstructed data (see table 4) is caused by the plausibility check (e.g. material and construction year) between cast and ductile iron pipes because only 0.98% were not known. Cast and ductile iron were used for all diameters of the network, while PE-pipes can only be observed for diameters up to 200mm and steel pipes up to 300mm. The average age of the network results from a length weighted estimation in 46.03 years.

Table 4: Comparison of material distribution in the water supply network of case study 1 between original data and reconstructed data

Pipe material	Original data		Reconstructed data	
	Length [m]	Percentage [%]	Length [m]	Percentage [%]
Cast iron	120,890.80	53.49	113,696.20	50.31
Ductile iron	84,646.18	37.46	94,041.50	41.61
PE	7,582.38	3.36	7,358.65	3.26
Steel	10,640.77	4.71	10,886.05	4.82
Unknown	2,222.27	0.98	0.00	0.00
Total	225,982.40	100.00	225,982.40	100.00

Water distribution failure recordings

The failure recordings (which were provided by the operating company) for this case study start in 1976 and last until 2013 and like the network data it only consists of data about distribution pipes and not about house connections. The data is in a very good condition, including the minimal conditions requirements of ÖWAV-RB 40 (2010), except for the fact that no construction years of the affected pipes were recorded. For 640 of the 795 recorded failures a failure cause is available. 72.03% of the failures were caused by soil settlement (unfortunately no reason for this settlement was recorded), 18.13% by corrosion of metal pipes and 9.84% were caused by a third party. Most failures were recorded for cast iron pipes, due to its big share of the total network and its high average pipe age. The failures here are mainly caused by ground settlement. For ductile iron pipes the three causes are nearly of the same importance and for the steel pipes the main failure cause is corrosion.
The reconstruction of the failure records was hampered by the fact that not all of network data was available and therefore only 643 of the 795 failures could be reconstructed. For this data with the available network data the failure rate following ÖVGW W 100 (2007) was estimated (figure 10). The average failure rate of 9.26 failures per 100km and year for distribution pipes is only a little higher than the low failure rate from the guidlines (7 according to ÖVGW W 100 (2007)). A high failure rate was not approached in any observed year.

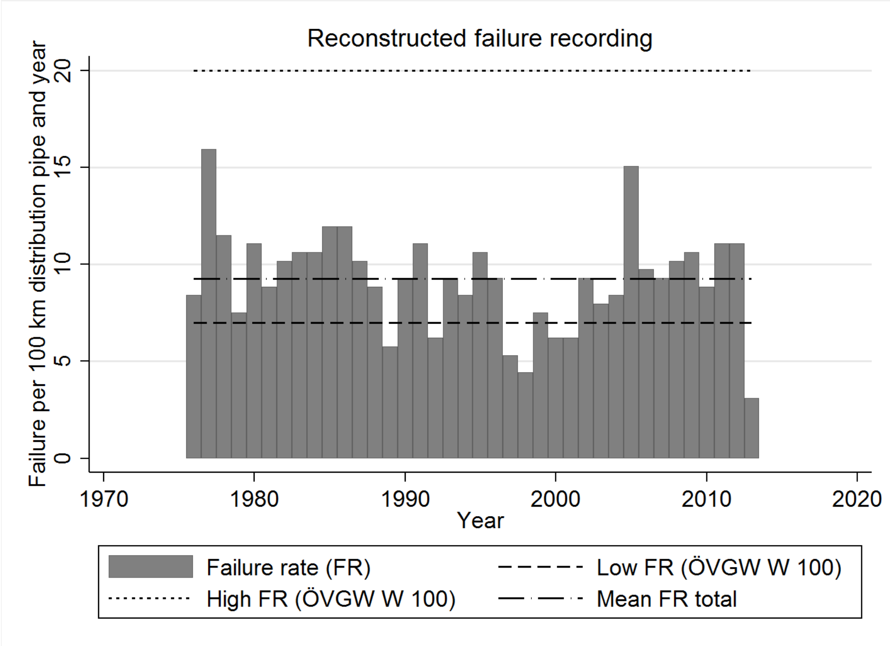

Figure 10: Failure rates for the water distribution network of case study 1

Figure 11 shows the frequency of failures depending on the age of the affected pipe. The distribution is similar to the one found by Gangl (2008) showing an decrease of pipe failures until 5 years and then increasing in numbers. The mean value of 46.14 years and the standard deviation of 27.65 is a little lower however. These early failures were mainly caused by third party influence or soil movement, which indicates construction errors. A classification of the failures by material shows that most of the failures occurred on cast iron pipes, which is not surprising given the fact that they form the oldest and largest partition. An estimation of a failure rate over the entire observation period of 38 years, assuming the current material distribution in pipe lengths as constant over time, shows however that the steel pipes with 5.33 failures/km are more vulnerable than cast iron pipes (4.69 failures/km) and the other materials.

What can be observed, as it is also mentioned in PAPER V, is a certain clustering of failures in some street sections (see figure 12). Out of 473 street sections 46% had no observed failure in the observation period, 89% less than four (a threshold for subsequent failures as shown in PAPER I). This results in the fact that 50% of the observed failures occurred in only 11% of the street sections. These clusters could be used for prioritisation, for example using an algorithm to detect regions with statistically significant and with an abnormally high occurrence of breaks (de Oliveira et al., 2011).

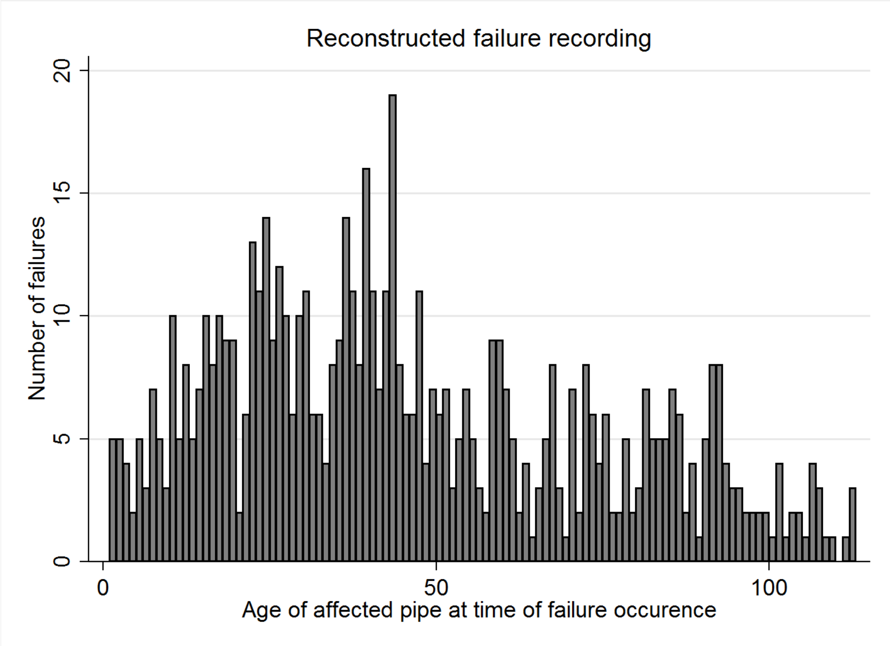

Figure 11: Number of failures depending on the affected pipe age for the water distribution network of case study 1

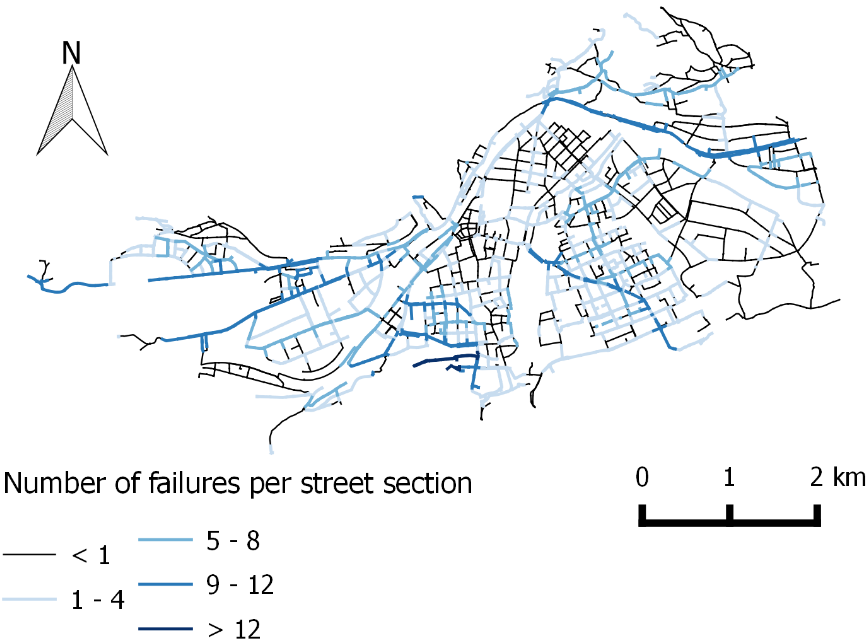

Figure 12: Clustering of failures in street sections for the water distribution network of case study 1

Urban drainage network and condition data

The case study with a total catchment area of 2076 ha (impervious area 774 ha), is drained with a gravity-driven combined sewer system with a total length of 253.50 km. Only one pumping station and some storage basins were present to reduce the combined sewer overflows at several outfalls. These data (together with missing information about sensors) was neglected due to the fact that we did not get any detailed information about condition, construction year and maintenance. Of the total network the information about the following qualities were available in the original data:

- 92.98% of the construction years (figure 13),
- 93.65% of the pipe materials,
- 96.78% of the pipe diameters.

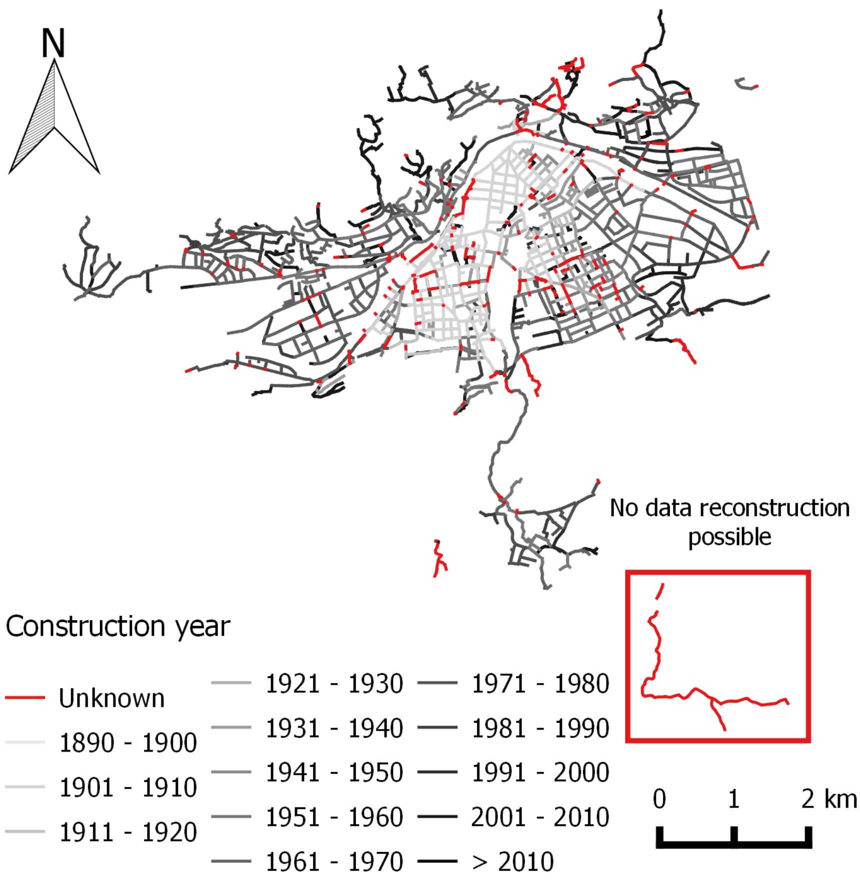

Figure 13: Construction years of the sewer network of case study 1 before reconstruction

Therefore a reconstruction of the data (especially construction years) was necessary to enable further analysis and subsequently modeling.

The original data of the construction period of the network (figure 13) shows that connection sewers at the edge of the network (mainly from the south) have no construction year. Using the methodology in PAPER VI these gaps could be filled (compare figure 14), with the exception of the highlighted area which is not connected to the rest of the network. No reconstruction was possible there due to the fact that no starting point (e.g. sewers with similar qualities at a reasonable distance) was available. Therefore the total length of the reconstructed network was diminished to 246.43km. After reconstruction we see that the construction year distribution corresponds with the historical growth of the network (PAPER VIII). Figure 14 displays that after the initial construction of the sewer system between 1900 and 1910 (14.02% of the network), the main constructions were carried out between 1950 and 1980 (46.22%). These numbers unfortunately do not include the rehabilitated sewers for each year in the past and carry therefore a certain amount of uncertainty.
Table 5 shows the differences in material before and after the reconstruction. Due to the different network length only the percentages were compared. The majority of the pipes are made out of concrete and vitrified clay, which are also the main materials after the reconstruction (see figure 15). Other materials, such as polyethylene (PE), ductile iron (DI), polypropylene (PP), polyvinylchloride (PVC) and steel are seldom used. Cast iron disappears from the reconstructed data set because they are mainly in use in the south eastern part of the network which was not reconstructed. The remaining pipes were changed due to the plausibility check (compare construction years dating to 1996 in figure 16) to ductile iron pipes. If we look at the materials of pipes built over time we can see that the main part of the pipes in all of the construction periods are made out of concrete. Older pipes are also made out of vitrified clay, whilst since 2000 a lot of polypropylene pipes are in use. The network itself is old on average (compared to the results of KPC (2013)) resulting in a length weighted average age of 53 years.

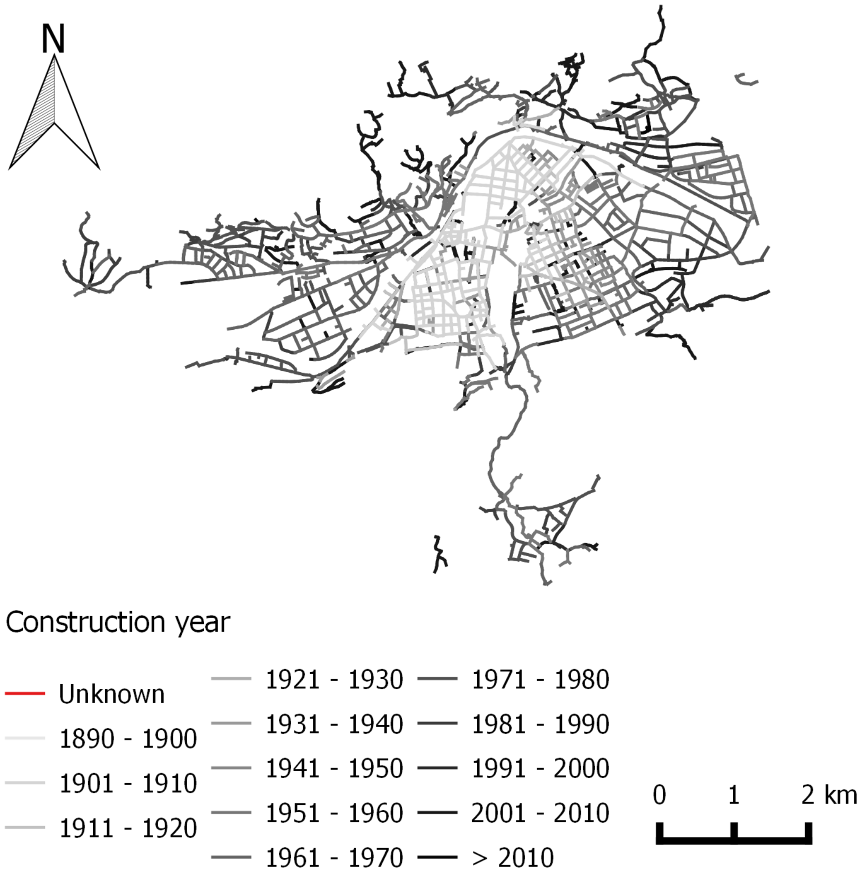

Figure 14: Construction years of the sewer network of case study 1 after reconstruction

Table 5: Comparison of the material distribution in the water supply network of case study 1 between original data and reconstructed data

Pipe material	Original data Percentage [%]	Reconstructed data Percentage [%]
Concrete	67.49	73.68
GRP	0.08	0.08
Cast Iron	1.61	0.00
Ductile Iron	0.18	0.91
PE	1.79	1.09
PP	5.98	5.78
PVC	0.52	0.68
Steel	0.22	0.32
Vitrified clay	15.72	17.46
Unknown	6.40	0.00
Total	100.00	100.00

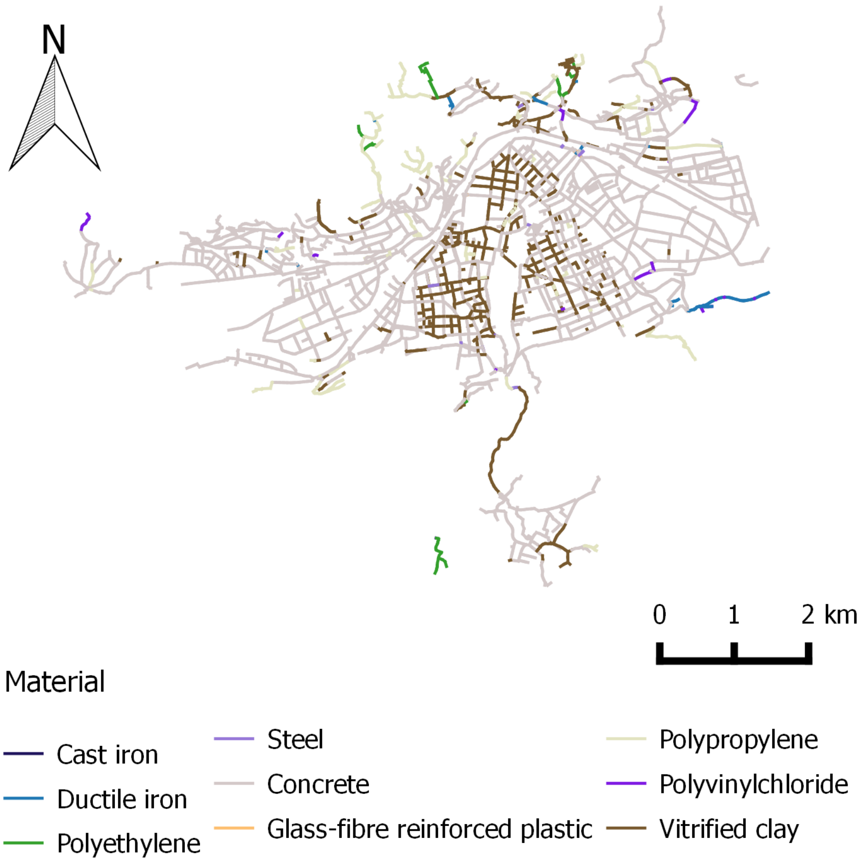

Figure 15: Pipe material for the sewer network of case study 1

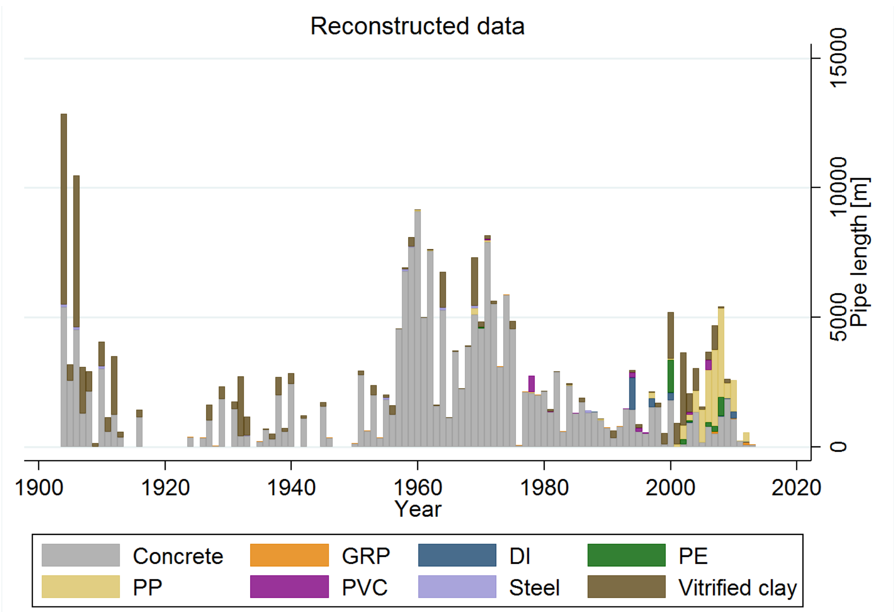

Figure 16: Pipe length partitioned by construction year and pipe material for the sewer network of case study 1

The pipe diameters for the whole network are known, also due to the existing hydrodynamic model. The main part of the network consists of pipes with a diameter between 250 and 500mm. Moreover, some collector pipes with diameters of more than 1500mm exist (figure 17). Additionally, data about the pipe shape was available. Mainly circular pipes were in use (76.62%) and to a smaller amount egg shaped pipes (19.15%). The rest of the pipes have specialised shapes. If we subdivide our network by pipe diameter and material we see that with increasing diameter it becomes more probable that the material used is concrete.
72.43% of the sewer network was inspected, mainly sewers constructed before 2000, were inspected and classified into condition states using the methodology following ISYBAU (Arbeitshilfen Abwasser 2004/242/D, 2012). Therefore the condition states range from 1 (no immediate need for action) to 5 (urgent need for action). In this case study only a small percentage is in this condition state (1.63% - compare figure 18). A reconstruction of missing condition states is not plausible and was not applied.
Another result from the data evaluation is that mainly concrete and vitrified clay pipes are in the bad condition states of 4 and 5, which can be explained by the smaller amount of other materials appearing in the network as well as the higher age of the pipes constructed with these materials. The newer PP-pipes were in quantity not inspected at all. We can also see that the higher diameters (above 1000mm) also have no condition states attached and are therefore not inspected or not classified.
What can be seen if we examine the condition states for the different construction years (figure 19) is the decrease of condition state 1 and the increase of condition states 3 and 4 over time. Nevertheless condition state 5 is also observable (and even more frequent) in sewers from 1945 to 1965 than in the oldest sewers from 1900.

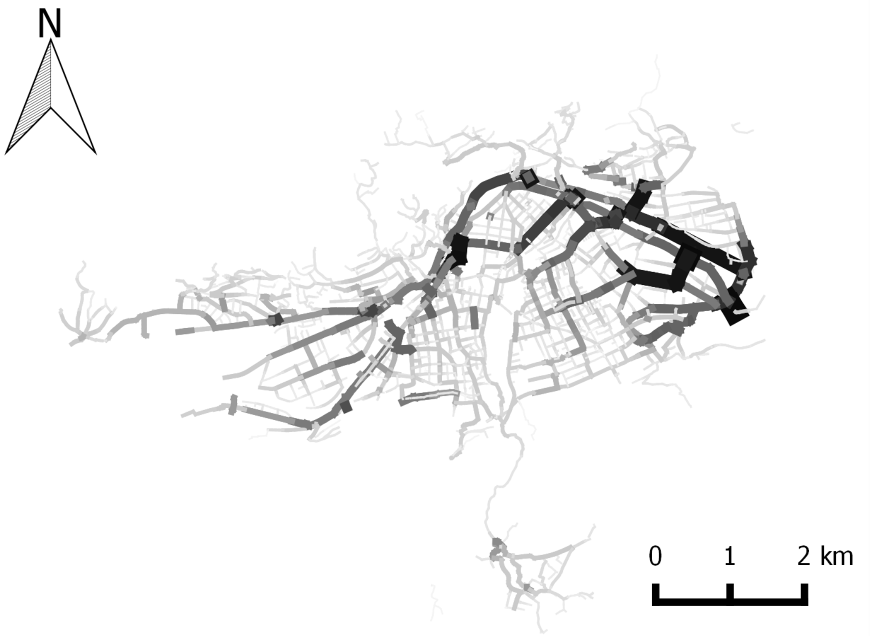

Figure 17: Pipe diameter for the sewer network of case study 1

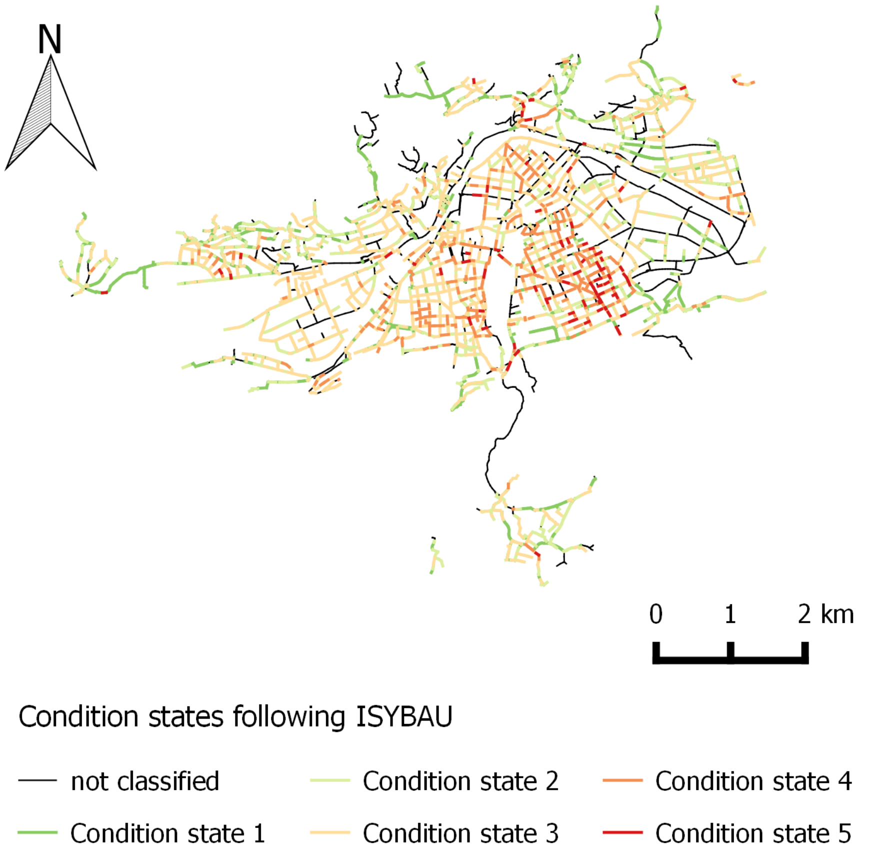

Figure 18: Condition states of the sewer network of case study 1

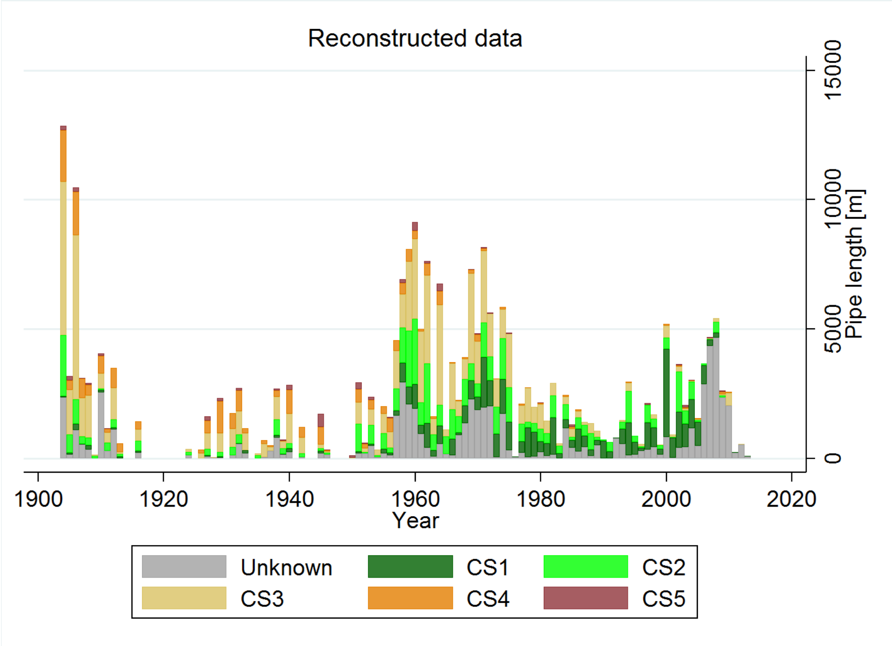

Figure 19: Pipe length partitioned by construction year and condition states of the sewer network of case study 1

If we take a closer look at the inspection data of a part of the network (665 pipes) and apply the pipe age at the inspection date we can get a snapshot of the development of failures over time. The examined conditions defined by ÖWAV-RB 43 (2013) and EN 13508-2 (2011) are the following:

- Defective connection
- Obstacles including roots, deposits and other obstacles
- Deformation: The cross-sectional shape has been deformed from its original shape
- Curvature of sewer: The route of a sewer deviates by means of a prefabricated bend or deviation that does not take place at a joint
- Surface damage: The surface has been damaged by chemical or mechanical action
- Fissure: Visible crack or fracture
- Break: pieces of pipe visibly displaced but not missing
- Defective repair
- Infiltration: The ingress of water through the wall of the pipe or through joints or defects

Overall we have 2% of breaks, 4.9% of defective connections, 23.8% of sewer curvature, 0.5% of deformation, 31.4% of fissures, 0.9% of infiltrations, 14.9% of obstacles, 0.9% of defective repairs and 20.7% of surface damages. These results (partly shown by Tscheikner-Gratl et al. (2013a)) correspond only in parts with the data from Berger and Falk (2011), which show a lot more defective connections and less fissures, sewer curvature and surface damages. However the low amount of breaks, deformation and infiltrations as well as the amount of obstacles correspond very well. These differences could be explained by the material composition. While this sample only consists of concrete and vitrified clay, Berger and Falk (2011) had a wider range of materials.

Figure 20 shows the observed conditions, divided by the length of inspected pipes to enable comparison due to the fact that much older pipes were inspected. It shows a quite linear increase over the pipe age, in comparison to the examination of the numbers only which show a nearly exponential increase. This behaviour is mainly caused by the pipe breaks, defective connections, surface damage and obstacles which show this pattern. For defective repairs the increase is much more exponential, while deformation is observed more in younger pipes than in older ones. The curvature of sewers shows a "bathtub"-like pattern with high values for young and old pipes. Fissures and infiltrations do not show a pattern at all. These time patterns however do not provide a picture in "real" time of occurrence of these conditions but only a snapshot of the conditions at the time of inspection. The failures could have occurred earlier. Of interest is the fact that in the very few young pipes (age < 10 years), that were already inspected, deformations, sewer curvature and obstacles could be observed. That indicates construction problems and would fit into the frame of 23% of failures being caused by construction (Plihal, 2013).

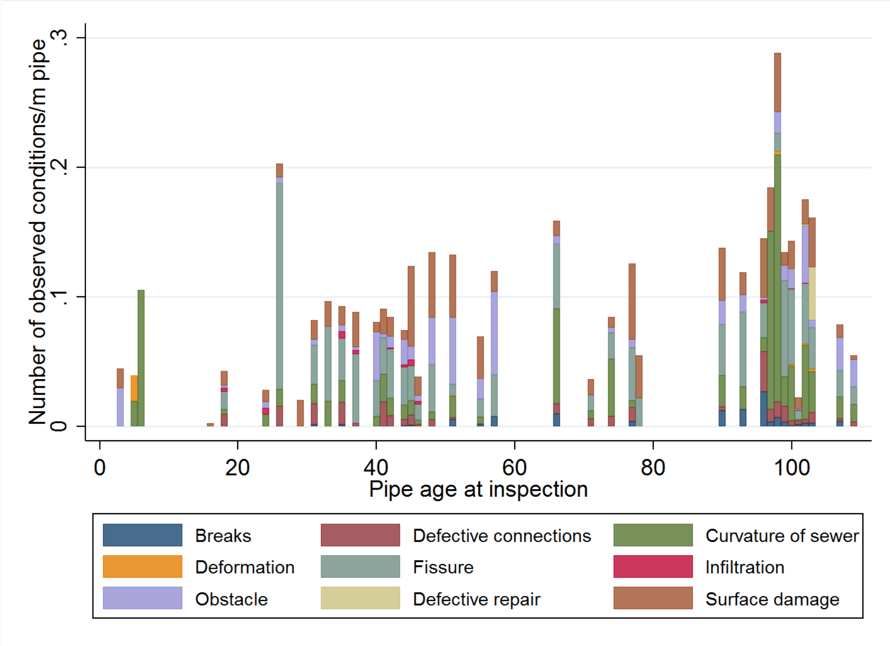

Figure 20: Condition of the sewers per inspected pipe of case study 1 observed at a certain pipe age depending on the visual inspection date

3.2.2 Case study 2

Water distribution network data

The data of the water distribution network of case study 2 was quite complete - though faulty at times. Of the overall length of 851.27km (including the house connections) data was available for:

- 91.35% of the construction years (see figure 21,
- 99.97% of the pipe material,
- 99.98% of the pipe diameter.

The first step was the plausibility check of the materials and construction years. After this the missing data was reconstructed using the method described in PAPER VI, in fact it is the case study used for this paper. Therefore only a brief overview of the data, with a focus on the ones not mentioned in the paper, is given. A problem was posed by the fact that the network was not divided using the sectioning of ÖWAV-RB 40 (2010) and in parts was not prepared for sectioning at all. Almost 10% of the network was not partitioned into street and valve sections at all so this subdivision had to be made before starting the reconstruction. Also failures in the data occurred such as wrong street section numbers and wrong or missing house connection numbers. Furthermore, house connections made out of three different materials, which is not impossible but should be remarkable. Additionally there exist pipes not connected to the network (as seen in figure 21). After the partition of the network was done the reconstruction could be carried out.

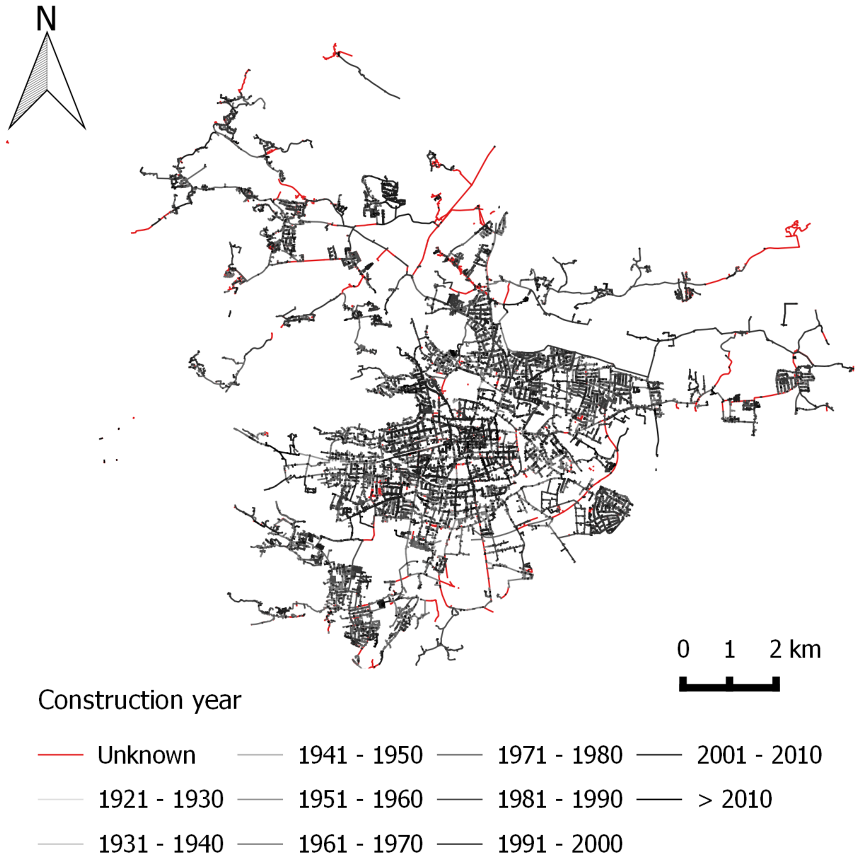

Figure 21: Construction years of the water distribution network of case study 2 before reconstruction

A total of 8.65% of the network without construction year data available (73,595m) is subdivided into 1679 pipe sections (43.83m/section), whereas 759 pipes were house connections (82.23m/section), 830 pipe sections were distribution pipes (12.69m/section), 78 pipe sections hydrant pipes (8.31m/section) and 12 pipe sections had no pipe type data. The main part of the pipes without construction year date were in the diameter range between 100mm and 200mm and had been mainly made out of polyvinylchloride (PVC), asbestos cement (AC) and cast iron (CI).
If we look at the original data of the network we see that the main part of the house connections had a diameter of 25mm although the diameters range between 15mm and 100mm. For the distribution

pipes mostly 100mm pipes are in use out of a range between 25mm and 600mm. The pipes used for connecting the hydrants diameters range from 80mm to 100mm. After the reconstruction of the missing data these ratios did not change. Finally, the result of the reconstruction for diameters can be seen in figure 22.

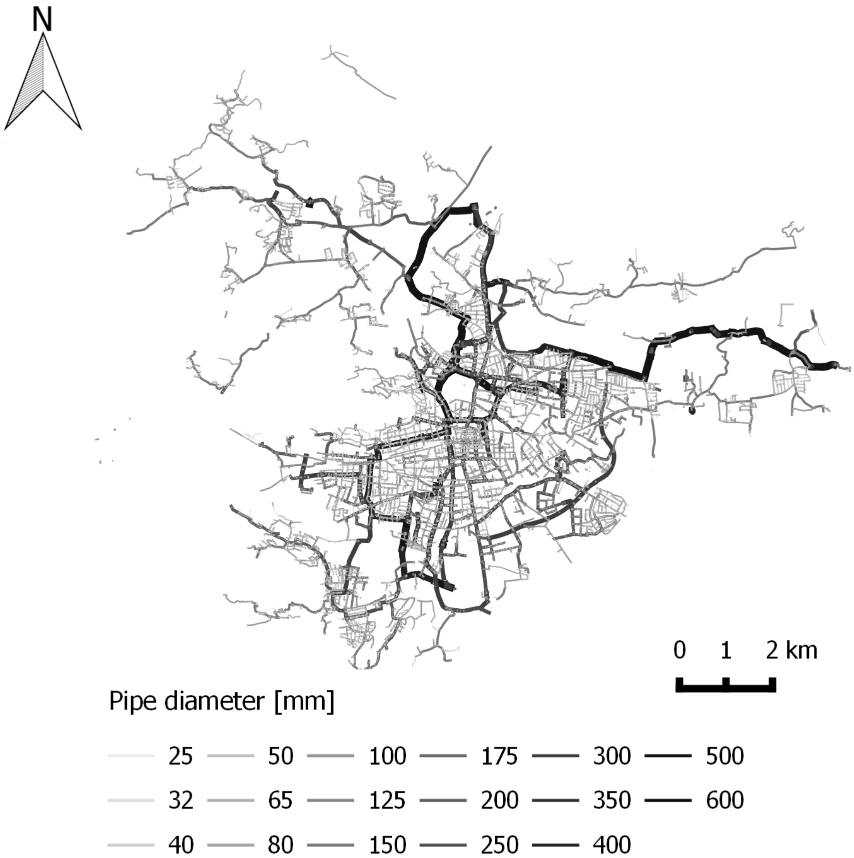

Figure 22: Pipe diameters of the water distribution network of case study 2 after reconstruction

Regarding material (for which the data was quite complete) the network consists mainly of Polyvinylchloride (PVC), Asbestos cement (AC), cast iron (CI) and ductile iron (DI) for distribution pipes and out of Polyethylene (PE) and Steel (ST) for house connections. Smaller parts of the network are made of glass-reinforced plastic (GRP), Polypropylene (PP) and also some lead pipes (Pb). Since the nineties the use of Asbestos cement pipes in construction, repair and rehabilitation is prohibited in the European Union, but to maintain existing ones is allowed (Fritsch et al., 2011). So these pipes should be replaced as early as possible. The same is true for the lead pipes whose usage is also prohibited due to the thresholds of lead in the drinking

water regulated in the drinking water regulation (BGBl. II Nr. 359, 2012).
The reconstruction changed the ratios between the materials due to the fact that mainly PVC and cast iron pipes had information about the construction year outside of the plausibility range. This explains the shift to ductile iron and PE in table 6.

Table 6: Comparison of material distribution in the water supply network of case study 2 between original data and reconstructed data

Pipe	Original data		Reconstructed data	
material	Length [m]	Percentage [%]	Length [m]	Percentage [%]
Asbestos cement	104,694.42	12.30	99,802.34	11.72
GRP	265.10	0.03	265.10	0.03
Cast iron	134,324.84	15.78	92,147.81	10.82
Ductile iron	61,945.75	7.28	109,019.90	12.81
PP	1,999.92	0.24	2001.40	0.24
PE	243,926.14	28.65	282,201.50	33.15
PVC	245,282.60	28.81	203,796.10	23.94
Lead	185.69	0.02	185.69	0.02
Steel	58,386.56	6.86	61,851.89	7.27
Unknown	260.71	0.03	0.00	0.00
Total	851,271.73	100.00	851,271.73	100.00

Figure 23 subsequently shows the distribution of the reconstructed materials over the whole network. Examining the connection between material and diameter a trend for cast and ductile iron for high diameters and for PE for smaller diameters (house connections) can be observed. The results of the reconstruction changes the ratios of the materials (due to the plausibility check), while for pipe type and pipe diameter these ratios only marginally change mainly due to mistakes in the original data and not due to the plausibility check.
The result of the reconstructed construction years in the network shows that the oldest part is in the city centre from where it reaches out into the surrounding areas. If we look at the pipe age of the network we can clearly see in the original data that some implausibility exists. For example cast iron pipes with a pipe age of less than 10 years exist, which should not be possible. Even more the median age of house connections made of cast iron is 18 years. Overall the length weighted average network age for the whole network between the original and the reconstructed data does only differ marginally from 31.98 of the original to 23.34 in the reconstructed data. The same small differences apply if we make a partition into house con-

nections and distribution pipes, where the average age of the house connections is lower with 30 years than the distribution pipes with 33.

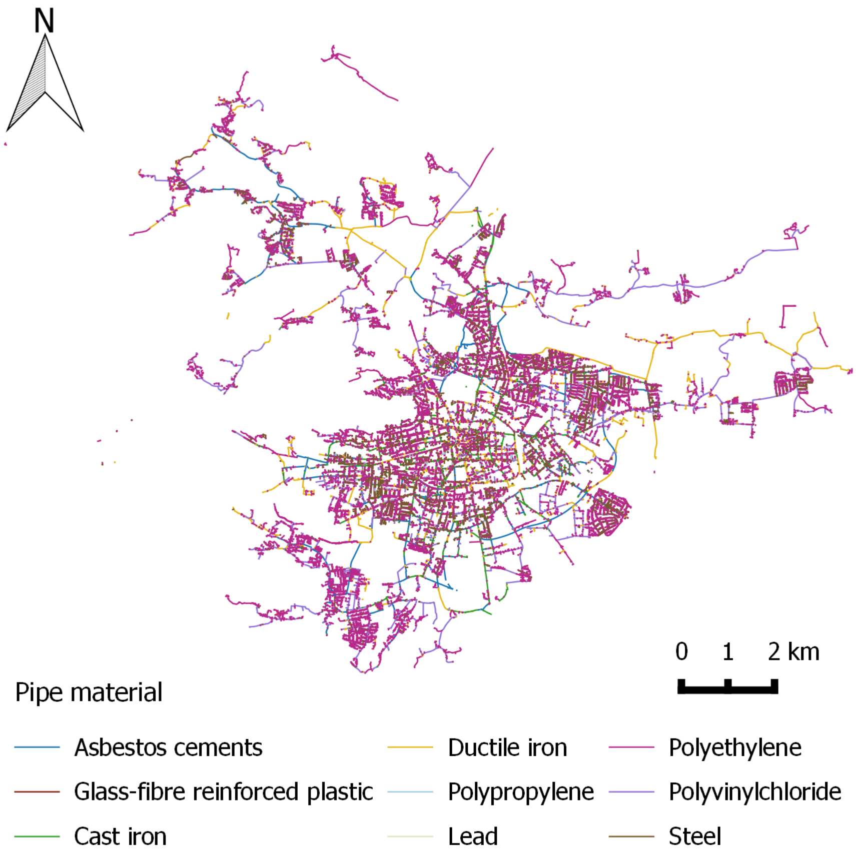

Figure 23: Pipe material for the water distribution network of case study 2

Water distribution failure recordings

The failure recordings were recorded from 1983 until 2010 but with gaps (1984, 1988, 1999, 2000) or implausibly low failure rates (1992, 1993, 2001, 2010). Moreover, the quality of the data was of varying composition. While the pipe diameter of the affected pipes was known for nearly 80% of the damages the construction year of the pipes was only known for little more than half of the data. Out of the 3760 failures 3743 (99.55%) could be reconstructed and located using the method described in PAPER VI. From the original data 30% of the recorded failures were linked to a certain kind of failure type, while mostly no failure type or those not specified were recorded. This lack of information could not be undone by the reconstruction, some of the information even had to be discarded due to plausibility issues (for example corrosion on PVC pipes - see figure 24). If we examine the type of failures for the different materials (see figure 24), under the condition that more than 10 failures for the material were recorded, we can see that circular cracks are the most frequent failure symptom. For some materials other failure mechanisms are more important. While for asbestos cement and cast iron circular cracks are the most probable failure type whilst for steel it is corrosion. For PE pipes, aside from the circular cracks, damage on the pipe connections also form a major part of the failures. Another type of crack (longitudinal) is important for PVC pipes.

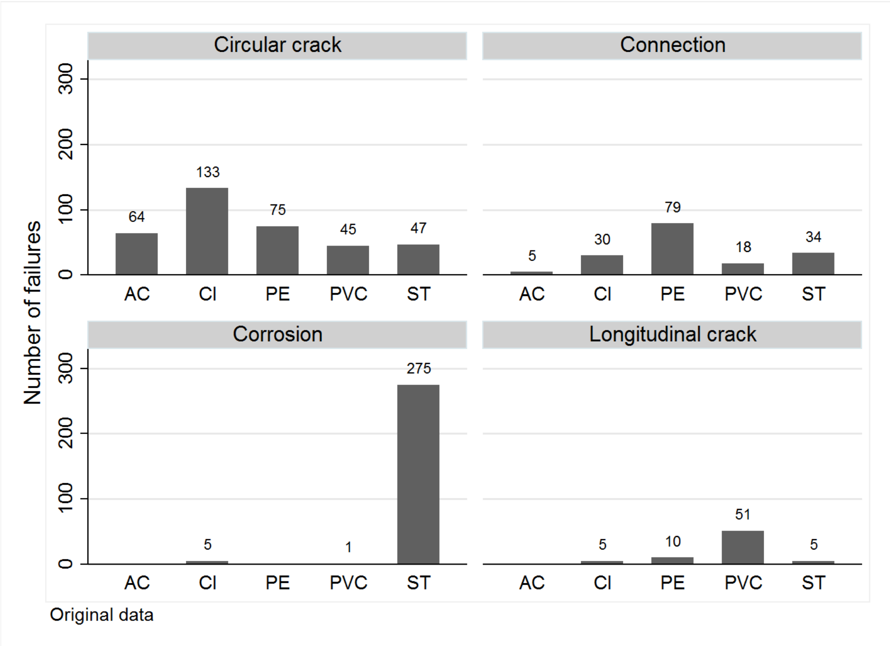

Figure 24: Observed failure mechanisms in water distribution network of case study 2

The reconstruction of the construction year for the damage recordings was not only necessary due to missing information but also because of false date which led to unreliable information about the pipe age at the moment of failure occurrence. This information varied from -8000 years to 2000 years. Even if we only look at a plausible time range of 0 to 200 years we still have a high amount of failures which have occurred at a pipe age of around 100 year old, which could be possible, but for a network with an average age of around 32 years together with the oldest network pipe dating from 1924 seems at least in this quantity dubious. After reconstruction the amount of these failures was visibly reduced. However, this was not entirely erased due to pipe information which did not contradict the given construction year in the failure recordings because the pipes have seemingly been replaced at the time of the failure which does not

allow to exclude the early construction year. Furthermore it was possible due to the history of the water distribution network.
Figure 25 shows the frequency of failure occurrence for house connections and distribution pipes. Partitioned by material after reconstruction the pipe age at failure occurrence for PE and steel pipes peaks earlier, than for other materials, because they are the main materials for house connections (compare with figure 25). The other materials have a more flat curve and ductile iron has very few failures recorded until today. The same phenomena can be observed if we subdivide by pipe diameter. The reconstructed data of the pipes with a diameter $\leqslant$ 25mm show a peak before they are 50 years old also originating that these are the most common diameters for house connection pipes. In general the mean failure occurrence time in the data-set is quite low - 26 years for house connections and 31 for distribution pipes. This is remarkably lower than the one found by Gangl (2008) with 52.2 and the mean value of case study 1 of 46.14 for the distribution pipes. For house connections no comparison data was available. The difference for distribution pipes could be explained however by the erratic data-set, which lacks lots of information as well as observations over longer periods of time. Furthermore, the average network age in general is very low, which could lead to the recording of only the starting phase of failure occurrence. For the house connections a lower life expectancy and higher failure rate could be assumed (see also PAPER V), due to the lower quality of workmanship, lower soil coverage and the observation of Berardi et al. (2008), which showed that smaller diameter pipes are more susceptible to failures.
Another effect which has to be considered is the possibility of several failures occurring on one pipe section, as defined by ÖWAV-RB 40 (2010). This definition, as well as the common practice of data storage of the operating company, causes an inhomogeneity in pipe section length, as already observed by Gangl (2008). However, 95% of the pipe sections were shorter than 100m and 99% shorter than 250m. Due to the fact that on average pipe lengths of 100 - 200m are rehabilitated (Gangl, 2008), these pipe section lengths allow for a plausible statement of the failure distribution. After reconstruction we observed that mainly the first failures on one pipe section where recorded (at least in the observation time). But also a pipe section with 8 failures in the relatively short available time period could be observed. If we look at the box plots of the pipe age at the time until the first failure and then subsequent ones (figure 26) on one pipe for distribution pipes as well as for house connections, we see that after 4 failures on average no further lifetime can be assumed and therefore it seems to be the ideal time for replacement. This trend can be also observed in PAPER I.

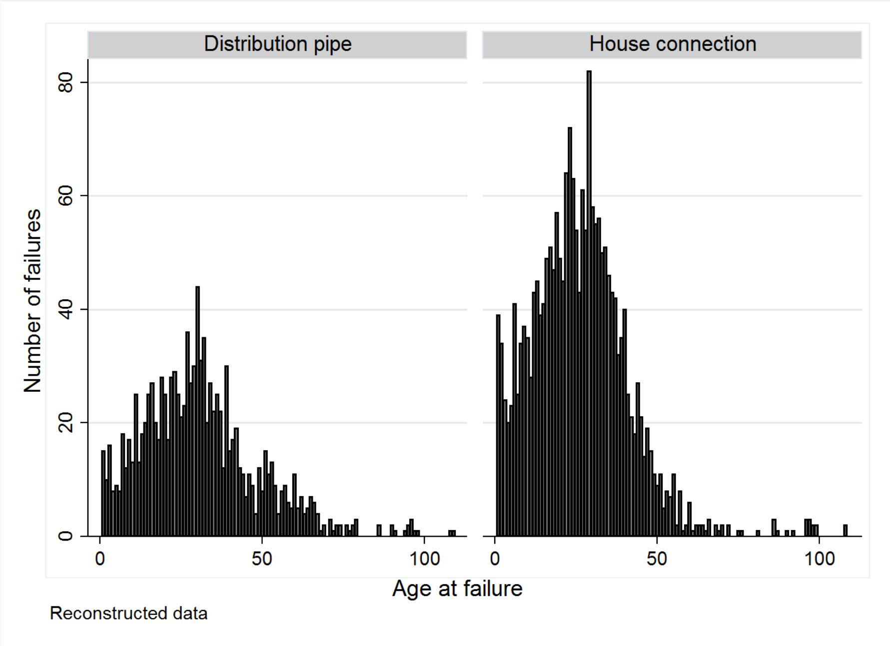

Figure 25: Number of failures depending on the affected pipe age and type for the water distribution network of case study 2

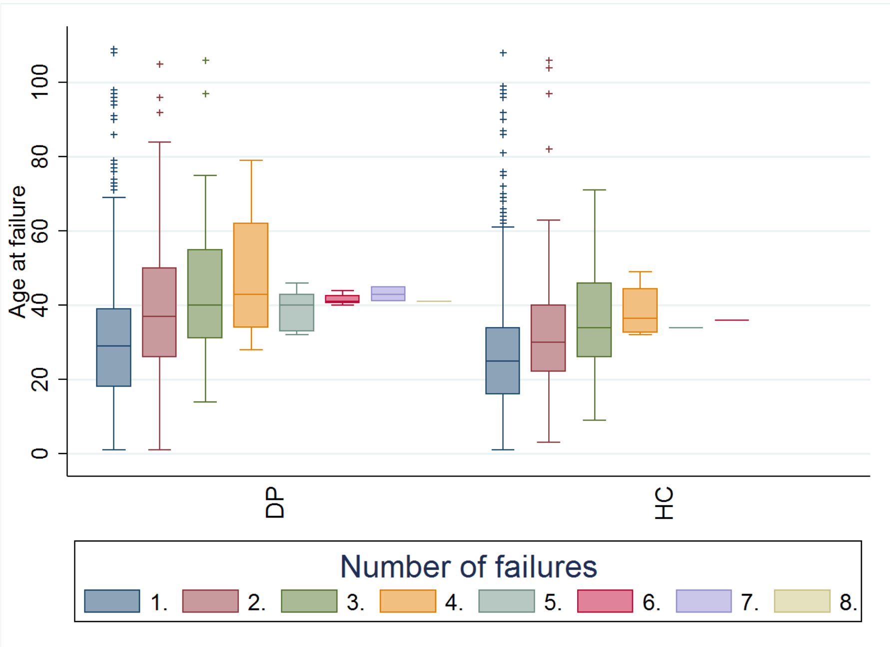

Figure 26: Boxplot of the age of failure occurrence for cascading failures on house connections (left) and distribution pipes (right) in case study 2

Finally, looking at the failure rates for the different pipe types following ÖVGW W 100 (2007) for distribution pipes (figure 27) and for house connections (figure 28) shows us once more the gaps and implausibility mentioned earlier.

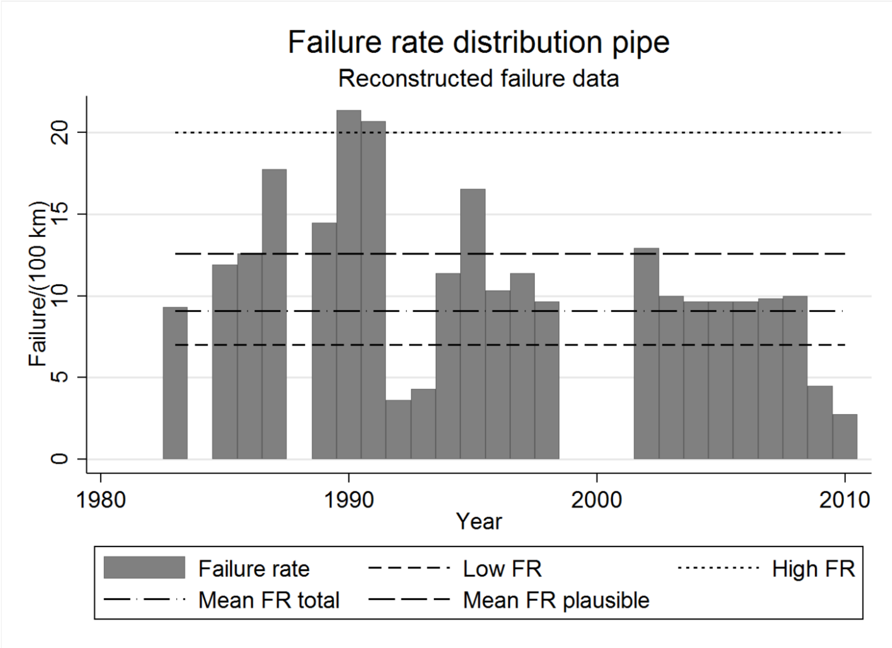

Figure 27: Failure rates for the water distribution pipes of case study 2

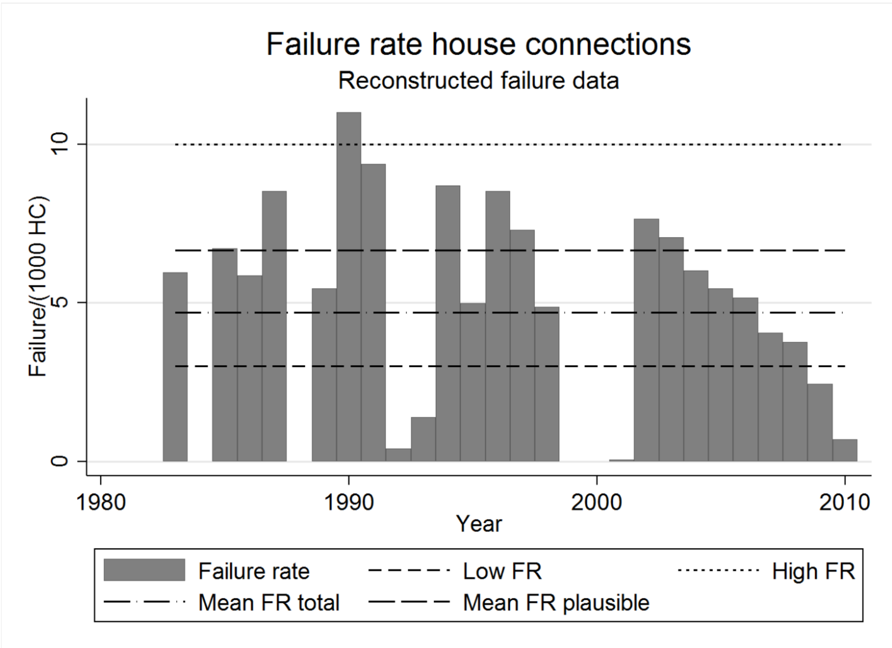

Figure 28: Failure rates for the house connections of case study 2

Whereas in some years even the highest failure rate (as determined in ÖVGW W 100 (2007)) is reached in other years not even the lowest

failure rate is approached. This of course lowers the average failure rate. To compensate this obvious flaw of the existing data the average failure was re-estimated using only the plausible years.
What can be observed, as also mentioned in PAPER V, is a certain clustering of failures in some street sections. Out of 1396 street sections 34% had no observed failure in the observation period, 76% less than four (a threshold for subsequent failures as shown in PAPER I and figure 26). This results in the fact that 50% of the observed failures occurred in only 11.5% of the street sections.

3.2.3 Case study 3

Case study 3 stands out of the used case studies in various aspects. First of all it is the smallest case study. Secondly it includes three networks: sewer, water and gas supply. Nevertheless the data situation is the worst of all the case studies, emphasising that bigger municipalities appear to have better data management (Younis and Knight, 2010b). Also no division at all (into valve or street sections) was present in the original data. Additionally, it can be seen that the networks consist of up to 6 parts which (at least in the available data) were not connected to each other. Therefore data reconstruction (PAPER VI) proved to be difficult. As a result the biggest interconnecting area (which was also the center of the municipality) was chosen for data reconstruction and the others neglected. The application and results of this reconstruction can be seen in Stibernitz (2014) and partly in PAPER II and Egger (2015). Therefore I will limit the description of this case study in this thesis to the original data and its quality.

Water distribution network data

The data of the water distribution network of case study 3 was of mediocre quality. Of the overall length of 192.08km, including the house connections, the data available were:

- 86.35% of the construction years (see figure 29),
- 96.59% of the pipe diameter (see figure 30),
- 95.56% of the pipe material (see figure 31).

One of the major problems was that unknown construction years were at first glance not recognisable and were labeled with a construction year of 2012. After careful examination of the labeled pipes this information was rejected due to the implausibility of almost 14% of the network having only been built in the year 2012 and the fact that for all pipes in 2012 the construction date 12.03.2012 was identical to the recording date of the information. Another characteristic of this network is the higher share of house connections on the entire network length due to a system of longer house connections, which was used in the past and is now gradually being adapted. The main part of the pipes without a construction year are of a diameter of 32 - 40mm (for house connections) and around DN100 (for distribution pipes). The main part of the pipes without construction year are mainly made out of cast iron (CI) and Polyethylene (PE). The known and plausible construction years of the network start with the year 1900 and end with 2011. The average network age is quite low - 27.93 years for the whole network, 27.20 for the house connections and 28.21 for the distribution pipes.

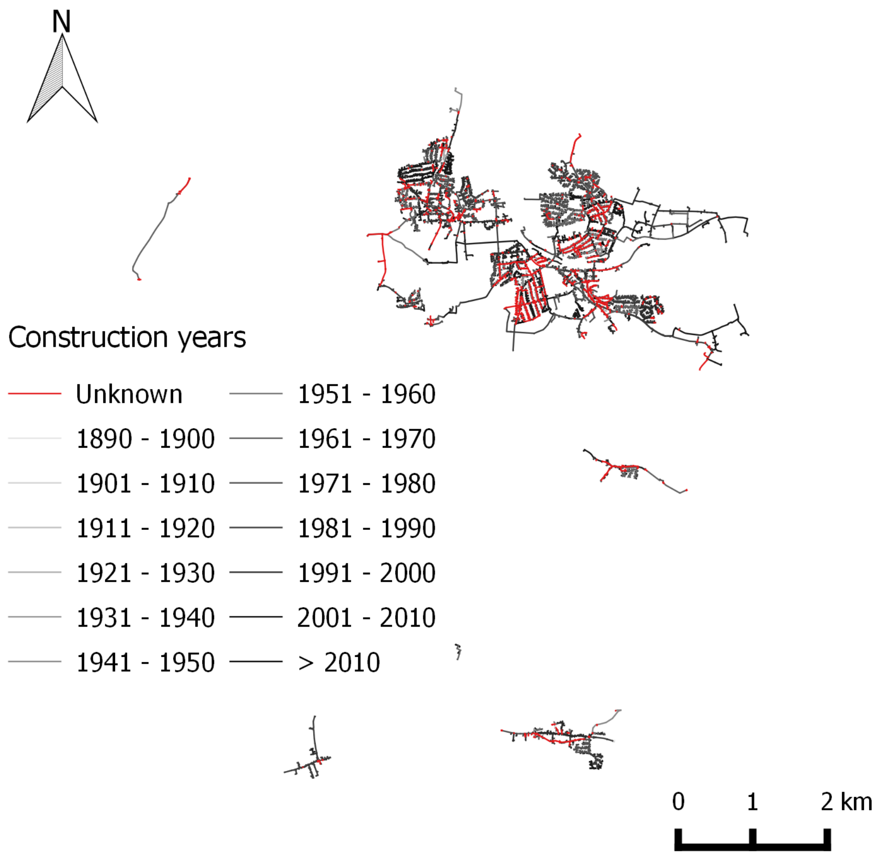

Figure 29: Construction years of the water distribution network of case study 3

The main part of the house connections of the network with known construction years have a diameter of 32mm although the diameters range between 20 and 150mm. The distribution pipes consist of mostly pipes of a diameter of 100mm and range between 25 and

400mm. The materials of the network are mainly Polyethylene (PE) for house connections and ductile and cast iron for distribution pipes. Smaller parts of the network are made of Polyvinylchloride (PVC) and steel.

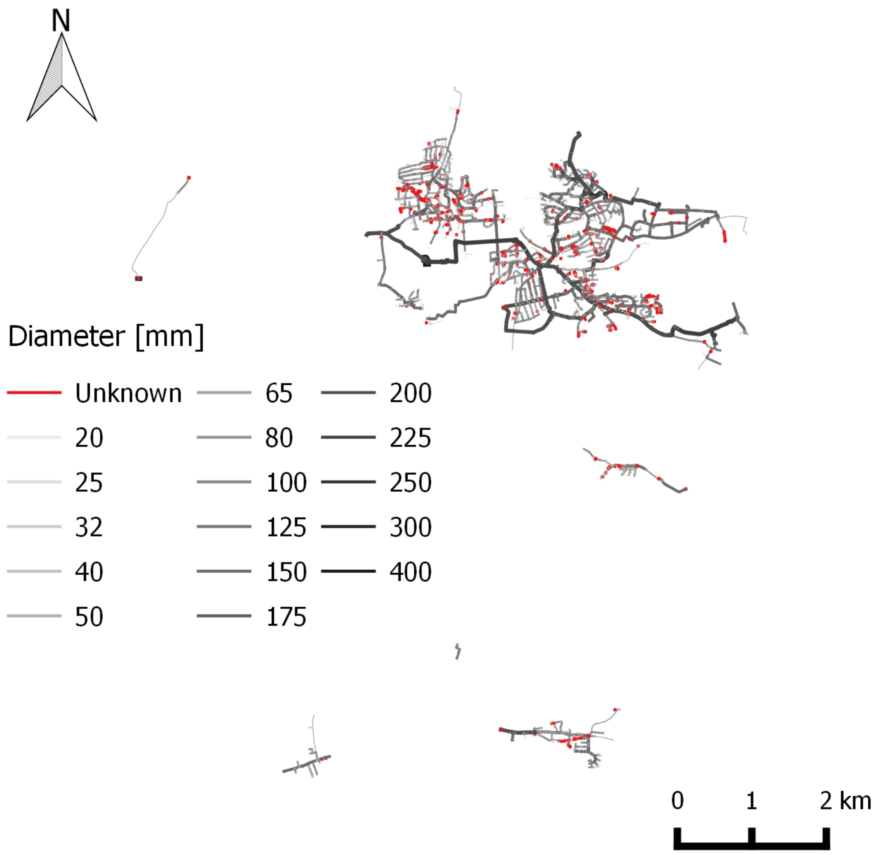

Figure 30: Pipe diameters of the water distribution network of case study 3

In the original data we see that the materials are to a large extent not plausible according to Roscher (2000) especially the cast iron pipes have implausible construction years, for example 2005. Due to the fact that no valve and street sections are available for reconstruction only a plausibility check was applied and then the pipe sections without construction years were extrapolated (figure 32).
For 10.65% of the pipe connections we have information about the connection type, where mainly plug-in and screw-locked sleeves are in use, to a smaller extent flanges, lead joints, welded connections as well as special company products. Also 14.35% of the pipe sections include information about the exterior pipe protection this hardly seems to be applied for any pipe. To a smaller amount coatings with Bitumen, Cink, Cement, PVC and PE are in use.

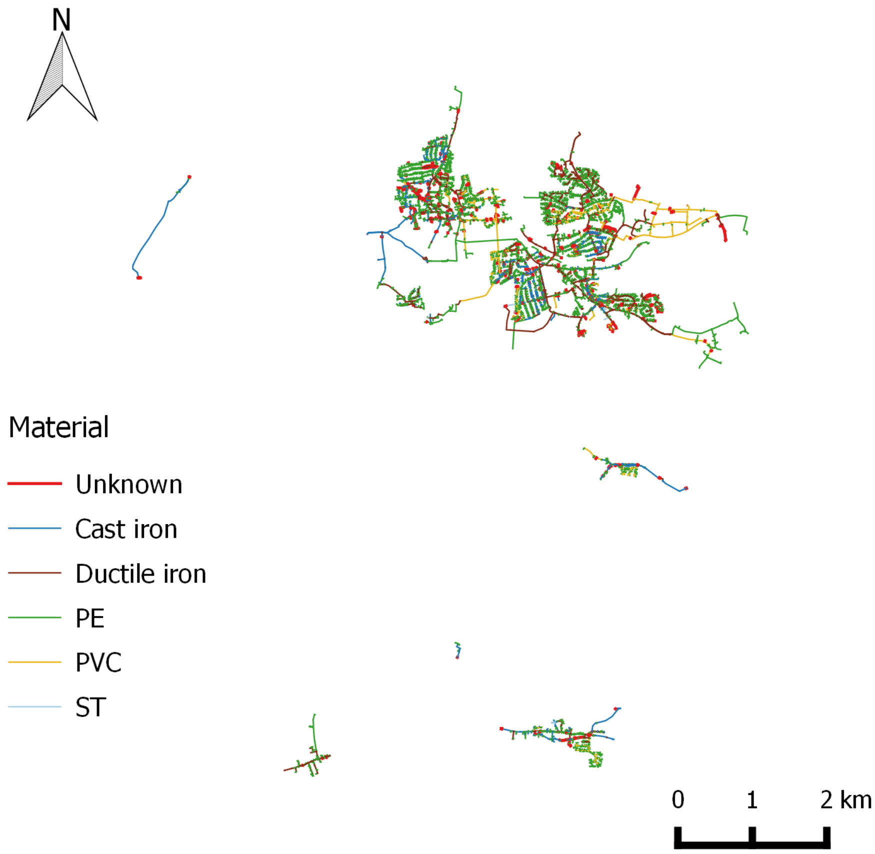

Figure 31: Pipe material of the water distribution network of case study 3

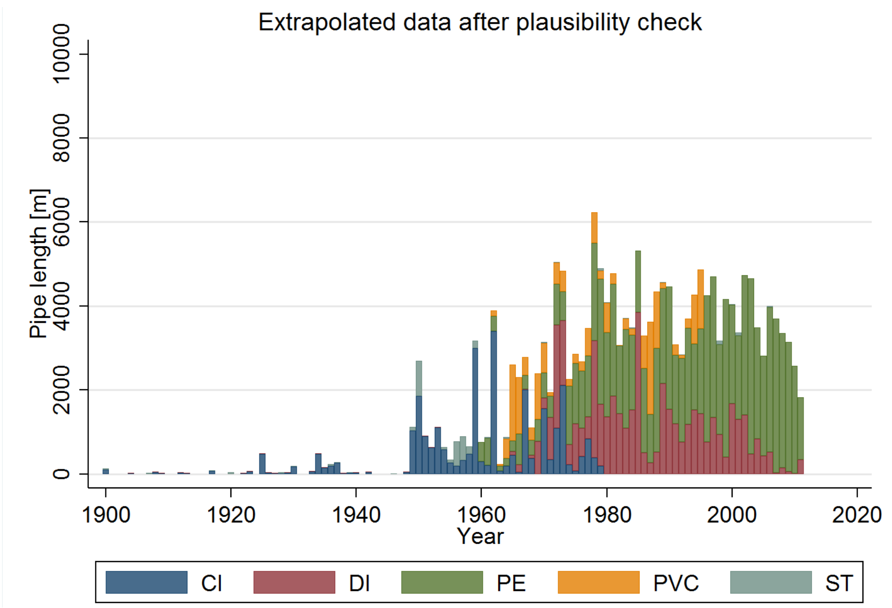

Figure 32: Pipe length of the water distribution network of case study 3 divided by material

Water distribution failure recordings

The failure recordings only started in 2002 and lasted until 2011 but the quality is on the whole good except for the construction year of the affected pipes. Only 14% of the failures have a construction year attached while only 8.14% have a plausible construction year. Out of 467 failures 100% could be located and reconstructed however using not only the method described in (PAPER VI) but also using analog data (e.g. plans), where most of them were located. Further additional information about the failures was available. The most interesting additional information was the pipe depth of the affected pipes. Most of the failures occurred at a depth of less than 1 meter and then declined nearly exponentially with increasing depth (figure 33). The ranges of construction depths were between 0.9 and 5 meters, which is less than the recommended 1.5m of ÖNORM B 2533 (2004), but is plausible as shown by Friedl (2014). The pattern is in contrast to the findings of Sorge (2006), who found that the load on a pipe in dependence of the laying depth has maximum values at 0.8 and 2m depth and a minimum at 1.2m. This would explain the high amount of failures at 0.9m but not the exponential decrease.

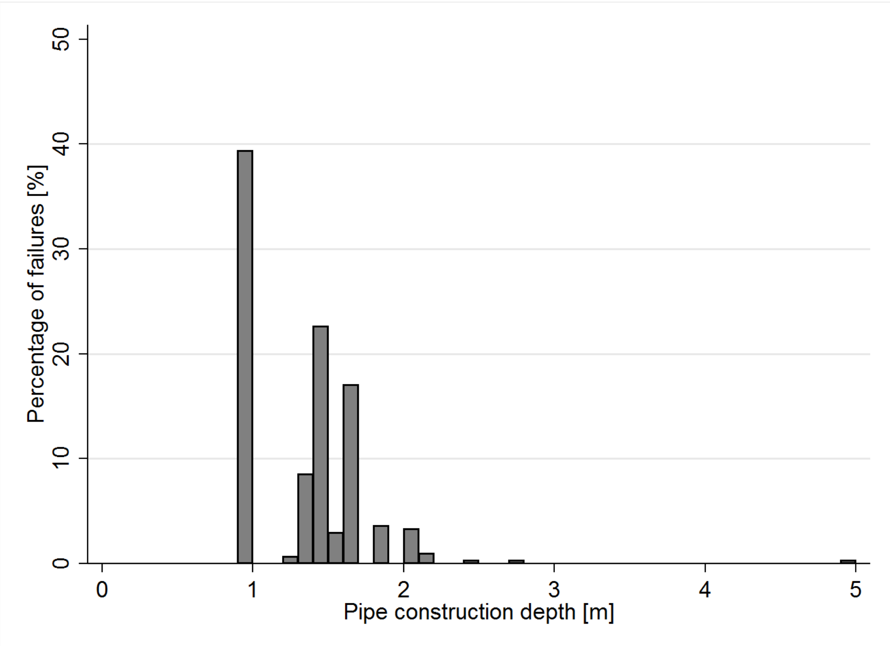

Figure 33: Number of failures of the water distribution network of case study 3 depending on construction depth

The type of failures recorded (70.24% of the failures have a failure type attached) could be subdivided into 4 different classes: cracks (unfortunately no further subdivisions), corrosion, connection and pipe breaks. Mainly cracks and breaks were recorded and a smaller amount of corrosion and connection damages. These gaps of information could not be recovered by the reconstruction, some of the information had even to be discarded due to plausibility issues (for example corrosion on PE pipes). If we subdivide the type of failures into materials (under the condition that more than 10 failures for the material were recorded) we can see that only two materials are left. Breaks were mainly observed for cast iron pipes whilst for PE-Pipes cracks were the main failure type. The reasons for the failures were also recorded (in 67.88% of the failures), but the data was not diverse as for 81% soil movements were deemed to have caused the failures. Additionally, the information about the bedding material (for 57% of the failures recorded) was not very diverse - 75% of the bedding material was marked as "stony". Further information about the location of the failure was given by the division between different surfaces (mainly street or no street). Out of the 267 failures which had this information 50% happened in pipes under streets.

The distribution of the number of failures depending on the age at occurrence of the failure of the original data is not very meaningful, due to the small amount of existing data. The frequency of failures occurring at a certain pipe age show that the number of failures are mainly distributed between 30 and 50 years of pipe age, with a mean value of 33.54 and a standard deviation of 13.91. Mainly failures of PE-pipes with a diameter of 32 and 40 mm are observed - this combination is mainly used for house connections. Another major combination which was observed was cast iron pipes with a diameter of 100 and 125mm, which in this case are mainly for distribution pipes. The number of failures observed in distribution pipes was considerably lower (only 13.06% of the observed failures).

Finally, looking at the failure rates for the different pipe types following ÖVGW W 100 (2007) as shown in figure 34 for house connections and in figure 35 for distribution pipes. Whereas for the house connections the highest failure rate (as determined in ÖVGW W 100 (2007)) is reached for distribution pipes not even the lowest failure rate is reached. This is due to the fact of the higher amount of failures on house connection pipes (406 of 467 failures) and also that the house connections are longer (on average 23.65m per house connection) than normal (for example in case study 2 it is only 15.57m per household connection). Moreover, it is of note that we only have 6 street sections with more than or equal to 10 failures or more in the whole observed time span, which is caused by the short observation time. Therefore the clustering of failures can only be observed in parts.

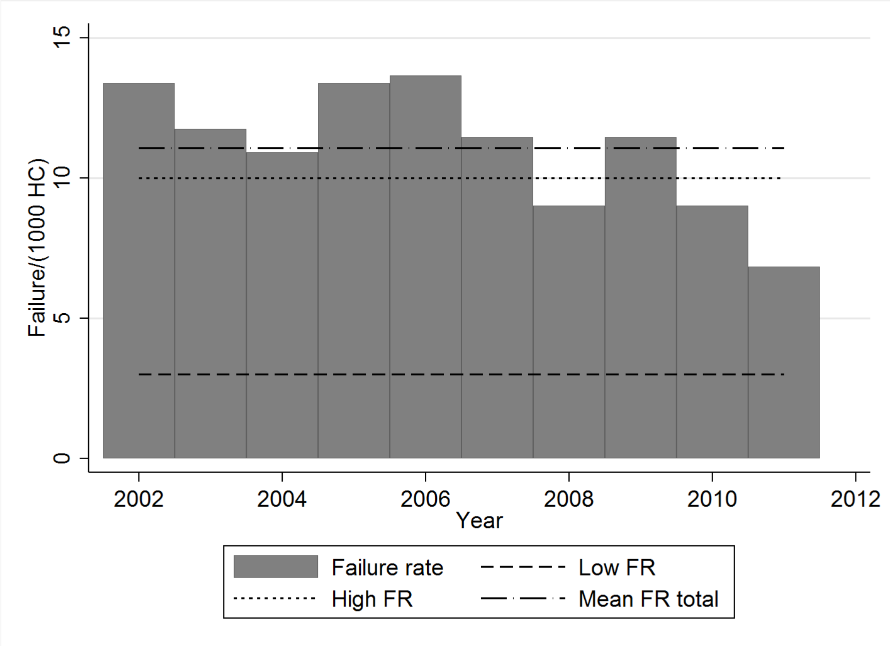

Figure 34: Failure rates for the house connections of case study 3

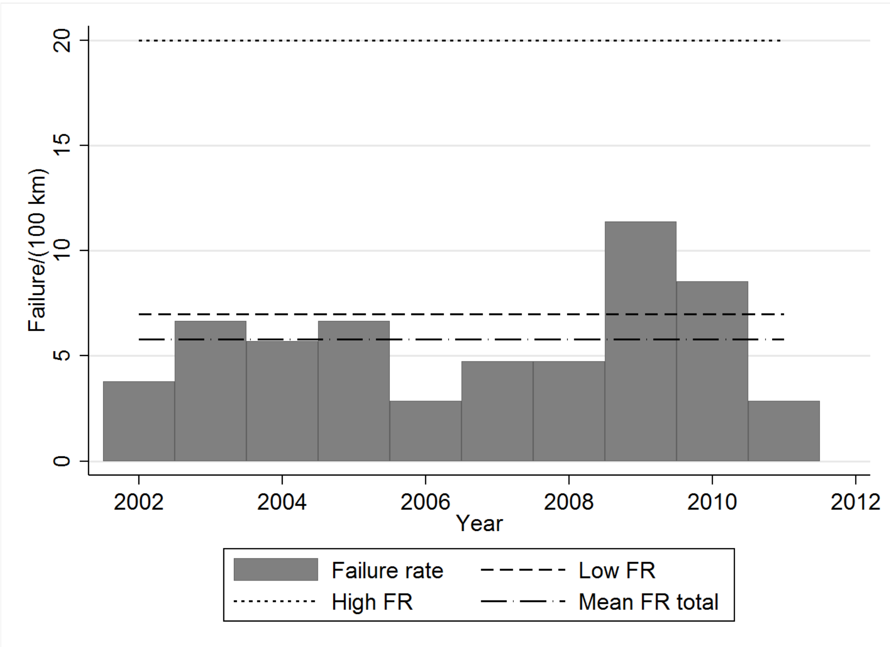

Figure 35: Failure rates for the water distribution pipes of case study 3

Urban drainage network and condition data

The network data of the sewer system was of mediocre quality available only as analog plans, without any data about house connections. The first step of implementing the files into the GIS system was a time consuming task. Finally, the data available covered a length of 92.29 km partitioned into 4 separate areas. 68.39% (63.11 km) of the network are operated as a combined sewer, 15.18% (14.01 km) are purely waste water sewers and 16.44% (15.17 km) stormwater sewers. Of the total network length data were available for:

- 86.87% of the construction years but only rough estimations from the operators knowledge (see figure 36),
- 80.67% of the pipe diameter (see figure 37),
- 21.57% of the pipe material.

Due to the fact that only a very small percentage of the network length has material information an analysis and therefore also a reconstruction of this information is not sensible. Mainly in use are vitrified clay and concrete pipes and to a smaller amount asbestos cement, ductile iron, polypropylene and polyvinylchloride. The range of diameters used start at 200mm and go up to 1600mm. It can also be seen that the waste water sewers have a smaller diameter than the combined sewers (as is plausible). The oldest part of the network was constructed around 1950 in the center of the city.

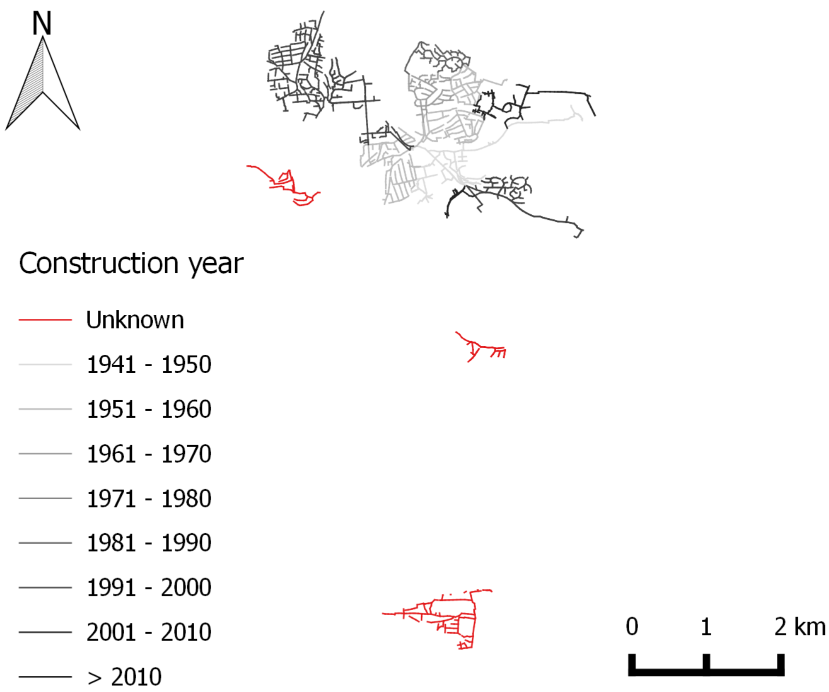

Figure 36: Construction years of the urban drainage network of case study 3

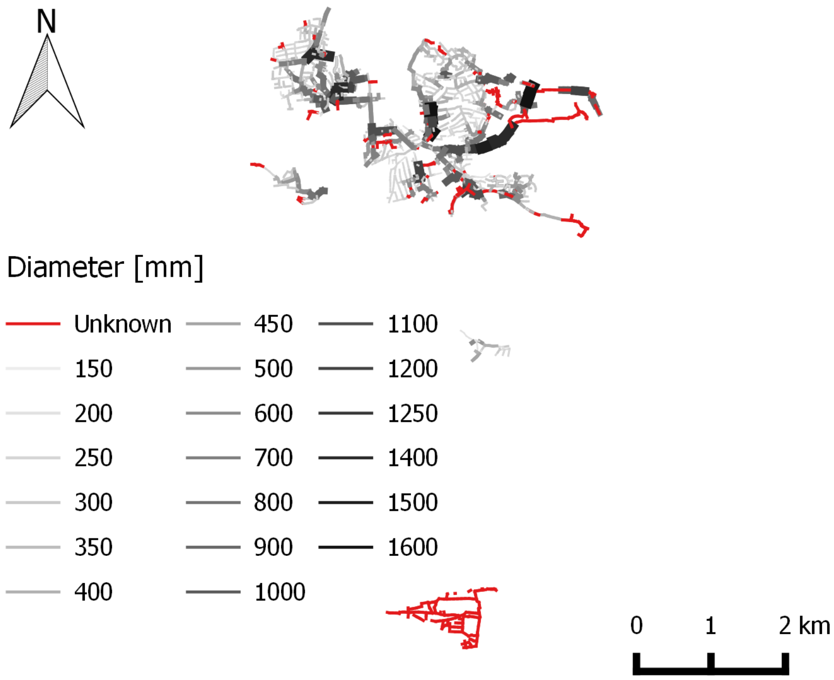

Figure 37: Pipe diameters of the urban drainage network of case study 3

Another piece of information available (for 58.60% of the total network in the city centre) is the hydraulic capacity utilisation of the network, as defined by Arbeitshilfen Abwasser 2004/242/D (2012) as the ratio of maximum estimated flow (by hydrodynamic simulation or time coefficient method) to full pipe flow. Figure 38 shows the distribution of the utilised capacity of the total network. It can be seen that 10.69% of the network is exceeding its hydraulic capacity (e.g. part time pressure flow). Pressure flow could lead to surcharge and flooding of the orographic upper manholes. However it is not a sufficient parameter to determine an overload of the network capacity. A further investigation of the hydraulic functionality of the network, for example the estimation of hydraulic condition states (ÖWAV-RB 22, 2015), could not be carried out due to missing information and/or a hydrodynamic model.
Furthermore, 46.22% of the network was inspected and was divided into 6 condition states using DWA-M 149-3 (2007) from condition state 5 (very good) to condition state 0 (very bad). 1.23km of the sewers are therefore in a very bad condition and in urgent need of repair (figure 39). It can be observed that the condition state 0 mainly appears for the construction year 1960 and not in the oldest pipes from 1950.

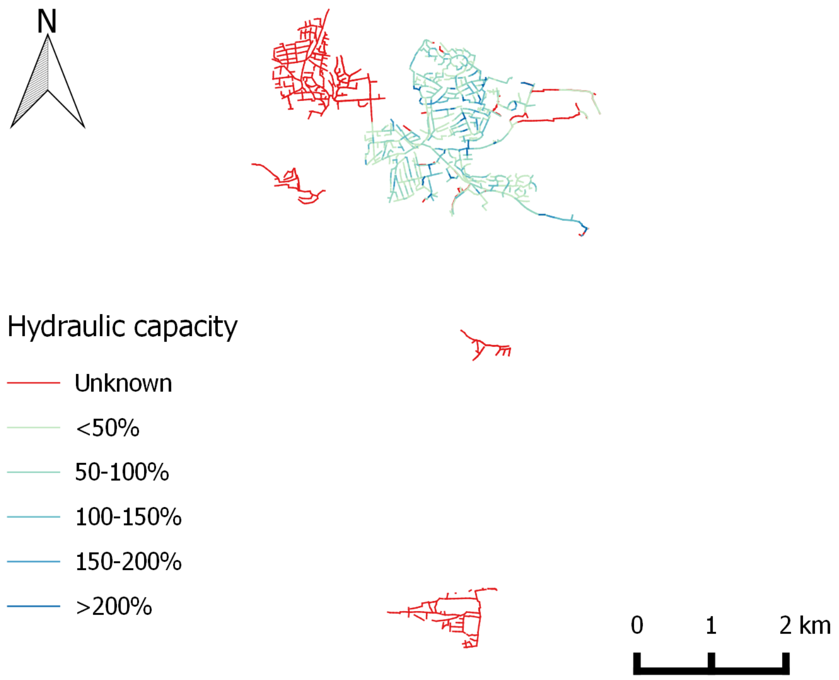

Figure 38: Hydraulic capacity utilisation of the urban drainage network of case study 3

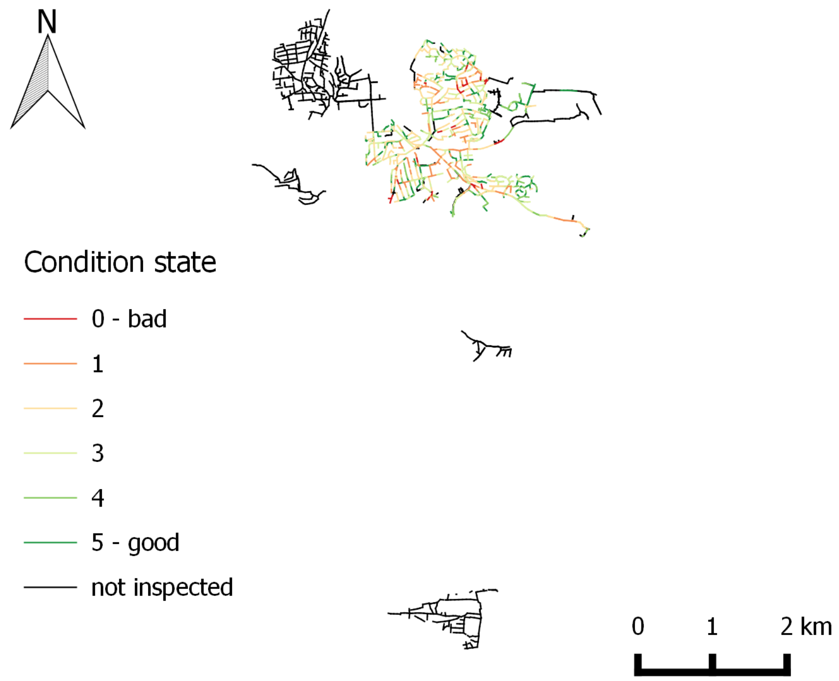

Figure 39: Condition states using DWA-M 149-3 (2007) of the urban drainage network of case study 3

Gas distribution network data

The data of the gas distribution network of case study 3 was of mediocre quality. Of the overall length of 134.24 km data were available for:

- 75.60% of the construction years (see figure 40),
- 96.66% of the pipe material (see figure 41),
- 95.05% of the pipe diameter.

One of the major problems was that no division at all (into valve or street section) was present in the original data. Other than the water distribution network, which consists of 6 parts which (at least in the available data) were not connected to each other, the gas distribution network only has 2 parts (see figure 40). The observed network consists of 47.19km house connections (15.26m/house connection) and 87.05km distribution pipes.

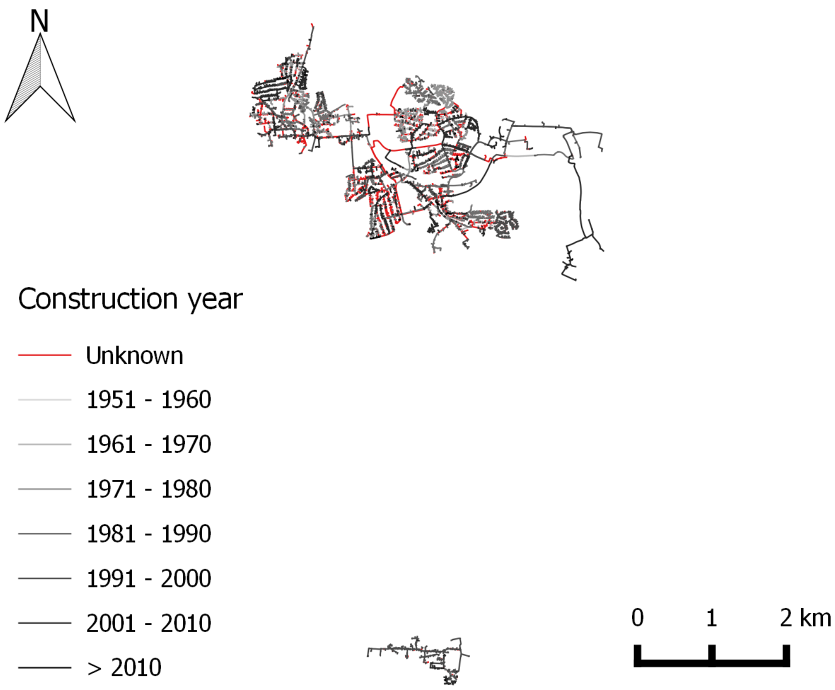

Figure 40: Construction years of the gas distribution network of case study 3

The 75.60% of the network without construction year data available (32,753m) is subdivided into 1532 pipe sections (21.38m/section), where 901 (9,223m) are house connections (10.24m/section) and 415 sections (16,990m) are distribution pipes (40.94m/section). The main part of the pipes with missing material are made of steel while the rest have no material information at all. The network mainly consists of steel pipes and to a smaller amount of PE pipes (compare figure 41).

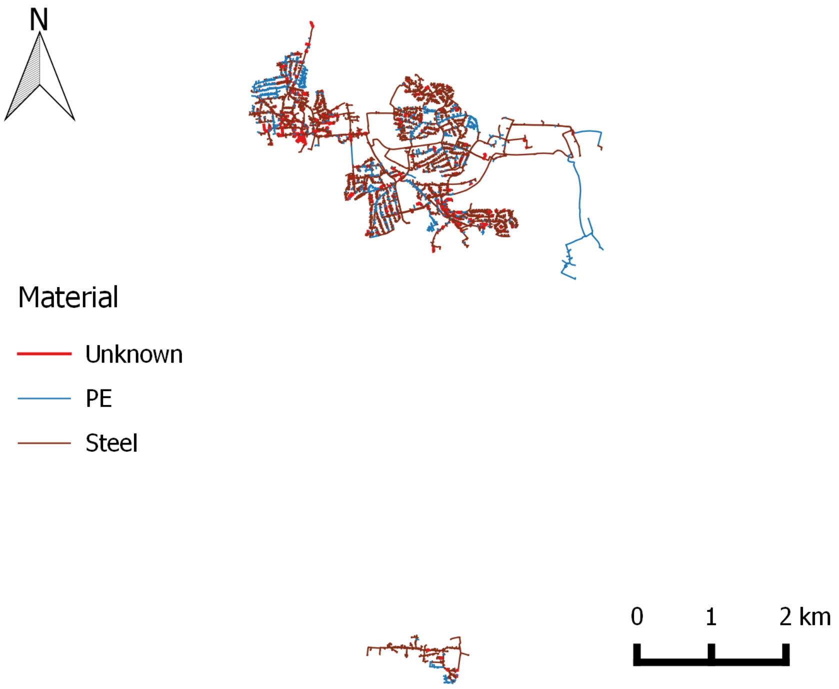

Figure 41: Pipe material of the gas distribution network of case study 3

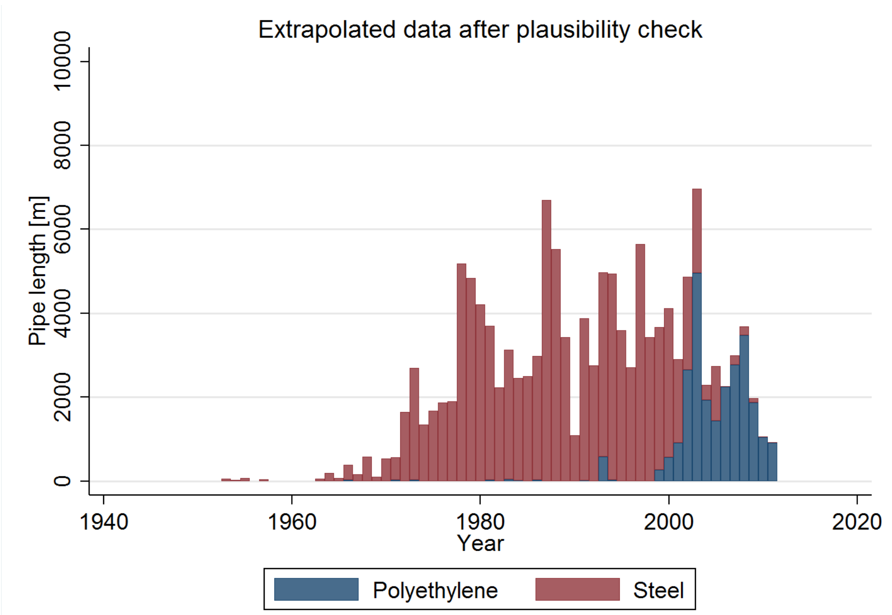

Figure 42: Constructed pipe length of the gas distribution network of case study 3 divided by material and construction year

It can be observed that the older pipes are the steel pipes while newer parts of the network are made of PE. The house connections range between 25 and 50mm, whereas the pipes with a diameter of 25mm are more likely to be made of PE. All other diameters up to a maximum of 250mm are most likely to be made of steel. The network has an average age of 22.35 years. It can be observed that the PE pipes are on average nearly 10 years younger than the steel pipes. It can also be seen that pipes of 25mm diameter are younger than the others due to the fact that they are mainly made of PE. Due to the missing street sections the data reconstruction was not applied but only the plausibility check using the material construction periods from DVGW G 402 (2011), giving no plausibility to polyethylene pipes constructed before 1960 and then using extrapolation to reconstruct the missing network information (resulting in figure 42).

Gas distribution failure recordings

The failure records started in 2002 and range until 2011. The quality of the failure recording was on the whole good except for the construction year of the affected pipes. 32.21% of the failures already had a construction year (and only one failure had implausible information about it), while 87.92% of the failures had a material attached and 85.23% the diameter. The material information was in parts implausible because materials (like PVC and CI) were mentioned which were not available in the network data. All of the 149 failures could be located using the method described in PAPER VI. 60.40% of the failures have a failure type attached and mainly corrosion of the steel pipes were observed. To a smaller extent holes, breaks and connection damages were recorded but cracks were only recorded for PE pipes (although only 5 failures were recorded for PE-pipes at all). The distribution of the number of failures, depending on the age at failure occurrence, of the original data is not very meaningful due to the small amount of existing data. The failures occurred between an age of 1 and 40 years, with a mean of 21.97 and a standard deviance of 11.77, but no age had a significant higher amount of failures - the maximum was 4 failures.
The major part of the failures occurred in Steel pipes which is of course plausible due to the fact that steel is the material used most as well as on average the oldest. Such a clear distinction cannot be made for the pipe diameters. While most failures occur in diameters of 32, 40 and 100mm. The estimated failure rates (resulting in figure 43), if we use the same characteristics as for water distribution networks after deleting all failures cause by third party responsibilities as recommended by DVGW G 402 (2011), for the distribution pipes fluctuate strongly over the years ranging from 2.8 to 19 failures/100km

with a mean of 8.65 failures/100km. Especially the year 2003 with an overall of 42 failures peaks the failure rate for the distribution pipes as well as for the house connections. For the house connections the failure rate of this year is significantly higher with 6 failures/1000 house connections than for the other years, which are nearer to the mean of 2 failures per 1000 house connections. Again we can observe that failures accumulate in a small amount of streets. For example only one street with 7 failures in the observation time range while 33 streets have only one failure.

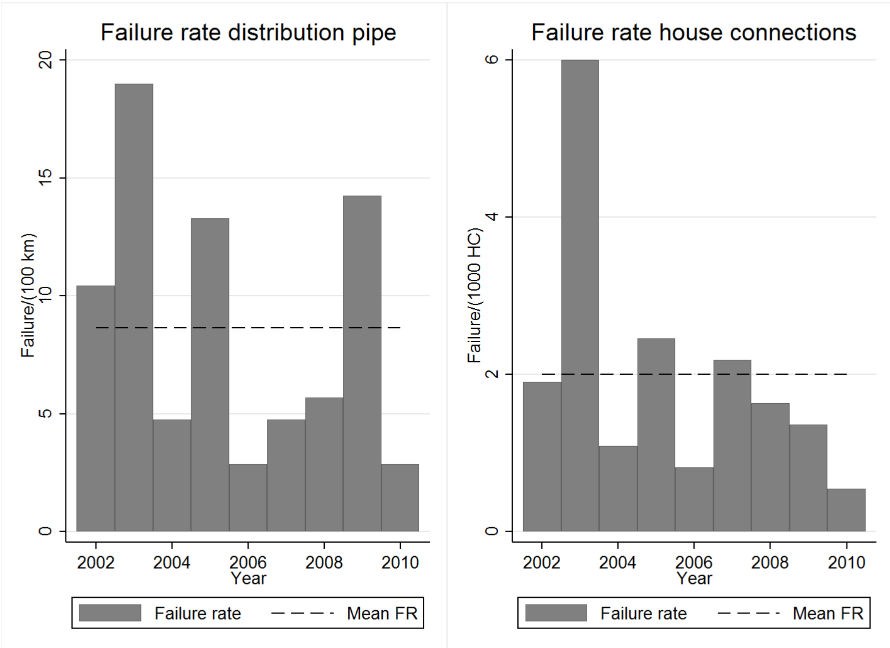

Figure 43: Failure rates for distribution pipes and house connections of the gas distribution network of case study 3

3.2.4 Characteristics of the case studies

Along with the data issues (which are summed up in the following chapter) some characteristics for the case studies could be examined regarding:

- Clustering of failures for the gas and water distribution network,
- Failure rates in general and per pipe section for the gas and water distribution network,
- Average network age,
- Length and number of house connections,

- Construction depth of the sewer networks
- Distribution of condition states of the sewer networks.

The clustering of failures of the gas and water distribution networks in certain street sections was one of the main found characteristics and could be observed in all three of the examined case studies, as it is also mentioned in PAPER V. In case study 1 46% out of 473 street sections had no observed failure, 89% less than four while 50% of the observed failures occurred in only 11% of the street sections. In case study 2, 34% of 1396 street sections had no observed failure in the observation period, 76% less than four and also 50% of the observed failures occurred in only 11.5% of the street sections. In case study 3 due to the short observation period only a trend could be observed for both networks. The water distribution network has only 6 street sections with more than or equal to 10 failures, while for the gas distribution network one street has 7 failures and 33 streets have only one failure. The cause for this clustering could be found in different levels of craftsmanship in certain street sections, external influences as for example adjacent construction sites, the change of load (e.g. change of traffic, change of surface) or other influences. These influences will have to be observed more closely to understand this phenomena. For case study 1 a study about the influence of earthquakes using data from ZAMG was made, but showed no statistical significant increase in failure rate in the time periods after the earthquakes.

The clustering of failures of the gas and water distribution networks in certain street sections was the main found characteristic.

Table 7 shows the characteristics of the water distribution network in terms of network age, length and number of house connections and failure rates. It can be seen that case study 1 has a lower failure rate on the distribution pipes (no data about the house connections were available) than case study 2, which has the considerably younger network. Furthermore, the failure rate in case study 2 would in reality be higher and is only decreased by some years of implausibly low failure rates of 0. Case study 3 has a lower failure rate for a younger network, however only for the distribution pipes. The house connections show a significantly higher failure rate. This can be explained by the higher average length of house connections. Moreover, it can be observed, that the number of failures per pipe section varies over the case studies. One explanation therefore is the differences in pipe section length and another of course is the different observation time period. Furthermore, it can be seen that only a limited amount of pipes with more than 4 failures per pipe section exist in the datasets. This can be explained by rehabilitation prior to the occurrence of such an amount of failures.

4 failures per pipe section seems to be the optimal threshold between repair and rehabilitation.

The observed gas distribution network of case study 3 consists of 3,093 house connections (15.26m/house connection) and 87.05km distribution pipes and has an average network age of 22.35 years. The failure records started in 2002 and range until 2011. The failure rate for the distribution pipes fluctuate strongly over the years ranging from 2.8 to 19 failures/100 km with a mean of 8.65 failures/100 km. For the house connections the mean failure rate of 2 failures per 1000 house connections can be observed with a range between 0 and 6.

Table 7: Characteristics of the water distribution system of the case studies

Data	Case study 1	Case study 2	Case study 3
Average network age [years]	46.03	31.98	27.93
Failure records since	1976	1983	2002
Average failure rate for distribution pipes over the entire observation period [Failures/100 km per year]	9.26	10.59	5.78
Maximum failure rate for distribution pipes [Failures/100 km per year]	15.93	21.37	11.39
Minimum failure rate for distribution pipes [Failures/100 km per year]	3.10	0.00	2.85
Average failure rate for house connections over the entire observation period [Failures/1000 HC per year]	-	5.47	11.08
Maximum failure rate for house connections [Failures/1000 HC per year]	-	9.38	13.64
Minimum failure rate for house connections [Failures/1000 HC per year]	-	0.06	6.82
Number of pipe sections with more than 1 (4) failures recorded	86 (5)	409 (8)	39 (0)
Network length including house connections if available [km]	225.98	851.27	192.08
Average length of distribution pipe section [m]	28.52	52.36	28.92
Number of house connections	-	17,263	3,665
Average length of house connection [m]	-	15.57	23.65

Case study 1 is drained with a gravity-driven combined sewer system with a total length of 253.50 km with an average pipe section length of 38.17m. The sewers are in quite a narrow range regarding construction depth with mean depth of 3.30m and an interquartile range of 1.26m. The network itself is old on average, resulting in a length weighted average age of 53 years. 72.43% of the sewer network was inspected, mainly sewers constructed before 2000, were inspected and classified into condition states using the methodology following ISYBAU (Arbeitshilfen Abwasser 2004/242/D, 2012). Therefore the condition states ranges from 1 (no immediate need for action) to 5 (urgent need for action). In this case study only a small percentage of the network is in this condition state.
Case study 3 is drained by an urban drainage system with a length of 92.29 km with an average pipe section length of 34.87m. The sewers have an average construction depth of 2.36m with an interquartile range of 1.47m. The network itself is on average young, resulting in a length weighted average age of 29 years. 46.22% of the network was inspected and was divided into 6 condition states using DWA-M 149-3 (2007) from condition state 5 (very good) to condition state 0 (very bad). As a result of the inspection data 1.23km of the sewers are therefore in a very bad condition and in urgent need of repair.
Figure 44 shows the percentages of survived (and inspected) pipes depending on the pipe age at the time of inspection. We see a trend for the decrease of good conditions over time. However it can be seen that some of the very old pipes in case study one are still in a very good condition. This is due to the fact that these old pipes, which have survived until this time, are only a small percentage of the entire network and therefore only this small percentage has not been rehabilitated. This is one of the difficulties for deterioration modeling - the selective survival bias, owing to observations being restricted to a limited observational window and as a consequence, the older the observed pipes are, the slower are their deterioration speeds, as the most rapidly deteriorating pipelines have a very low probability of having survived until the observational time window (Le Gat, 2008).
In case study 3 this trend is also seen. However, due to the sparsity of data for the construction years and the relatively low average network age, the information as such is less exact than in case study 1.

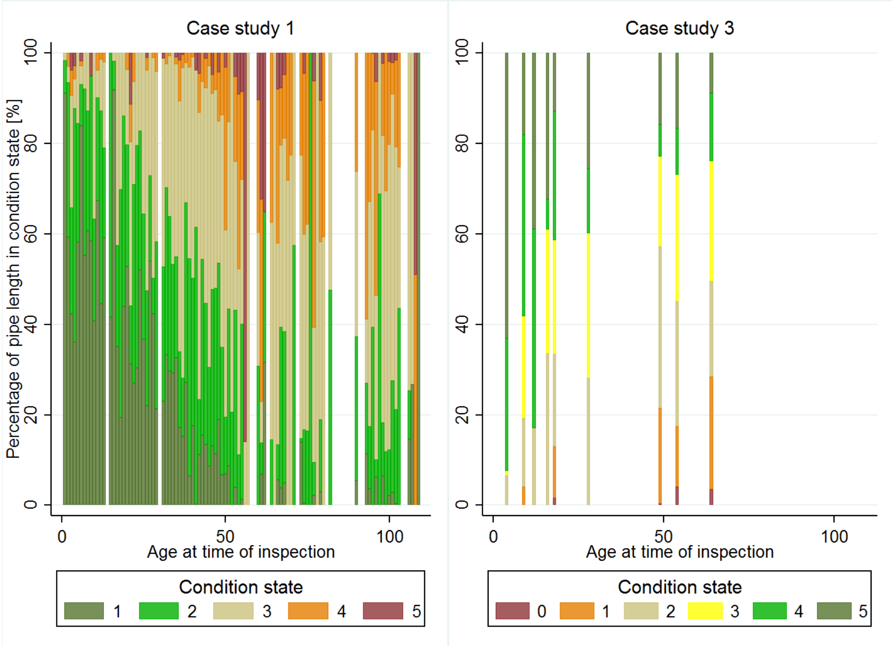

Figure 44: Distribution of condition states of the sewer networks in case study 1 (classified into condition states using the methodology following ISYBAU (Arbeitshilfen Abwasser 2004/242/D, 2012)) and case study 3 (divided into 6 condition states using DWA-M 149-3 (2007))

3.3 RECAPITULATION OF ISSUES AND RECOMMENDATIONS FOR DATA MANAGEMENT

Recurring nuisances are missing and implausible data, documentation, models and measurements.

After looking at these three case studies some data issues were a recurring nuisance, hampering the usage of data for further processing. I want to give a short overview over these problems here:

- Missing or implausible network data: The most often occurring problem as seen in the case studies. Important data about the network is missing or wrong data was implemented (for example the date of implementation into data management as construction year).

- Missing or implausible condition data: Ranging from not reproducible condition rating derived from visual sewer inspection (Dirksen et al., 2013) to varying quality of failure recordings depending on the year.

- Missing documentation and uninformative naming: The names of data fields gives no or little information about the data itself (e.g. units, abbreviations used) and no documentation for the data exists making it difficult for external or even internal (if it is not the same person who created the data) processing.

- Missing documentation of rehabilitation works and the background for the rehabilitation decision: Often replaced pipes are also replaced in the datasets and recorded nowhere. This destroys important data for deterioration modeling as well as for future decision making.
- Missing or badly documented models: Here especially hydrodynamic models for sewers and hydraulic models for water distribution networks, which could provide great insight into the functionality of the network and the vulnerability to failures, are often missing or not up to date.
- Missing measurements and calibration: Networks need to be calibrated to provide the best possible performance and therefore measurements are necessary.
- Missing environmental data: The network data is often not related to other data. Every network has its own database without any interconnection and foreign information (for example ground water levels, street network data, etc.) is not implemented.

And then some overall recommendations to overcome or at least minimize their occurrence:

The most important recommendation: Start with data management.

- Start with data management: The first recommendation is the simplest and hardest one. Although data management can mean a lot of things, including analog plans, a geographic information system is recommendable. A good starting point for the necessary data is the digital pipe information system (ÖWAV-RB 40, 2010). In Austria at the moment 34% of the total sewer length and 46% of the water supply network length are in the process of getting this system (KPC, 2014).
- Don't settle for the minimum: The minimum data requirements (e.g. to get funding) are a good starting point but should by no means be the end of data management. Get as much data as possible for your network. It is better to have data you don't need (at the moment), than need data that you don't have.
- Get help if necessary: Especially small operators and municipalities have limited resources (financial and personnel) and know how (mainly in using a GIS environment). Getting external help could fill these gaps, either from external engineers or by combining the resources of several municipalities, for example under the roof of regional wastewater or drinking water boards.

- Plan before you start and document what you do: Proper planning avoids double the effort in analysing existing data, ascertaining necessary data and implementing it into a GIS system. Furthermore, it should be clarified beforehand in which units (e.g. diameters, pipe length and so on) the data should be implemented. All of this information and the changes and assumptions during the process should be included in a thorough documentation to enable other people to comprehend what has been done and what every bit of data means.

- Invest in data: Proper data implementation needs time and is therefore also cost intensive. If you want good data you have to expect personnel costs.

- Have the courage to leave gaps: If data is missing don't fill it with assumptions, or at least mark the data that everyone can see they are assumptions.

- Plausibility checks: Small errors (e.g. typos) can occur. These can be minimised or at least easily found by the use of simple queries to test plausibility. Are all construction years in a plausible period? Are all materials correctly written? Is a material used before its invention?

- Data management never ends: Data needs maintenance. To get the most put of your data it is necessary to keep it updated. Therefore it is recommendable to clarify responsibilities for the data. Either one person gets the data and is responsible for its implementation into the data set or everyone who implements data into the data set leaves meta data to track the data genesis.

- Do not delete "old" data: Memory space is comparatively cheap, restoring lost data can however be very costly. Data of replaced pipes and so on could help to understand the deterioration processes in your network. New employees could profit from lessons learnt from decisions of the past, so start documenting the decision argumentation for replacement measures (van Riel et al., 2014). Moreover, it could help the argumentation and estimation of future financial and personnel needs.

- Think outside the box: Consider interdependencies (Rinaldi et al., 2001), overlapping and possible synergies between different operators and networks. Using one data management system for several networks could have advantages by minimising costs for the maintenance of the data sets and also for simpler coordination between the network operators considering rehabilitation, construction works and so on. Also the acquisition and implementation of other environmental data could be recommendable (e.g. ground water levels, urban development).

- Start modeling and measuring: The way from data to a model (hydraulic/hydrodynamic) is not so far and the better the quality of the data the better the model gets. Kleidorfer et al. (2014) give an overview how to get from data to a hydrodynamic model of a sewer network. To calibrate the model measurements are necessary, which again produce data which should be implemented into the data set.

- Use and create open data and programs whenever possible: In times of initiatives for coherent data types (Directive 2007/2/EC, 2007) and transparency open data becomes a more and more important topic. More and more governmental data is open data. Therefore getting information which data is usable under which circumstances and requirements for adding value to our existing data is important. In Austria a lot of good open government data already exists - basemap.at (2015); data.gv.at (2015); Land Tirol (2015); OpenStreetMap (2015) and many more. It would be recommendable, when possible, to distribute all or parts of the data as open data if the operators are public property. A guideline on how to achieve this is given by Krabina et al. (2011). For GIS applications (Quantum GIS Development Team, 2015), statistical evaluation (R Development Core Team, 2008) hydrodynamic (Burger et al., 2014; Gironás et al., 2010; Rossman, 2010) and hydraulic models (Rossman, 2000) open source alternatives exist. Depending on the available knowledge more user friendly programs with a wider range of predefined possibilities could be preferable. The technical knowledge provided, the usage of open source software is however preferable, not only due to cost savings but also due to possibilities of manual adaptability to special problems.

4 DETERIORATION MODELING

> Probability is like the stick used by the blind man to feel his way. If he could see, he would not need the cane, just as if we knew which horse runs faster, then we would not need the probability theory.
>
> Stanislaw Lem

Pipe deterioration is considered a complicated process, which is affected by an extensive amount of factors, making the prediction as to when a pipe will fail a difficult task (Ana and Bauwens, 2010). Visual inspections (Dirksen et al., 2013) and pipe age, are insufficient to estimate deterioration (Fenner, 2000). However, they are mainly used due to the lack of a complete systematic description of how, when, and why the failure occurs and if it triggers other failures in the chain of events (Stanić et al., 2012). Deterioration modeling faces this task using different approaches to achieve the goal of predicting the end of the service life of an engineering component. This end of life is defined as the duration that the component has the adequate capacity to perform its function satisfactorily (Datla and Pandey, 2005). The life cycle of a buried pipe is described by the "bathtub curve". Depending if the asset is repairable or not (Røstum, 2000), distinguishing three phases regarding the hazard rate of failure (Kleiner and Rajani, 2001). The first phase is the Burn-In phase, where a higher failure rate is mainly caused by construction and material failures (Gangl, 2008). This then leads to normal operation phase with a low failure frequency (e.g. mainly caused by third party influence) where the deterioration process progresses until reaching the wear-out phase. In the wear-out phase, the hazard rate increases due to age. This understanding about deterioration is implemented in the models. The models used are divided into three approaches (Ana and Bauwens, 2010):

Three phases of deterioration: burn-In phase, normal operation phase and wear-out phase.

- Physical models,
- Artificial intelligence models,
- Statistical models.

Rajani and Kleiner (2001), Ana (2009), Liu et al. (2012) and Friedl (2014) give an extensive overview of the physical models, that attempt to predict pipe failure by estimating the loads applied to a pipe comparing it to its capacity of resistance against it. The models at the moment mainly treat a small amount of influencing factors at a time or for a certain kind of pipe material or failure type. (e.g. metallic pipes by Sorge (2006)). Missing documentation of failure types in failure recordings (compare with chapter 3) is therefore also a limiting factor for the application of physical models (Friedl, 2014). A true physically based model, which should be the ultimate goal in failure prediction, should however include all influencing factors. The main problem of these models is however the extensive need for data to apply them. Therefore only large water mains with costly consequence of failure may justify the accumulation of data that are required for physically based model application (Rajani and Kleiner, 2001).

A true physically based model, the ultimate goal in failure prediction, is still limited by the extensive need for data to apply them and the limited knowledge of all influencing processes.

Typical artificial intelligence models are genetic algorithms (a good overview of its usage is given by Nicklow et al. (2010)) and artificial neural networks (Yang, 2004). They emulate biological principles, such as inheritance, mutation, selection, and crossover, to solve complex optimisation problems (Liu et al., 2012). These are purely data driven approaches, that enable one to solve complex problems without using detailed model assumptions. Therefore a high amount of data and computational resources are necessary and the model itself stays a "blackbox" (Ana and Bauwens, 2010). These methods are in use for all kinds of infrastructure: Tran et al. (2010) used artificial neural networks to estimate the deterioration of stormwater pipes, Yang (2004) for road cracks, Al-Barqawi and Zayed (2008) for the performance of water mains, Ana (2009) used probabilistic neural networks to estimate the condition of sewers and Babovic et al. (2002) used genetic algorithms to determine the risk of pipe bursts.

Artificial intelligence models require a high amount of data and computational resources are necessary and the model itself stays a "blackbox".

Given the difficulties of physical and artificial intelligence-based models, and in view of the type and quality of data available, statistical models were developed (Ana and Bauwens, 2010). The statistical model seems to be an economically viable approach for infrastructures that cannot afford high costs for the data mining of the necessary data for physical and artificial intelligence-based models (Rajani and Kleiner, 2001). Statistical models can be divided into two main groups: deterministic and probabilistic models. Røstum (2000), Engelhardt et al. (2000), Kleiner and Rajani (2001), Gangl (2008), Ana (2009), Osman and Bainbridge (2011) and Liu et al. (2012) give a good overview of the statistical models used.

Statistical mmodels are the economically viable approach for limited data availability.

Deterministic models are mainly a time regression analysis using either an exponential or linear approach (Kleiner and Rajani, 2001). They mainly predict breakage rates and are hard to use for ordinal

condition ratings, not making them very useful to be applied for sewers. Furthermore, they can be only used on a pipe group level with the exception of the approach of Giustolisi et al. (2006) and Berardi et al. (2008) who used a hybrid data-driven modeling technique. These approaches offer an easy data analysis and well known parameter estimation techniques and have therefore been in use for a long time (Shamir and Howard, 1979) and widely spread (Kleiner and Rajani, 2001). DVGW G 403 (2011) offers for example an approach to calculate a breakage rate from failure recordings for gas distribution networks.
The probabilistic models can be divided into the following (Ana and Bauwens, 2010; Kleiner and Rajani, 2001):

- Cohort survival model (used in PAPER V and PAPER III): A wide spread model used by Hörold and Baur (1999), Herz and Krug (2000), Baur and Herz (2002), Ana (2009) and Egger et al. (2013) for sewers, by Herz (1998), Fuchs (2001), Herz (2002), Baur (2004), Gangl (2008), Malm et al. (2012) and Scholten et al. (2013) for water distribution networks and by Baur (2004) for gas distribution networks.

- Markov-chain based models: A Markov chain represents a discrete time stochastic process X, where the conditional probability of the future state, at time $t + \Delta t$, only depends on the present state, at time t (Çınlar, 2011). Also in use are semi-markov chains, with an additional property in the form of a waiting time in each condition state (Ana and Bauwens, 2010). The conditions are either condition states for the sewer system or the break history for water and gas supply. Dirksen and Clemens (2008), Le Gat (2008), Tran et al. (2008), Ana (2009), Tran et al. (2010) and Marzouk and Omar (2013) used this approach for urban drainage systems and Kleiner (2001) in general for large infrastructure. Caradot et al. (2015) used the approach of Le Gat (2008) for a sewer system and showed the applicability of this method for a small amount of inspection data (3% of the network).

- Logistic regression models (used in PAPER I and PAPER IX): Davies et al. (2001), Ariaratnam et al. (2001), Ana (2009), Younis and Knight (2010a), Younis and Knight (2010b), Fuchs-Hanusch et al. (2012), Ahmadi et al. (2013), Ahmadi et al. (2014a), Ahmadi et al. (2014b) and Ahmadi et al. (2015) used this methodology for urban drainage infrastructure while Friedl et al. (2012) and Friedl (2014) applied it to the water distribution network.

- Proportional hazards models: Cox (1972) defined a failure prediction model in the form of $\lambda(t, z) = \lambda_0(t) \cdot e^{z\beta}$. t is the time,

$\lambda(t, z)$ is the hazard function, which is the probability of failure at time $t + \Delta\ t$ given the survival until time t, z is the vector of co-variates, $\lambda_o(t)$ is an unknown function giving the hazard function for the standard set of conditions $z = 0$ and β is the vector of coefficients which have to be estimated by regression. This fundamental function was used and adapted by several studies (Lei and Sægrov, 1998; Park et al., 2008, 2011; Røstum, 2000), mainly for the estimation of water main breakage rates.

- Accelerated lifetime models: Lei and Sægrov (1998) defined this approach, assuming that the lifetimes of pipes can be treated as independently and identically distributed random variables.

Due to the data quality of the case studies (see chapter 3) and the focus on small and medium sized municipalities which will most likely not have the funds for extensive data surveys, statistical models were used. Due to the extensive literature available, I will give only a brief overview of the two methods used in the annexed publications (cohort survival and binary logistic regression model). I will also show simplified approaches for the modeling of the necessary rehabilitation rates without extensive deterioration modeling as a first rough estimation.
Model specific problems are discussed for the specific models. However, common problems of deterioration modeling are firstly missing and discarded data about network qualities and network growth as well as repair and or rehabilitation. Further censoring (e.g. lack of observation time span) is a problem (Scheidegger et al., 2013). Additionally, not all models are easily applicable to ordinal condition ratings (e.g. sewers), break rates (e.g. water and gas distribution) and/or life spans. Further differences between pipe group and pipe level models exist (Ana and Bauwens, 2010). While the first considers the entire networks or cohorts (parts of the network with the same qualities) the latter predict the deterioration of individual sewers.

Common problems of deterioration modeling are missing and/or censored data.

4.1 COHORT SURVIVAL MODEL

This model derives from demographic research where it is widely used for the forecast of population changes of different groups of people (Herz, 1998). The same approach can be applied to pipe networks, dividing them into homogenous groups regarding their qualities, the so-called cohorts (hence the name of the model). Herz (1998) defines four interrelated aging functions:

Advantages: conceptual and computational simplicity. Disadvantages: extensive data needed, group level, replacement is end of useful service life.

- lifetime probability function $f(x)$;
- survival function $1 - F(x)$;

- failure function $\frac{f(x)}{1-F(x)}$;
- residual lifetime expectancy function $R(x)$.

The difference between using the approach for water distribution and urban drainage networks is the fact that the survival function is used for life expectancy until pipe replacement for the water distribution network and for the urban drainage it can be used to estimate transition functions between transition states. This is mainly caused by the type of failure recording and the possibility of inspection for the different networks. While for water distribution networks in general the occurrence of bursts and the replacement of pipes are recorded, for sewers visual inspection is the state-of-the art inspection technique. Due to the estimation of condition states from the information of these inspections a more differentiated survival function can be applied giving a transition over time. For the water supply network it is on the other hand a merely binary outcome, although approaches for using subsequent failures in the same pipe section after repair as a condition states exist (Gangl, 2008). The survival function has the following form (Fuchs, 2001):

$$
\begin{aligned}
1 - F(t \leqslant c) &= 1 \\
1 - F(t > c) &= \frac{a+1}{a + e^{[b \cdot (t-c)]}} \\
1 - F(t = \infty) &= 0
\end{aligned}
$$

Therefore the aging functions form depends on three parameters (Ana and Bauwens, 2010; Baur, 2004; Fuchs, 2001; Herz, 1998):

- a is the aging factor: If $a = 0$ the failure function stays constant over time and the survival function changes into an exponential distribution.
- b is the failure or transition factor: It controls the velocity of the aging process. The bigger b the faster the aging process.
- c is the resistance time: Up to resistance time no rehabilitation takes place, only repairs if necessary.

These parameters have to be estimated for the specific situation of every network (Herz, 1998). Possibilities for estimating these parameters range from using the average technical design life and the standard deviation, the estimation from cohort ages until specified percentages (100 - 50 - 10%) of the network have survived to expert knowledge (Fuchs, 2001). Fuchs (2001) and Fuchs-Hanusch et al. (2007) adjusted failure statistics with a specified length per failure to the failure rate. Malm et al. (2012) estimate the survival function

by adjusting it with the method of least squares to the actual age distribution of a network. The necessary parameters were first estimated by using the specified percentages (100 - 50 - 10%) of the actual distribution. Ana (2009) assumes the resistance time c to be zero, as sewers can deteriorate immediately. Then the two other parameters can be estimated by the method of least squares (Agresti, 2002) for the actual data for the transition function of each condition state.
For the water distribution network of case study 2 (see PAPER III) the result of a cohort survival model was used as one input for the prioritisation of the network. For the estimation we used the approach of Malm et al. (2012), making plausibility checks however, due to the bad condition of the data, with lifetime expectancies from a survey published as PAPER VII and literature values (Scholten et al., 2013). The differentiation was made between the different materials as well as between house connections and distribution pipes (see figure 45). What can be seen is the lower life expectancy of the house connections for all materials except for the steel pipes.

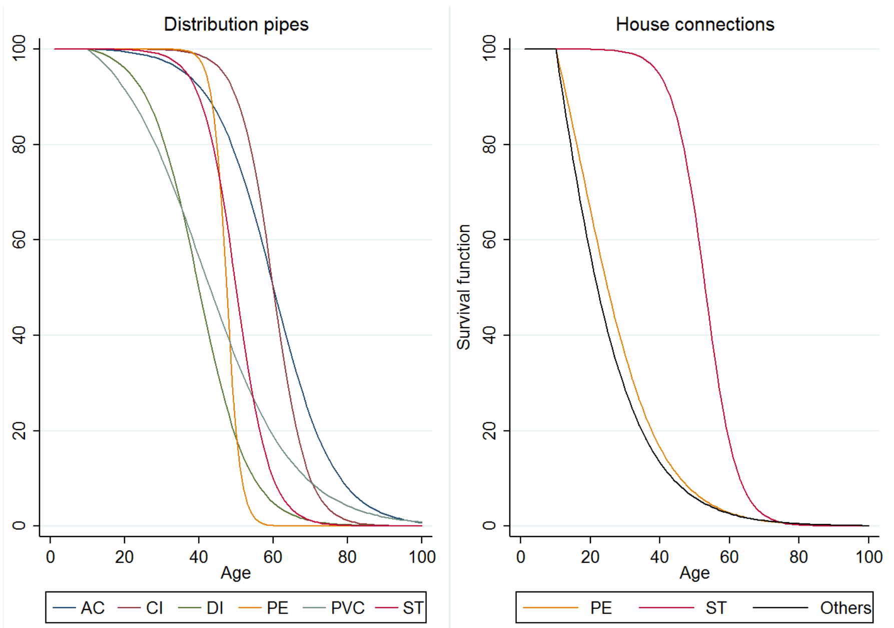

Figure 45: Results of the cohort survival model for the water distribution network of case study 2

In PAPER V a transition function for the urban drainage system of case study 1 is shown. The estimation of the condition states was carried out through the following ISYBAU (Arbeitshilfen Abwasser 2004/242/D, 2012) distinguishing 6 states from immediate action necessary (CS5) to no action necessary (CS0). For this case study the approach shown by Ana (2009) was used to estimate the transition functions for the different materials (concrete and vitrified clay) of the sewer system (see figure 46). We see that the average life expectancy for the different materials is quite high (around 120 years). This could be caused by missing rehabilitation data as well as historical data, which is often the case for smaller case studies. This could lead to an overestimation of the life expectancy (Scheidegger et al., 2011), which could be handled by the implementation of expert knowledge with Bayesian inference (Egger et al., 2013). On the other hand it is possible that the expert knowledge is already biased by existing models. Moreover, it is possible that the condition rating could be misleading, giving higher a condition rating to conditions that don't deserve it due to the coding system used. Therefore, a pre-filtering of condition states depending on failure type and cause could be advisable if this data is available.

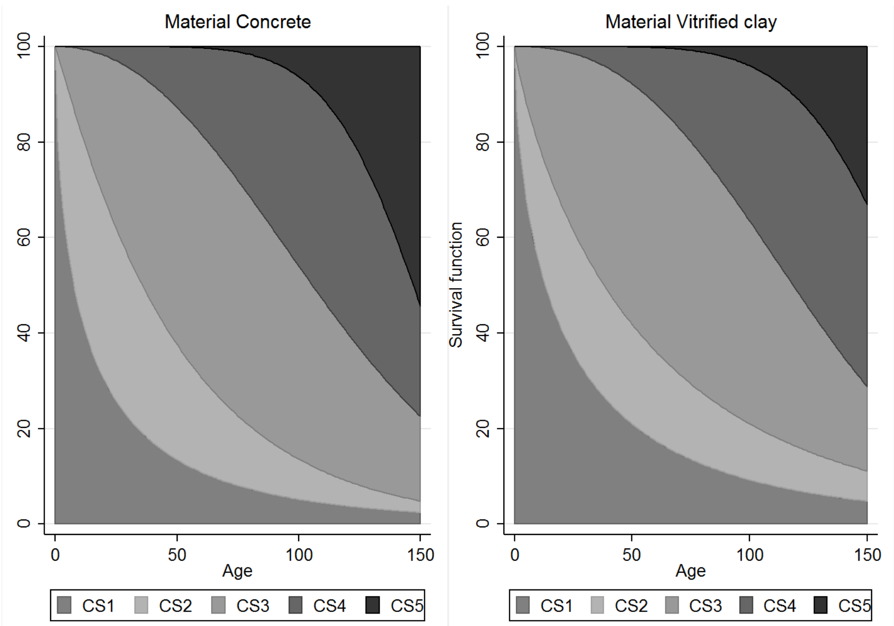

Figure 46: Results of the cohort survival model for the sewer system of case study 1

The major advantage of the cohort survival model is its conceptual and computational simplicity (Ana and Bauwens, 2010). Although it needs an extensive data-set (Fenner, 2000) and it can be difficult to find homogenous cohorts with sufficient inspection data. One of the shortcomings of this model is the fact that it can only deal with relatively large groups of pipes and not on the individual pipe level itself. Moreover, when dealing with water distribution networks there is also a weakness in that it links replacement with the end of its useful service life, which is not always true (Kleiner and Rajani, 2001).

4.2 BINARY LOGISTIC REGRESSION MODEL

Advantages: Individual pipe level, influencing factors can be identified, smaller data requirements. Disadvantages: prior knowledge about processes necessary, only binary outcome

For the binary regression model a dichotomous deficiency outcome with 0 representing "not deficient" and 1 representing "deficient" is assumed (Ariaratnam et al., 2001). This can be for water distribution systems failure or no failure and for sewer systems better than a certain condition state or not (PAPER V).
Ariaratnam et al. (2001), Kleiber and Zeileis (2008), Ana and Bauwens (2010), Urban and Mayerl (2011), Ahmadi et al. (2013) and Friedl (2014) describe it as following:
The methods employed in an analysis using logistic regression follows the same general principles used in linear regression. In regular linear regression however the expected value of the dependent variable y is modeled as a linear function of the explanatory x-variables. This is different in logistic regression - the outcome variable is not modeled directly, but the probabilities associated with the values of y, due to the fact that linear regression makes no sense with binary dependent variables. To enable the further usage of a linear function, which is advisable in terms of simplicity and interpretability, a link function is introduced. Given that y takes on values of 1 (e.g. pipe in a bad condition state) or 0 (e.g. pipe in a good condition state), the hypothetical population proportion of cases for which $y = 1$ is defined as $\pi = P(y = 1)$. This results that for the cases $y = 0$ it is $1 - \pi = P(y = 0)$ and the odds of having $(y = 1)$ are equal to $\frac{\pi}{1-\pi}$. This is the link function introduced for the logistic regression. Hereby logistic regression is based on a linear model for the natural logarithm of the odds (i.e., the log-odds) in favour of $(y = 1)$ - used in PAPER IX. We can therefore state:

$$\log\left[\frac{\pi}{1-\pi}\right] = \log\left[\frac{P(y=1|x_1, x_2, \ldots, x_k)}{1 - P(y=1|x_1, x_2, \ldots, x_k)}\right]$$
$$= \beta_0 + \beta_1 \cdot x_1 + \ldots + \beta_k \cdot x_k = \beta_0 + \sum_{j=1}^{k} \beta_j \cdot x_j$$

β_0 is the intercept term and β_j are the regression coefficients associated with the k predictor variables x. Using an exponential transformation this equation can be converted to the probability that $y = 1$:

$$P(y=1|x_1, x_2, \ldots, x_k) = \frac{e^{\beta_0 + \sum_{j=1}^{k} \beta_j \cdot x_j}}{1 + e^{\beta_0 + \sum_{j=1}^{k} \beta_j \cdot x_j}}$$

The parameters β are estimated from the available data using the maximum likelihood estimation (MLE).
The results of a binary logistic regression model are used for PAPER I

and PAPER IX. PAPER IX describes in detail the modeling and quality control as well as the influencing factors for the sewer system of case study 1. The distribution of the results on the network is shown in figure 47.

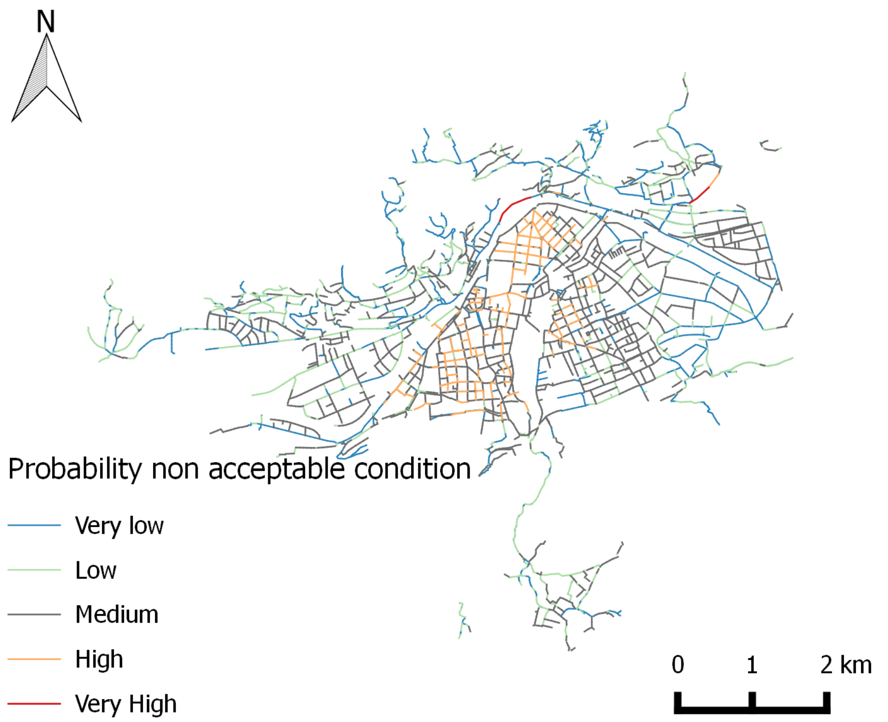

Figure 47: Result of the binary logistic regression model for the sewer network of case study 1

In PAPER I the same approach is also used for the water distribution network of case study 1, but not described in detail. Therefore it is shown here as an example for the applicability of the method for deterioration modeling. Figure 48 shows the receiver operating characteristic (ROC) curves of the model used. For the ROC-Curve the true positive rate is plotted against the false positive rate for every cutoff value. For a sensible predictive model it should be above the diagonal (representing random guessing), as near as possible to the upper left corner which represents the perfect fit (Kleiber and Zeileis, 2008). We can see that the fit of the model is reasonable (area under the ROC-curve 0.7932). To reach a sensitivity and specificity of around 0.75, a cut-off value between the binary variables of 0.07 is estimated by using the sensitivity/specificity plot. The distribution of the results on the network is shown in figure 49.

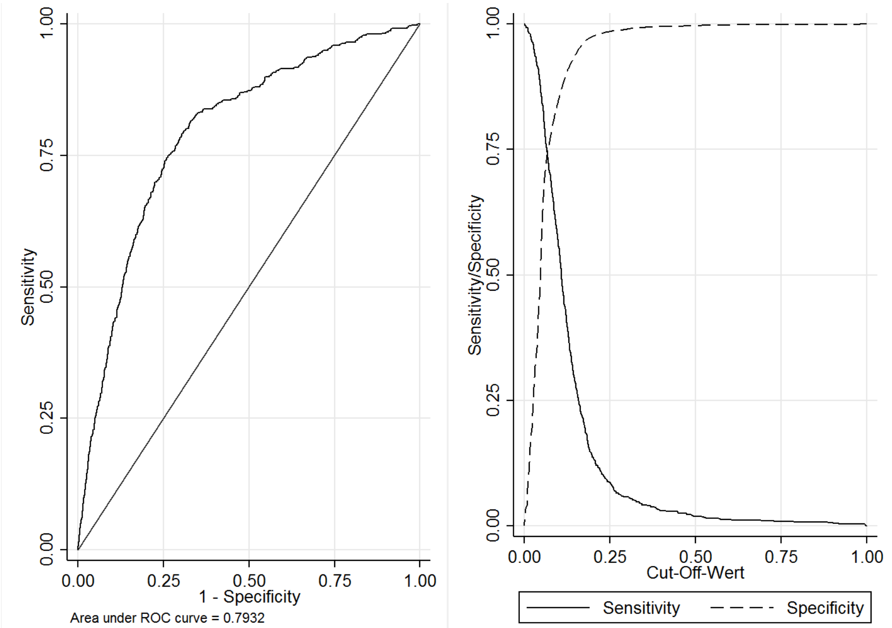

Figure 48: ROC-curves (left) and sensitivity/specificity plot (right) for the water distribution network of case study 1

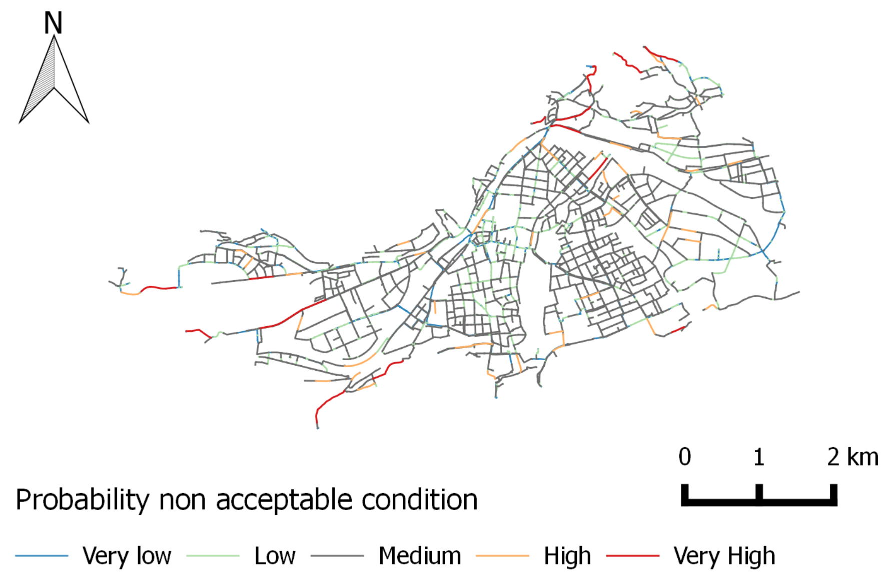

Figure 49: Result of the binary logistic regression model for the water distribution network of case study 1

Table 8 summarises the significant factors derived from the binary logistic regression. It can be seen, that the probability of failure rises with the advancing age and pipe length and declines with higher diameters as also seen by Friedl (2014). The material parameter is the difference between steel pipes and all other materials, showing that steel pipes have a much higher failure probability which contrasts with the findings of Friedl (2014). The operator however stated that there were problems with steel pipes and therefore it can be seen as network specific and plausible.

Table 8: Significant factors of the binary logistic regression model for the water distribution network of case study 1

Significant factors	Coefficients β	Standard errors	Wald statistics	Significance levels
Pipe age	0.006	0.002	13.32	0.000
Pipe diameter	-0.010	0.001	117.51	0.000
Pipe material	0.501	0.177	8.07	0.005
Pipe length	0.018	0.001	290.70	0.000

The main advantage of this model is, as can be seen in the figures 47 and 49, that this model permits the estimation of failure probabilities on an individual pipe level. Another advantage is, that it provides insight into the deterioration process by identifying the most important variables affecting the process (Ana and Bauwens, 2010). Another upside is the smaller data requirements in comparison to other methods. Ahmadi et al., 2015 showed that 1,000 segments out of 9,810 could be representative for the whole asset stock of a sewer system. Having data even with huge amounts of uncertainty is thereby preferable to having incompleteness within the utility database (Ahmadi et al., 2014a). Nonetheless, the model still requires a sufficient amount of data, specifically on the possible factors affecting sewer deterioration, to obtain reliable estimates of the regression coefficients (Ana and Bauwens, 2010). The model results will only be as good as the quality of data collected (Ariaratnam et al., 2001). Disadvantages could be the problem of identifying independent variables, which needs a prior understanding of the deterioration processes, as well as the limitations regarding the outcome variables being either binary or ordinal if the model is enhanced to an ordinal regression model (Younis and Knight, 2010a).

4.3 SIMPLIFIED APPROACHES FOR THE MODELING OF REHABILITATION RATES

Simplified approaches for the modeling of rehabilitation rates with limited data. Starting point for more sophisticated modeling and data survey not final approach.

With the necessary data the aforementioned models can provide useful information about the necessary rehabilitation rates in the future. When these data are not available however, which can be a concern mainly in the starting phase of data collection and rehabilitation planning, simpler approaches can provide a first overview:

- Prognosis adding life expectancy to existing data
- Simplified approach using average life expectancies and failure distribution (PAPER V)
- Prognosis using average network age as a quality indicator (PAPER VI)
- Prognosis using failure rate either using average failure rate or from deterministic models

The first three approaches only require basic data such as the length of the existing network classified into material and type of the pipes as well as the construction year. This can be either known or acquired by data reconstruction or even extrapolation of an existing data sample. The fourth approach is a little more complex and requires failure recordings to enable modeling.
For the first two approaches the average life expectancies for different groups are assumed, either using expert knowledge (PAPER VII) or by the available data or literature (Baur, 2004; Scholten et al., 2013). They are used to predict future rehabilitation rates by simply adding them to the existing data (first approach) or under the assumption of a normal distributed life expectancy (second approach). The main uncertainty of these prognoses is the assumption of certain life expectancies. This has therefore to be done with extreme care. Literature values can have a wide range, therefore a plausibility check with the operator is highly recommendable. In addition, the implementation of another type of distribution other than a normal distribution (like for example a Herz-distribution (Herz, 1998) or Weibull-distribution (Røstum, 2000)) would have effects and could be considered.
PAPER VI shows how to use the average network age as an indicator of failure risk and objective function for the rehabilitation rate using assumptions by Theuretzbacher-Fritz et al. (2006) and Fuchs-Hanusch et al. (2009). For choosing a certain average age as objective function failure recordings are helpful. They are needed for the last approach to estimate failure rates for different groups using approaches as for example shown in DVGW G 403 (2011). The estimated failures are connected to a certain rehabilitation length, which depends on the operator, but could range between 100 - and 200m (Gangl, 2008). While the first three approaches are easily applicable to sewers as well as other networks, the fourth approach could be more difficult for sewers due to the fact that when the necessary data for this kind of model is available a more sophisticated modeling approach may be possible.
To show the application for the networks I will show two examples from the case studies used. Case study 2 was already shown in PAPER VI. For the distribution pipes of the water distribution network

of case study 3 it was assumed that the failing pipes are replaced by a material with a higher life expectancy. Cast iron is replaced by ductile iron and asbestos cement by PVC. Figure 50 shows the result of the second approach for this dataset using literature values from Baur (2004).

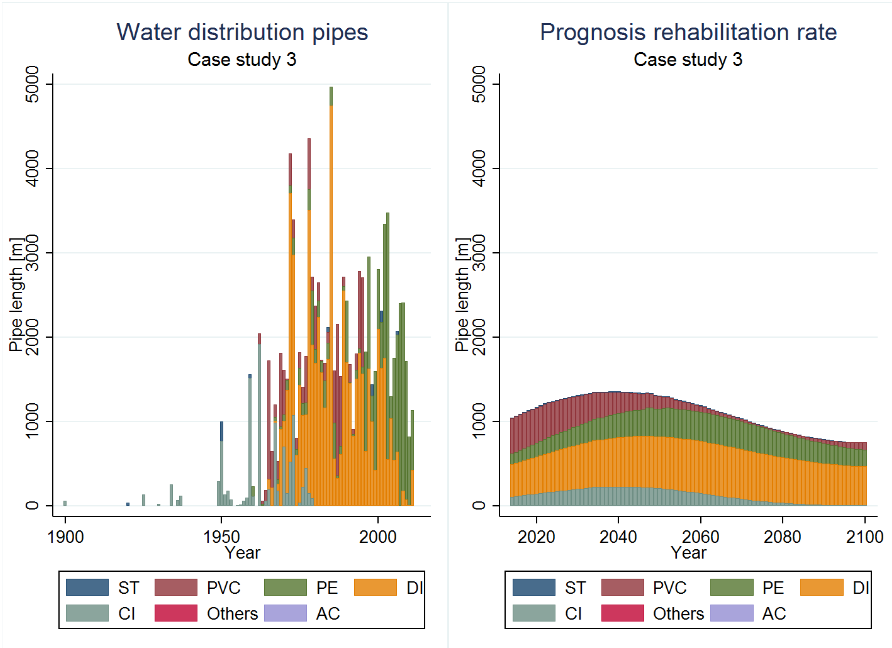

Figure 50: Simplified approach using average life expectancies and normal failure distribution for the water distribution pipes of case study 3

If we compare the different approaches (figure 51) we see quite large differences between the different approaches, which underlines the importance of carefully choosing the approach. The first approach shown is the result of figure 50 with used literature values. For a comparison we used the same approach but with the survey data of PAPER VII. The differences are small but the peak of rehabilitation moves forward around 20 years which could change financial planning considerably. Another approach (described in detail in PAPER VI) is the usage of the average network age as an indicator for failure risk and rehabilitation rate (Fuchs-Hanusch et al., 2009) assuming a connection between higher failure rate and a higher network age (Theuretzbacher-Fritz et al., 2006). If we would therefore like to keep the actual average network age of 27 years, being content with the network performance in terms of failure rate, we would need considerable rehabilitation rates of around 3.5% per year which is implausible. This is not only due to financial reasons but also due to the fact that 27 is quite young and no high failure rate is observed.

If we would allow the average network age to rise to 50 years by not rehabilitating any part of the network (just doing the necessary repairs) and keeping it constant from this point we would then need rehabilitation rates of 2% until 2100.
The failure rates were estimated using the approach of DVGW G 403 (2011) and every failure was connected to 150m of necessary rehabilitation length (Gangl, 2008). It can be observed that this approach delivers a lower rehabilitation rate of around 0.5% per year. This however may be caused by the short failure recording time. For this dataset the approach using expert knowledge is the most plausible.

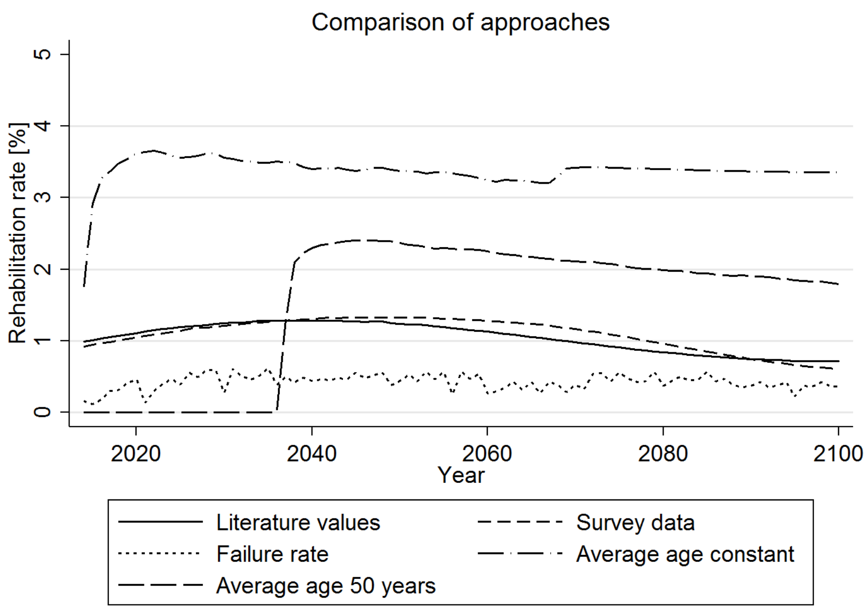

Figure 51: Comparison of the different approaches for the water distribution pipes of case study 3

For the sewer network of case study 1 (see figure 16 for the network data) we also used different approaches (see figure 52). First we just added life expectancies without any distributions to the network age: 50 and 100 years following the range of depreciation time defined in LAWA (2005). For reasons of illustration the first year of rehabilitation need is not depicted due to the fact that the percentages of the network older than 50 (50.30%) and 100 (16.97%) years would change the scale in a manner that no difference between the different approaches would be visible. This also illustrates one shortcoming of this approach - if the network is already quite old a high amount of rehabilitation would be shown at the beginning and is not distributed. This could however be countered by applying a maximum rehabilitation rate (as shown in PAPER VI). If we use an approach with a failure distribution we get a less ragged rehabilitation rate. Here again the life expectancy used is important. If we use a value of 80 years (corresponding to the average technical design life of replaced pipes given by Berger and Falk (2011)), we would have a rehabilitation need of 1.75% in the next year decreasing to 1% until the year 2065. If we use the average life expectancies estimated by the cohort survival model for case study 1 the rehabilitation rate would require 0.75% of replacements the next year increasing until 2065 again until 1% is reached. If we use literature values (Hörold and Baur, 1999) an even lower rate (from 0.10% to 0.60% in 2065) is estimated. Due to the fact that here there was enough data available for a cohort survival model, the results of this model are the most plausible. It can be seen however that the differences between the approaches are large. Although overestimating the rehabilitation need, the average value of 80 years seems a good compromise for a first estimation. However due to the simplicity of the approaches and the low data requirements the estimation and comparison of all of them is possible and could show shortcomings and necessities in data recording as well as different views on rehabilitation strategies.

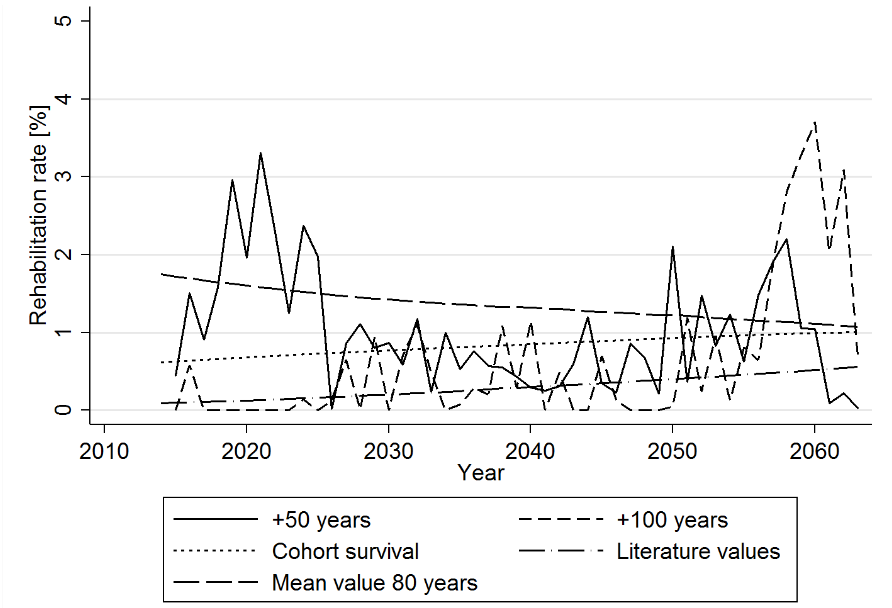

Figure 52: Comparison of the different approaches for the sewer system of case study 1

5 MULTI-CRITERIA DECISION SUPPORT MODELS

In any moment of decision, the best thing you can do is the right thing, the next best thing is the wrong thing, and the worst thing you can do is nothing.

Theodore Roosevelt

Most real-world planning contexts are characterised by multiple, noncommensurate, and often conflicting goals or objectives (Bogetoft and Pruzan, 1997). A good tool for providing aid in rehabilitation planning of urban infrastructure is the prioritisation of the infrastructures (Osman and Bainbridge, 2011). Multi-criteria decision making (MCDM) can help operators to produce a preference ranking of their systems in order to invest their capital efficiently, by supporting them to make choices in cases with multiple and conflicting criteria taking their preferences into consideration (Bogetoft and Pruzan, 1997).

The goal of multi-criteria decision support models: Every decision should be repeatable, reviewable, revisable and easy to understand.

Larger municipalities (>50,000 inhabitants) have normally a better asset management and use software tools for prioritizing their rehabilitation projects. However, many municipalities still use the 'do not fix it if it is not broken' strategy (Younis and Knight, 2010a). This is especially the case of small municipalities with limited data availability and insufficient inspections of their networks. There, mostly expert knowledge or the experience of engineers are used in order to define rehabilitation and replacement projects. The support of smaller municipalities making their prioritisation is important since the majority of the infrastructure networks in the world serve populations of less than 100,000 (Alegre and Coelho, 2012). Furthermore, their pipe length is longer based on the inhabitants. Moreover, if the construction cost is smaller due to the smaller diameters, the specific costs are still higher than for larger towns (Maurer et al., 2010).

Good decisions can best be reached when everyone included in the process has a clear view of how the process will work and has acknowledged the procedure (Baker et al., 2001) and at the end is confident of their decisions (Løken, 2007). Multi-criteria decision-making (MCDM) provides this systematic approach in combining different inputs with benefit/cost information and decision-maker or stakeholder views to rank the alternatives (Kabir et al., 2014). Such a decision-making process provides the following advantages (Baker et al., 2001):

- Structure for approaching current and future complex problems;
- A rational view on the problems and rational ranking of the possible solutions;
- Consistency and objectivity in the decision making process;
- Documentation of all the assumptions used, criteria, and values used to make decisions for later review and for usage for future problems;
- Every decision is repeatable, reviewable, revisable and easy to understand.

Multi-criteria decision-making models used for planning infrastructure management are limited to give suggestions for infrastructure managers about where and when rehabilitation works can be executed. The actual operational decisions for when, with whom, where and how works are executed are taken by a variety of stakeholders. Therefore, setting up the priority model by the various stakeholders involved together creates a shared understanding of each others reasoning. This may be beneficial to integrated planning in the future. The discussion should however lead to at least the recording of decisions and their reasons by the operating company (van Riel et al., 2014) so as to evaluate existing plans and enhance future planning processes. Political influence or operational decisions or legislation (for example mandatory infiltration or the banning of a certain material) could be implemented using either socio-economic models (De Haan et al., 2011) or by working closely with the decision makers and implementing their decision at short notice. Finally, factors which derive from the operator's experience, such as problems with the quality of workmanship in certain areas or similar cannot be grasped by statistical means, the so called intuition (van Riel et al., 2014), could be considered as well. Although these are complex concepts, they could be used for a scenario analysis and a discussion basis for stakeholders and decision makers. What also has to be established is for which purpose the decision support model is used. For the decision about rehabilitation it is only viable if all information is available, especially condition data. If no, or only patchy condition data is available (visual inspection in sewers or failure recordings for water supply) a final decision may not be taken but merely an prioritisation for inspection or further investigation of the area. PAPER I and PAPER II approached this shortcoming by first giving merely a prioritisation of areas and then applying a further decision step if data is

or becomes available. A further step would then be the decision for a certain rehabilitation method, as for example shown by Ochs (2012) for sewers.
The last decades have intensified the interest in the application of formalised decision-analytical tools, due to the complexity of problems as well as the higher availability of data (Huang et al., 2011). Belton and Stewart (2002); Egger (2015); Løken (2007) categorized the method into three schools:

- Value measurement models: a numerical score for each alternative is constructed. Furthermore, a weight w is assigned to each criterion, which represents the importance of the criterion (e.g. Weighted Sum Model, Analytic Hierarchy Process).
- Goal, aspiration and reference level models: these methods measure how good alternatives reach determined goals or aspirations (e.g. TOPSIS, VIKOR).
- Outranking models: these methods compare the alternatives pairwise for each criterion, finding the strength of preferring one over the other (e.g. ELECTRE, PROMETHEE).

Kabir et al. (2014) showed that in the field of water and wastewater infrastructure the most used multi-criteria decision-making methods were the following either exclusively used or in combination:

- Analytic Hierarchy Process (AHP) (used for estimation of weights in PAPER I): A widely used approach for obtaining of preferences or weights of importance to the criteria and alternatives for a variety of research fields. Al-Barqawi and Zayed (2008) used it in combination with an artificial neural network to evaluate the performance of water mains. Birgani et al. (2014) and Sabzi and King (2015) applied it to urban flood management to determine the priority of flood vulnerable areas considering the technical, social and environmental aspects. Lee et al. (2009) and Yang et al. (2005) included it into a decision making support system for the rehabilitation planning of sewer systems and Young et al. (2010) for the management of stormwater networks. Furthermore, it is often used in combination with GIS for example for the landslide vulnerability of areas (Feizizadeh et al., 2013) or forest fire risks (Feizizadeh et al., 2015). It was chosen for the paper due to the well-known methodology, although it requires substantive preparation and analysis in order to get the decision factor weights.
- ELECTRE - ELimination Et Choix Traduisant la REalite: These are a set of models including ELECTRE I, II, III, IV, A, IS and TRI

(Kabir et al., 2014). They are often used in Europe (Kabir et al., 2014) in the wake of the CARE-W (Sægrov, 2005) and CARE-S (Sægrov, 2006) projects. Baur and Herz (2006) and Carriço et al. (2012) used it for thw rehabilitation planning of sewers and Moura et al. (2006) as well as Martin et al. (2007) for urban stormwater drainage management. Sabzi and King (2015) applied it to urban flood management. Haider et al. (2014) estimated performance indicators for small and medium sized water utilities using this approach, while Le Gauffre et al. (2007) used it for the rehabilitation management of water mains. Morais and Almeida (2007) applied it to estimate the amount and place of investments in water distribution networks and Trojan and Morais (2012) for maintenance management.

- PROMETHEE - Preference Ranking Organisation METhod for Enrichment Evaluations: These are also a family of models including PROMETHEE I, II, III, IV, V, VI, GDSS, TRI and CLUSTER (Behzadian et al., 2010). This is seldom used in the field of rehabilitation management. Al-Rashdan et al. (1999) used it to prioritise environmental projects in Jordan and to evaluate their environmental impacts. Gervásio and da Silva (2012) showed the comparative assessment of alternative infrastructures with this method taking into account environmental, economical and social criteria evaluated over the complete life-cycle applying it to bridges. Behzadian et al. (2010) gives a good overview over the application of the method in fields like environmental management, hydrology and water management, business and financial management, chemistry, logistics and transportation, manufacturing and assembly, energy management, social and other topics.

- Compromise programming (CP): It was introduced by Zeleny (1973). It is a distance based method designed to identify solutions that are closest to an ideal solution by some distance measure. It is easy to use and easily understandable and gives good performance when compared with more sophisticated methods but it is also time consuming (Kabir et al., 2014). Dorini et al. (2011) used it for sustainability assessment, mainly focusing on uncertainties, and Abrishamchi et al. (2005) used it to select alternatives for water supply management, while Sabzi and King (2015) applied it to urban flood management.

- Weighted sum models (WSM) or simple additive weighting (SAW) (used in PAPER III and PAPER IX): Weighted sum models are often used for single dimensional problems, as for example for only one network with limited amount of data, providing good performance when compared with more sophisticated methods (Kabir et al., 2014). In rehabilitation management this is seldom the case due to the large amount of data and influences, hence it is seldom used alone but mainly in combination. Ochs (2012) showed for example its application for sewer rehabilitation methods and Coutinho-Rodrigues et al. (2011) for the planning of urban infrastructures in general and Sabzi and King (2015) applied it to urban flood management. In the above mentioned papers it was mainly used, due to its simple application and due to the fact that a more complicated approach would have required a higher data quality.

- TOPSIS - Technique for order of preference by similarity to ideal solution: This method was developed by Hwang and Yoon (1981). The main idea came from the concept of the compromise solution to choose the best alternative nearest to the positive ideal solution (optimal solution) and farthest from the negative ideal solution (inferior solution). Then, choosing the best one at sorting, which will be the best alternative (Tzeng and Huang, 2011). The benefits are that the only judgments required are weights, while relative distances depend on the weights and on the range of alternatives themselves. The non-linear relationship between single dimension scores and distance ratios produces smoother tradeoffs (Huang et al., 2011), considering both the positive and negative ideal solutions (Pires et al., 2011). A weakness of the method is the need for vector normalisation for multi-dimensional problems (Kabir et al., 2014). This method is mainly used for strategic decisions, energy and sustainable manufacturing problems (Huang et al., 2011). However Moura et al. (2006) used an adapted approach to design stormwater scenarios, Sabzi and King (2015) applied it to urban flood management and Coutinho-Rodrigues et al. (2011) to the planning of urban infrastructures in general.

- VIKOR - Vlse Kriterijumska Optimizacija Kompromisno Resenje (used in PAPER II): This method was mainly used to evaluate policy options and short- and longterm strategic planning for water resources such as river basin, watershed and dams and problems of structures such as multi-housing projects (Kabir et al., 2014). Sabzi and King (2015) applied it to urban flood management and Milojković and Andrić (2009) used it for performance indicator evaluations of sewerage systems. It was used for PAPER II due to the applicability using attributes with different units as well as the usage without the interactive participation of decision makers.

PAPER I uses a novel combined approach using AHP for the estimation of weights and then a weighted sum model with the implementation of economical and technical thresholds. This was applied for the inter-network prioritization of street sections. PAPER II uses a revised VIKOR approach (Huang et al., 2009) for the same purpose. PAPER III and PAPER IX use a weighted sum model for a single network prioritization. Baker et al. (2001), Stone et al. (2002), Butler et al. (2003), Kiker et al. (2005), Tzeng and Huang (2011), Dorini et al. (2011), Huang et al. (2011), Ochs (2012), Kabir et al. (2014), Sabzi and King (2015) and Egger (2015) give a good overview over the methods and how to approach a decision problem. In the following sections a short outline of the methods used in the papers and the most important for the field as mentioned by Kabir et al. (2014) is given.

5.1 ANALYTIC HIERARCHY PROCESS

Advantages: qualitative and quantitative criteria can be used, easy to explain to decision makers. Disadvantages: compensation effects between the different criteria, time-consuming for increasing number of criteria.

Saaty (1980) introduced this method to aid in the decision making process by reducing complex decisions to a series of pairwise comparisons, and then synthesising the results. To apply it one needs a hierarchic or a network structure to represent the problem and pairwise comparisons to establish relations within the structure (Saaty, 1987). Each element of the hierarchy is considered independent of all of the rest and each other including the decision criteria and the alternatives (Kabir et al., 2014). The application can be described using 5 steps:

- Problem definition: A hierarchy is established including the focus of the decision, the criteria and sub-criteria and the examined alternatives. The hierarchy should be complex enough to capture the situation, but small enough to be sensitive to changes (Saaty, 1987).

- Estimation of the values of each criterion for each alternative.

- Criteria weighting: In order to compute the weights for the different criteria, the AHP starts creating a $m \times m$ pairwise comparison matrix $\mathbf{W}$, where m is the number of criteria. The comparison rates, as introduced by Saaty (1980), range from 1, which means the two criteria are equally important, to 9, which signifies that one is extremely more important than the other. All pairwise comparison matrices are reciprocal (Sabzi and King, 2015).
  The next step is developing the weight vector which is accomplished by solving for the principal Eigen vector $\vec{w}$ of the matrix and then normalizing the result (Saaty, 1987). Care has to

be taken that the consistency of subjective perception is ensured (Tzeng and Huang, 2011). Saaty (1980) suggested two indices for this purpose - the consistency index (C.I.) and the consistency ratio (C.R.):

$$C.I. = \frac{\lambda_{max} - n}{n-1} \leqslant 0.1$$
$$C.R. = \frac{C.I.}{R.I} \leqslant 0.1$$

λ_{max} is the largest eigenvalue and n is the dimension of the comparison matrix. R.I. is an average random consistency index of a randomly generated reciprocal matrix (Saaty, 1987). Both values should not exceed 0.1 for the matrix to be consistent.

- Estimation of the score matrix for the alternatives: The next step is to set up matrices $\mathbf{A}^{(j)}$ of paired comparisons of the alternatives for each criteria $j = 1, \ldots, n$, using the estimated values of step 2. For each matrix $\mathbf{A}^{(j)}$ the approach of step 3 is applied resulting in a score vector $\vec{s_j}$. These vectors are combined to obtain the score matrix $\mathbf{S} = [\vec{s_1} \ldots \vec{s_n}]$.
- Ranking the alternatives: We can obtain the vector of global scores for the alternatives by $\vec{a} = \mathbf{S} \cdot \vec{w}$. Then sorting in a descending order provides the global ranking.

The advantages of this method are the possibility to use qualitative and quantitative criteria, the ordered fashion of the decision making which allows a good traceability of the decision and the quality assurance given by the consistency indices. The disadvantages are certainly the loss of information due to the compensation between the different criteria (Macharis et al., 2004) and the, depending on the number of criteria and alternatives, complex and time-consuming implementation (Kabir et al., 2014).

As an example, the application of this method to estimate the weights (as done in PAPER I) of three influencing factors (condition, importance and economics) for the prioritisation of a sewer system is shown using the data of Egger (2015). For the estimation expert knowledge was used giving a comparison matrix of the three criteria (see table 9).

Table 9: Comparison of the criteria according to the AHP scale (Egger, 2015)

K_l	Condition	Importance	Economics
Condition	1	5	7
Importance	1/5	1	3
Economics	1/7	1/3	1

Using the quantification from table 9 in matrix $\mathbf{A}$, the maximal eigenvalue λ_{max} and the comparative weights w_l can be determined:

$$\mathbf{A} = \begin{bmatrix} 1 & 5 & 7 \\ 1/5 & 1 & 3 \\ 1/7 & 1/3 & 1 \end{bmatrix}$$

$$(\mathbf{A} - n\mathbf{I})\mathbf{w} = 0 \quad \Rightarrow \quad \lambda_{max} = 3.065 \quad \Rightarrow \quad w_l = \begin{bmatrix} 9.025 \\ 2.327 \\ 1.000 \end{bmatrix} = \begin{bmatrix} 0.731 \\ 0.188 \\ 0.081 \end{bmatrix}$$

When calculating the consistency index (C.I.) and consistency ration (C.R.), it can be seen that the value does not extend the suggested one of 0.100. This indicates that the quantified judgements between the criteria are consistent and the result is therefore reliable:

$$\text{C.I.} = 0.032 \quad \Rightarrow \quad \text{C.R.} = 0.056 \leqslant 0.100$$

The so estimated weights can then be used for prioritisation. This simple example taken from Egger (2015) shows the possibilities of this method to prioritise in a simple way different influencing factors. In its simplicity it is easy to explain to decision makers and can therefore be a powerful tool. However, it needs to be well prepared with quality and validity checks (done by double questioning) for the information taken by the experts, due to the fact that it is only sensibly applicable when exact and total information is collected (Pires et al., 2011). Egger (2015) for example had to discard some of the expert knowledge due to the inconsistency of the given information. Furthermore, this example also shows the main weakness of the method. While for small amounts of influencing factors it is easy to apply, the more factors used the more complicated it gets.

5.2 WEIGHTED SUM MODEL

Advantages: simple and well known method. Disadvantages: compensation effects between the different criteria, normalisation is required to solve multi-dimensional problems.

The weighted sum model is a simple and well known method for ranking alternatives introduced first by Churchman et al. (1954). The objective function for alternatives can be represented and compared with each other as a linear combination of weighted criteria (Sabzi and King, 2015) in the form of $p_i = \sum_{m}^{j=1} w_j \cdot r_{ij}$, where p_i is the performance value of the ith alternative; w_j denotes the weights of the jth criterion; r_{ij} is the normalised preferred ratings (depending if the criteria is a benefit or cost one) of the ith alternative with respect to the jth criterion and the criteria are assumed to be independent of each other (Tzeng and Huang, 2011). The estimation of the weights can either be achieved by using the methodology of AHP, by simple pairwise comparison (Ochs, 2012) or by using expert knowledge. Normalisation is required to solve multi-dimensional problems which can be considered as a weakness of the method Pires et al. (2011). Furthermore, compensation effects between the different criteria can be observed. Sabzi and King (2015) found out however that it produces similar final ranks as other more sophisticated problems and can be used due to its easy application as a control for other methods.

5.3 ELECTRE

ELECTRE is a family of outranking methods consisting of 7 different models derived from the original ELECTRE I (Benayoun et al., 1966). The shortcomings of ELECTRE I are that it can only find the kernel solution and cannot rank the order among alternatives and since the final results are varied with the vote threshold, how to determine the appropriate threshold remains unknown (Tzeng and Huang, 2011). The most commonly used variation of this method is ELECTRE III (Kabir et al., 2014), developed by Roy (1978). This is the method I will outline here (Belton and Stewart, 2002; Buchanan and Vanderpooten, 2007; Solecka, 2014; Tzeng and Huang, 2011):

Advantages: applicable even with missing information, no compensation effects. Disadvantages: time consuming, complex application, insecurity of reaching the preferred alternative.

- Construction of assessment matrix and definition of decision makers preferences: The first step is defining a consistent criteria family **G** assessing the alternative set **A**. Next, the decision makers preference model is built by determining indifference q_i, preference p_i and veto v_i thresholds as well as criteria weight indexes w_i. Those thresholds determine the preferences range between the alternatives. For alternatives $a, b \in \mathbf{A}$ in the case of $g_i(a) \geqslant g_i(b)$ the two alternatives are considered equivalent if $g_i(b) < g_i(a) < g_i(b) + q_i(g_i(b))$, alternative a is weakly preferred if $g_i(b) + q_i(g_i(b)) < g_i(a) < g_i(b) + p_i(g_i(b))$, strongly preferred if $g_i(a) > g_i(b) + p_i(g_i(b))$ and incomparable if $g_i(a) > g_i(b) + v_i(g_i(b))$.
- Building the outranking relations: For each ordered pair $(a, b) \in \mathbf{A}$ the concordance index $C(a, b)$ and a discordance index for each criterion $d_i(a, b)$ is estimated. The concordance index is defined as

$$C(a, b) = \frac{\sum_{i=1}^{m} w_i \cdot C_i(a, b)}{\sum_{i=1}^{m} w_i}$$

  where $C_i(a, b)$ is the outranking degree of alternative a and alternative b under criterion i. It is defined as

$$C_i(a,b) = \begin{cases} 0 \text{ if } g_i(b) - g_i(a) > p_i(g_i(a)) \\ 1 \text{ if } g_i(b) - g_i(a) \leqslant q_i(g_i(a)) \end{cases}$$

with linear interpolation between this thresholds. The discordance index is defined as

$$d_i(a,b) = \begin{cases} 0 \text{ if } g_i(b) - g_i(a) \leqslant p_i(g_i(a)) \\ 1 \text{ if } g_i(b) - g_i(a) > v_i(g_i(a)) \end{cases}$$

with linear interpolation between these thresholds.
Finally, the degree of outranking is defined by:

$$S(a,b) = \begin{cases} C(a,b) \text{ if } \forall_{j \in J(a,b)}\ d_j(a,b) \leqslant C(a,b) \\ C(a,b) \prod_{j \in J(a,b)} \frac{1-d_j(a,b)}{1-C(a,b)} \ otherwise \end{cases}$$

where $J(a,b)$ is the set of criteria for which $d_j(a,b) > C(a,b)$.

- Application of the outranking relations: At this stage, two complete pre-rankings are obtained from either a descending (Z_1) or ascending (Z_2) distillation process. The algorithm is based on the determination of value $\lambda = \max S(a,b)$ and the cut-off threshold $s(\lambda)$. Only the alternatives are analyzed for which $S^(a,b)$ are sufficiently close to λ, determined by the result of $\lambda - s(\lambda)$. The qualification coefficient k_w is determined for objects which satisfy this relation. It is defined for each alternative by the difference between the number of alternatives to which it is preferred and the number of alternatives to which are preferred to it. The alternative with the highest qualification index is ranked first in the descending pre-order. In further order, from among the remaining variants the best one is selected again and it is placed on the subsequent rank in the classification. The procedure is repeated until the variant set is exhausted. The ascending order is obtained analogically, ranking the alternative with the worst qualification index first. The final order can be obtained after the downward order and upward order are averaged:

$$Z = \frac{Z_1 + Z_2}{2}$$

The main disadvantage is it is time consuming and its complex application and the insecurity of reaching the preferred alternative (Pires et al., 2011). On the other hand it can be applied even with missing information and can take into account uncertainties (Kabir et al., 2014) and even when there are incomparable alternatives (Pires et al., 2011). Another main advantage of ELECTRE III is it is non-compensatory by using a veto threshold v. That means, that a bad score on one particular criterion cannot be compensated by some good scores on other criteria (Buchanan and Vanderpooten, 2007).

5.4 PROMETHEE

The PROMETHEE family of outranking methods, including the initial PROMETHEE I method were introduced by Brans (1982). It is based on the comparison of alternatives considering the deviations that alternatives show according to each criterion, using positive and negative preference flows for each alternative to generate rankings in relation to decision weights (Kabir et al., 2014). Here I will outline the PROMETHEE II method, due to the fact that it is fundamental to be able to implement the other PROMETHEE methods and the majority of researchers have refered to this version (Behzadian et al., 2010). Behzadian et al. (2010) and Tzeng and Huang (2011) define four steps for this method:

Advantages: applicable even with missing information, no normalisation necessary. Disadvantages: time consuming, rank reversal problem.

- Determination of deviations using pair-wise comparison: The first step is defining a consistent criteria family **G** assessing the alternative set $\mathbf{A} = [a, b, \ldots, n]$.

  $$d_j(a, b) = g_j(a) - g_j(b)$$

  estimates the differences between the two alternatives for each criterion.

- Application of the preference function: The preference function translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. Six basic function types were proposed by Brans and Vincke (1985), which can be used particularly easily. For each criterion, the value of an indifference threshold q, the value of a strict preference threshold p and the value of a well-known parameter directly connected with the standard deviation of a normal distribution σ have to be set. The preference of alternative a to alternative b for each criterion can therefore be expressed as:

  $$P_j(a, b) = F_j[d_j(a, b)] \qquad j = 1, \ldots, k$$

- Calculation of an overall preference index: This index is in fact the weighted sum over the preference for each criterion:

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b) \cdot w_i \qquad \forall a,b \in \mathbf{A}$$

  The overall preference index gives the intensity of preference of the decision maker for a over b, all criteria being considered.

- Estimation of the outranking flows: In order to evaluate the alternatives three flows are defined: the leaving flow $\phi^+(a)$, the entering flow $\phi^-(a)$ and the net flow $\phi(a)$.

$$\phi^+(a) = \frac{1}{n-1} \cdot \sum_{x \in \mathbf{A}} \pi(a,x)$$
$$\phi^-(a) = \frac{1}{n-1} \cdot \sum_{x \in \mathbf{A}} \pi(x,a)$$
$$\phi(a) = \phi^+(a) - \phi^-(a)$$

  The higher the leaving flow and the lower the entering flow, the better the alternative. The indifference case in this method between two actions only occurs when the corresponding flows are strictly equal.

The main advantage of this method is the fact that it allows for the direct operation on the variables included in the decision matrix, without requiring any normalisation and is applicable even when there is information missing (Pires et al., 2011). However, it can be time consuming and difficult to keep an overview over the problem when a lot of criteria are involved (Kabir et al., 2014). Furthermore, it is possible that the rank reversal problem occurs, which means that, in some cases, the ranking of the alternatives can be reversed when a new alternative is introduced (Macharis et al., 2004).

5.5 VIKOR

Advantages: decision-maker does not have to be able, or know how to express preferences at the beginning. Disadvantages: linear normalisation necessary.

This method was first introduced by Opricovic (1998). It determines the compromise ranking-list, the compromise solution, and the weight stability intervals for preference stability of the compromise solution obtained with the initial weights (Opricovic and Tzeng, 2004). It focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria, based on a particular measure of "closeness" to the "ideal" solution (Opricovic, 1998). Therefore it determines a compromise solution that could be accepted by decision-makers (Kabir, 2014). Huang et al. (2009) improved the algorithm by altering the maximum group utility and minimum individual regret of the opponent functions. The revised algorithm was however described already in PAPER II and therefore the original method is outlined here. It has the following steps (Huang et al., 2009; Opricovic and Tzeng, 2004; Tzeng and Huang, 2011):

- Determine the best f_i^* and the worst value f_i^- for all criteria $i = 1, \dots, n$

- Compute the maximum group utility S_j and the minimum individual regret of the opponent R_j for all alternatives $j = 1, \dots, J$ using the weights of the different criteria w_i in the relations:

$$S_j = \sum_{i=1}^{n} \frac{w_i \cdot (f_i^* - f_{ij})}{f_i^* - f_i^-} \qquad R_j = \max_i \frac{w_i \cdot (f_i^* - f_{ij})}{f_i^* - f_i^-}$$

- Estimate the synthesised index Q_i introducing the weight of the strategy of the "majority of the criteria" ν with the equation:

$$Q_j = \nu \cdot \frac{S_j - \min_j S_j}{\max_j S_j - \min_j S_j} + (1 - \nu) \cdot \frac{R_j - \min_j S_j}{\max_j R_j - \min_j R_j}$$

- Sort by the values S, R and Q establishing three ranking lists.

- Compromise solution: Use the ranking list of Q and examine the alternative, which is ranked best (a'). a' can be proposed as a solution if two conditions are satisfied. Firstly $Q(a") - Q(a') \geqslant \frac{1}{J-1}$ with $a"$ being the next best solution and J the total number of alternatives. Second Alternative a' must also be the best ranked by S or/and R.
  If only the second condition is not fulfilled alternatives a' and $a"$ are proposed as compromise solutions. If both conditions are not fulfilled the alternatives $a', a", \dots, a^M$ are proposed as long as $Q(a^M) - Q(a') < \frac{1}{J-1}$.

The application of this methodology in case study 3 can be seen in PAPER II. It can be used in terms of infrastructure for the ranking of priorities for the different networks as well as an integrated ranking of all observed networks, for example in figure 53. It shows the prioritisation of street sections for further decisions, about either rehabilitating all networks at once, individual networks, further inspections and so on, using the VIKOR approach for case study 3 as described in PAPER II.

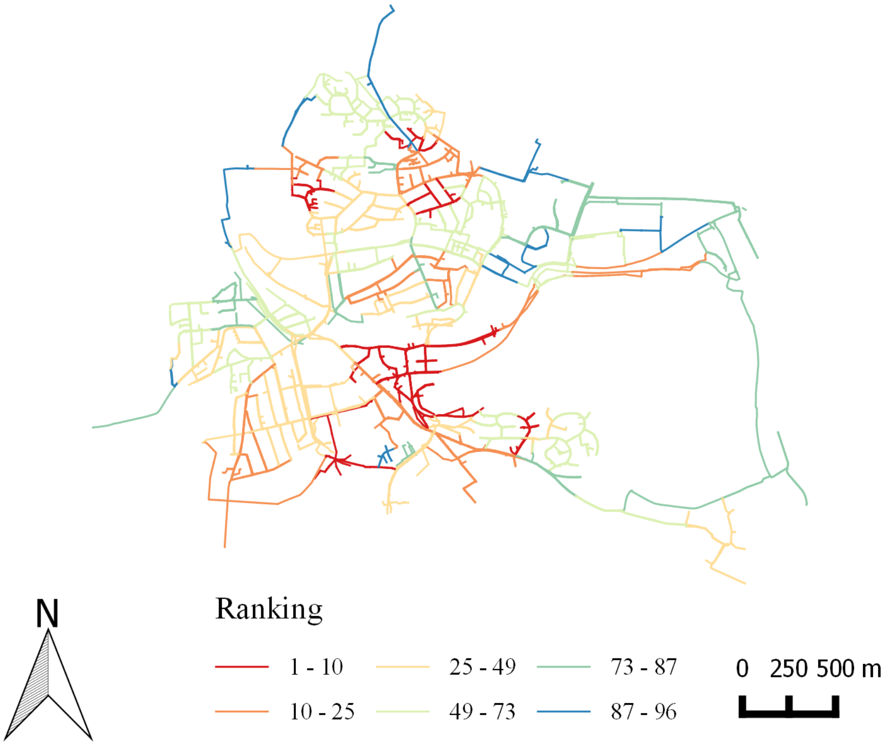

Figure 53: Total ranking of street sections using the integrated approach with a VIKOR decision support system for case study 3 using the data of PAPER II

The main advantages are that the decision-maker does not have to be able, or know how to express preferences at the beginning of the system design (Huang et al., 2009) and it can be performed without interactive participation of decision-makers because of the determination of the weight stability intervals (Opricovic, 1998; Tzeng and Huang, 2011). A weakness of the method is the necessary linear normalisation to solve multidimensional problems (Kabir et al., 2014).

5.6 COMPARISON OF METHODS

Sabzi and King (2015) showed that different methods of different complexity can produce comparable results. Similar results were obtained by Egger (2015) (see figure 54), who estimated however a wider variety of results depending on the method used. This can be on the one hand explained by the different amount of possible ranks (8 for Sabzi and King (2015) to 96 for Egger (2015)) and on the other hand it underlines the difficulties in weighting of different influences as well as the estimation of thresholds.

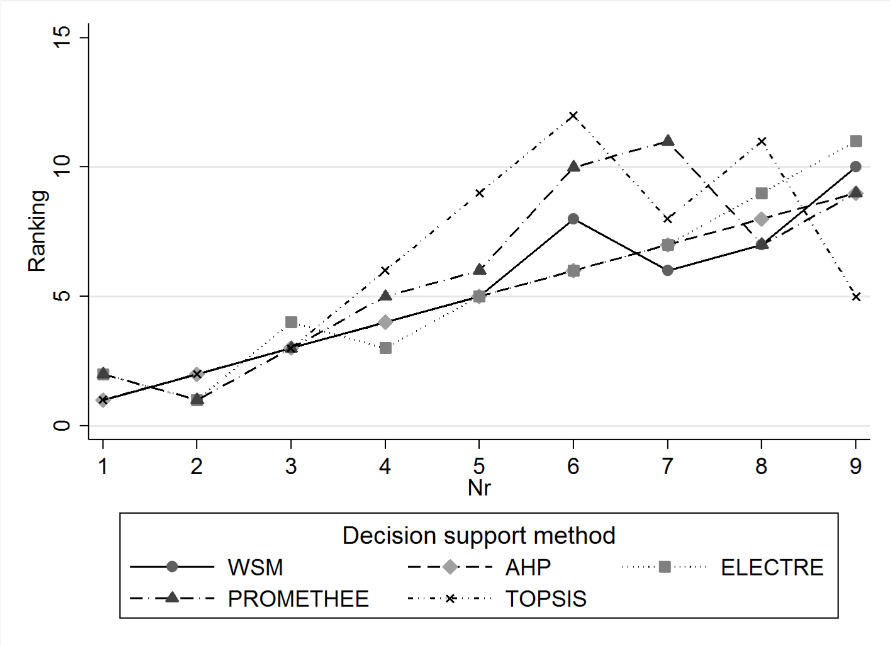

Figure 54: Total ranking of street sections using the integrated approach with a various decision support systems for case study 3 using the data of Egger (2015)

Due to the fact that weighting is a major influence on the decision support models extra care has to be taken in estimating them. That starts with the plausibility checks of the answers, for example by using two levels of specificity in a questionnaire for the same question to check for differences, also including the approach using fuzzy sets (Tzeng and Huang, 2013) and ranges to sensitivity analysis of the results (Triantaphyllou and Sánchez, 1997). Therefore the weights are varied to estimate the robustness of the decision. Either until the results given by the initial set of weights are altered, all other weights being kept constant (Mareschal, 1988) or by using a Monte-Carlo approach for sampling of different weights under the condition that the sum of weights has to be 1. A simple approach is looking at the differences when all weights have the same value (Ochs, 2012).

All methods provide a transparent and comprehensible result. Understanding and right application the chosen method is more important than complexity. Applying sensitivity analysis and various methods increases the reliability of the results.

Another issue is which method provides the 'right' result or rather a transparent and comprehensible result (due to the fact that a 'right' result does not exist), which is even more important. This is given by all the methods used, although different methods work in different ways and give different results (Løken, 2007), since the results and also differences between the methods are always comprehensible. With limited data, it was seen that simple methods such as the AHP gave results similar to the ones obtained with the complex outranking method PROMETHEE. Obviously, the main advantage of the AHP (and also WSM) is that these are simple and quickly understood methods, also for people who are not familiar with the multi-criteria decision support methods. Therefore, in some cases, it would be rational to use one of the simplest methods (Egger, 2015; Sabzi and King, 2015). However, to check for consistency and increase the reliability of the results the application of several methods is encouraged (Cheng et al., 2002).

6 ADAPTATION IN THE COURSE OF REHABILITATION

> Science always has its origin in the adaptation of thought to some definite field of experience.
>
> — Ernst Mach

Rehabilitation can participate in the adaptation. However, careful planning and decision making is necessary before we lay down our systems for the next period of 100 years.

As structures in urban water management have long life expectancies, today's existing systems are strongly influenced by historical decisions and implementations. That means that we are operating systems, designed using methods and guidelines from the past (sometimes 100 years old and more - see PAPER VIII) to face the challenges of the future. To do this adaptations are necessary and in the same way that these historical decision influence our current network, current decisions will have a long-term impact on the future systems. Furthermore, the adaptations have in-built resilience to face future uncertainties and challenges (Wong and Brown, 2009). To test different adaptation strategies various models exist (for an overview see Bach et al. (2014) and Urich and Rauch (2014)), but the link between adaptation and rehabilitation is still seldom addressed. An exception is the approach of Zischg et al. (2015) who investigated the performance development of a water distribution system during city transformation linking it with rehabilitation measures. It was shown that by the application of appropriate rehabilitation measures during the network transition, the partially insufficient minimum pressure performances are enhanced significantly. PAPER IX investigated if it is possible to combine rehabilitation and adaptation measures and therefore also to demonstrate the applicability of the prioritisation model, thereby addressing two main challenges for our infrastructure, using the example of case study 1. This was done by combining four influences:

- The influence of climate change on the rainfall intensity using a climate change factor as proposed by Arnbjerg-Nielsen (2012).
- The influence of urban development on the impervious area as well as the influence on adjacent construction sites using an urban development model (Mikovits et al., 2014, 2015).
- The influences of rehabilitation planning using a weighted sum priority model including a logistic deterioration model, a vulnerability estimation using the Achilles approach (Möderl, 2009;

Möderl et al., 2009) as well as the importance of affected streets (also seen in PAPER I and PAPER III).

- The influence of the different measures - open cut, sliplining and Cured-in-place pipes (CIPP) - on the hydraulic behavior of the sewer network.

PAPER IX shows that the necessary rehabilitation of the existing network can contribute to a certain amount (around 5 - 10% decrease in flooding volume) in the adaptation to the changing environment. Therefore different scenarios were observed with different rehabilitation rates varying from 0.5% to 2%. Variations could be observed between different rehabilitation techniques. A limiting factor here was the limitation on a maximum diameter enlargement of 100mm. Moreover, instead of the hydraulic condition used for this pipe enlargement as being conditional to the used type of design storm a more universal approach, for example hydraulic condition states as defined by Arbeitshilfen Abwasser 2004/242/D (2012) or ÖWAV-RB 22 (2015) (shown in figure 55) could be applied.

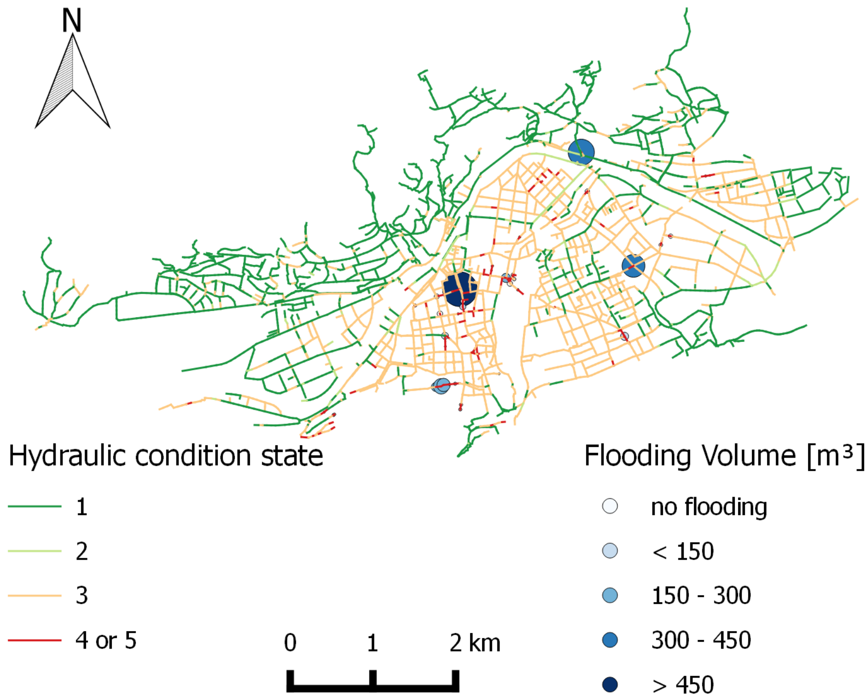

Figure 55: Hydraulic condition states following ÖWAV-RB 22 (2015) for the sewer system of case study 1

The differentiation defined is however too diverse, due to the fact that 3 condition states would be sufficient. The differentiation for example between condition state 4 and 5, differentiating between the possibility of diverting the flooded volume without damage to the surrounding structures, proves difficult with a hydrodynamic model without explicit flooding simulation (e.g. 1D-2D models). However, this needs an extensive data elicitation not only in terms of the volume leaving the sewer system, but information about flood paths and depths as well as information about buildings and other structures. At the same time this increases the difficulty in creating the model and the computational time Leandro et al. (2009). Also the differentiation between hydraulic function is fully given (condition state 1), is given (2) and is limited (3) could be simplified to 2 condition states.

Another important parameter that is considered are the costs of the different scenarios (Tscheikner-Gratl et al., 2014b). In figure 56 we see the total yearly construction costs for different rehabilitation methods (using costs by Zhao and Rajani (2002)) at different rehabilitation rates. What we can see is that, using a fixed rehabilitation rate, can produce a wide range of costs due to the different prices for the rehabilitation of different diameters. The open cut method is by far the most expensive one with nearly double the costs of the other two.

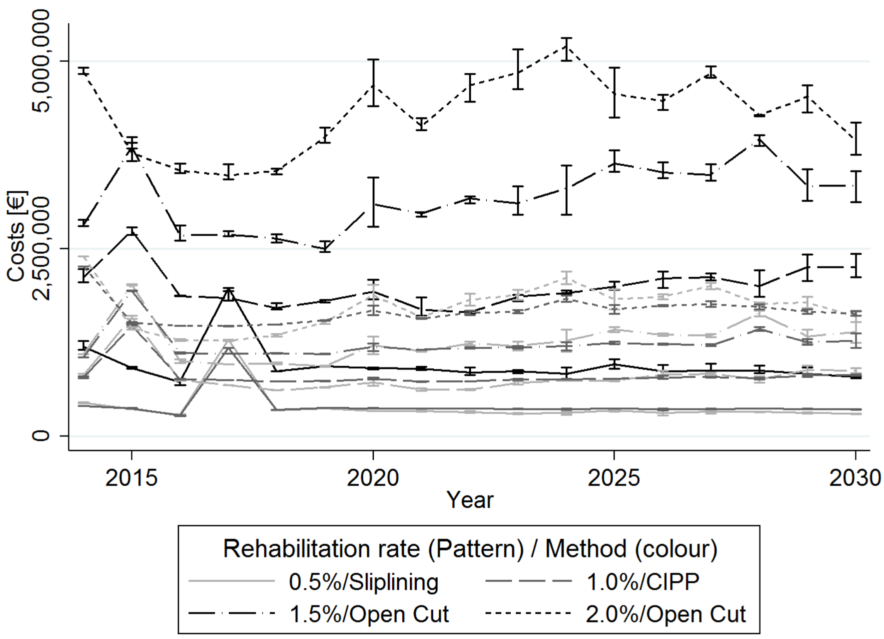

Figure 56: Yearly total costs of the different rehabilitation methods for different rehabilitation rates (Tscheikner-Gratl et al., 2014b)

If we assume however a different life expectancy for the different methods, as given by expert knowledge (Berger and Falk, 2011) (in our case 100 years for the open cut method and 50 for the other two), the picture changes (Figure 57) and in some years the open cut method is the most cost effective method. Therefore the usage of the different rehabilitation methods should be carefully planned (Ochs, 2012; Wolf, 2006).

The approaches of PAPER IX and Zischg et al. (2015) are only a first rough estimation of the possibilities offered by implementing the necessary rehabilitation methods into the adaptation plans of our urban water infrastructure. It can be seen that for the urban drainage system the possibilities are somewhat limited and the need for adaptation measures could overpass the need for rehabilitation measures. The possible flooding reduction could however be increased by coordinated measures together with decentralised solutions (Ahmed et al., 2015; Barbosa et al., 2012; Kleidorfer et al., 2009; Lerer et al., 2015; Matzinger et al., 2014; Mitchell, 2006; Sitzenfrei and Rauch, 2014; Smith, 2009; Wade et al., 2014; Yang and Li, 2013). The solutions themselves are known and studied but the interactions, possible synergies in terms of rehabilitation management and economic planning however are topics for further research. The approach must be flexible and multidisciplinary, and consider legal, economic, social and environmental aspects, among many others (Barbosa et al., 2012).

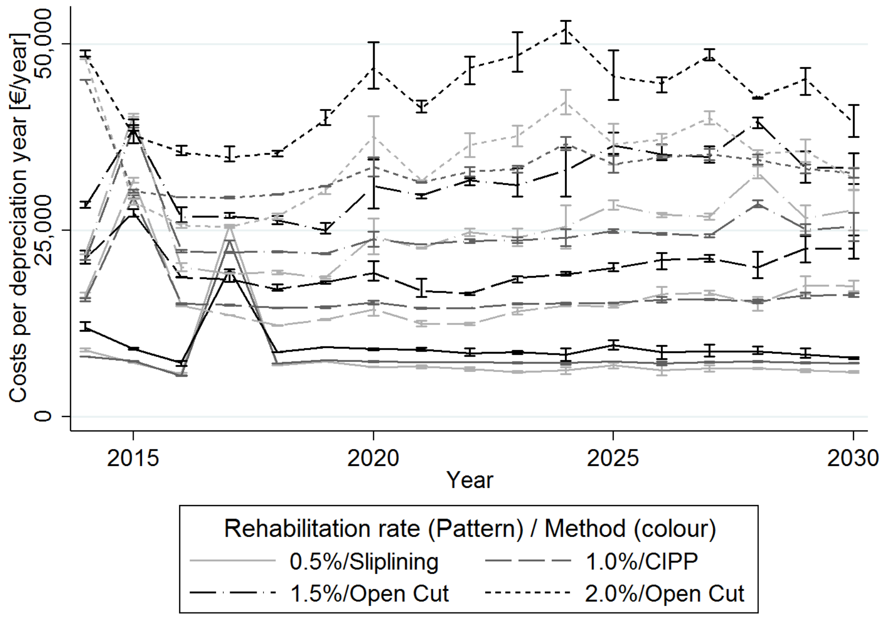

Figure 57: Costs of the different rehabilitation methods for different rehabilitation rates applied for different depreciation times (Tscheikner-Gratl et al., 2014b)

7 CONCLUSION, DISCUSSION AND OUTLOOK

Reasoning draws a conclusion, but does not make the conclusion certain, unless the mind discovers it by the path of experience.

— Roger Bacon

7.1 CONCLUSION

Three main points: Data management, integrated multi-utility approach for rehabilitation, rehabilitation and adapation.

This dissertation and the included papers show the possibility of an integrated approach for rehabilitation management crossing the boundaries of individual networks, its problems and application in different case studies. After introducing the legal basis the most important ideas and terminology of integrated rehabilitation management were discussed giving reference to the state-of-the-art methods in this field. The data problematic, which hampers the application of models for small and medium sized municipalities, was highlighted using 3 case studies of different sizes and quality. Furthermore, optimal and minimal data requirements for the application of the mentioned models and recommendations for future data management (see chapter 3) were given. This work used these inputs to develop approaches for data reconstruction and the estimation of the necessary rehabilitation rates using limited data availability. Moreover, the available models regarding deterioration and decision support and literature review on their application were given. The most used models were applied to the case studies and implemented in decision support models depending on the data quality and availability. This ranged from a simple weighted sum model, a VIKOR approach to a novel three-step methodology for the integrated prioritisation of different infrastructure networks used in a real case study. This methodology for the integrated prioritisation of the different infrastructure networks used in real case studies aims to rank, and thereby prioritise, areas for rehabilitation of the different networks if economically viable or for single networks if not. It is an easy to use rehabilitation management procedure for small and medium sized municipalities. It is adjusted to the main problems for small operators - missing or

only just begun data management and therefore bad or at best mediocre data quality. Furthermore, the simple and modular setup of the methodology enables the usage without extensive programming skills and provides the possibility of adding further information and networks. Finally by applying the established method for the sewer system of a case study the possible contribution of rehabilitation measures to the necessary adaptation to changing environment conditions was estimated. Figure 58 sums up the methodology of this work, pointing out the parts where existing methods were enhanced or new methods were applied.
Starting with the actual input data (in this work from 3 case studies and different networks), the methodology requires first a plausibility, validity and completeness test of the data. If the data does not have the sufficient quality a data reconstruction method (PAPER VI) is applied. The reconstructed data is tested again if it suffices the requirements of at least the necessary quality for the simplified approach. If not, data mining is necessary using either historical data (PAPER VIII) or in situ data collection. If the data quality is sufficient, it can be used for deterioration modeling, vulnerability and hydraulic assessment (for urban water infrastructure). The results of these assessments, or if the data has less quality of the simplified approach (PAPER II), are introduced into decision support frameworks together with data from adjacent networks (e.g. street and gas networks) and environmental influences (e.g. Urban development). The known decision support models are used in a three step decision approach (PAPER I and PAPER II) - (1) the prioritization of the individual networks starting with pipe sections and then for predefined street sections; (2) the multi-utility prioritisation of street sections using the results of step 1 and finally (3) to counter weaknesses of multi-criteria decision making technical and economical thresholds are introduced to establish a final ranking of street sections. This ranking shows the importance of a street section in terms of rehabilitation in comparison to the rest of the observation area. It is therefore a guide where to look first - the actual operational decisions for when, with whom, where and how works are executed are taken then by a variety of stakeholders. The environmental influences (e.g. urban development and climate change) are the drivers of adaptation of urban water infrastructure and are implemented using the mutual influencing of adaptation and rehabilitation (PAPER IX).

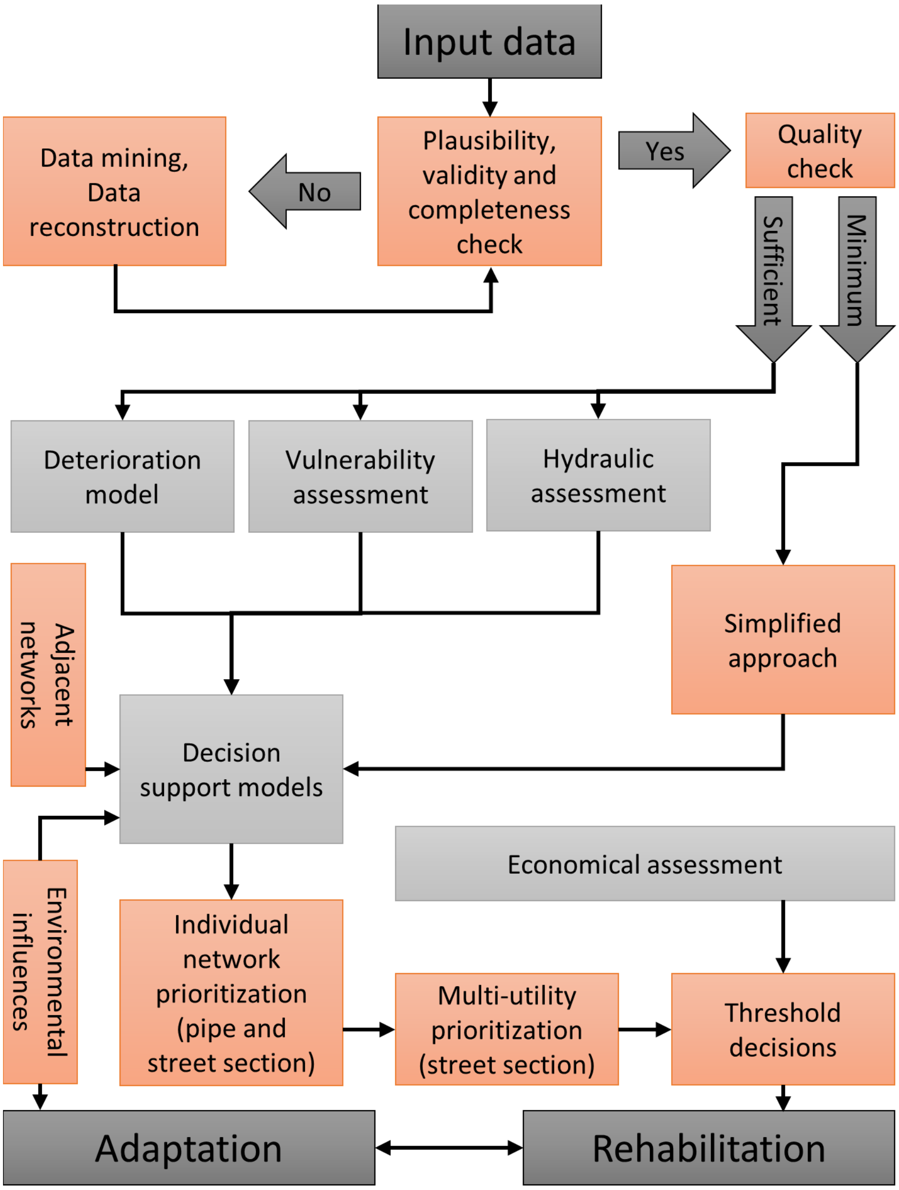

Figure 58: Methodology of this work - in the colored topics methods were developed or enhanced

To conclude three main points can be distilled from the work:

- The importance of data management;
- The importance and advantages of network spanning rehabilitation management;
- The possibilities to use rehabilitation as a chance in the adaptation process.

Data management is one of the main problems in rehabilitation management, as was shown in this thesis. All of the models used are just as good as the implemented data. It is important to advocate the creation of pipe information systems for all of our networks, but as well to encourage their maintenance, quality assurance and data exchange with other infrastructure and data sources. Open data in general and especially open government data, which is starting to be bigger topic at the moment, can be a big contribution to the information gathering for our models. Furthermore, the way forward from this data to models for infrastructure performance (e.g. hydrodynamic models for sewer) is a small one and should be followed. Moreover, a novel method for data validation and data reconstruction instead of mere extrapolation was introduced, together with a historical study about one case study. Finally minimal data requirements were formulated for the applied models.

Integrated rehabilitation management is an approach for understanding our infrastructure as an interconnected system. In times of limited budgets the importance of even small savings created by consultation, coordination and the cooperation of different operators of different networks, especially when they are all publicly owned, cannot be stressed enough. Furthermore, the possibility of minimising disturbances to other networks (e.g. public transport) could help to maintain a good public image for the operating companies. Of course the rehabilitation of networks at the same time is not always technically or economically viable, however, the testing of this viability is still necessary. The usage of models of different complexity for different problems to enable a repeatable, reviewable, revisable and easy to understand decision making process that can be defended under the perspective of these factors against the public opinion, the different stakeholders and the decision makers, was shown. This methodology for the integrated prioritisation of different infrastructure networks used in a real case studies aims to rank, and thereby prioritise, areas for rehabilitation. This is also important in respect to the observed clustering of failures in certain areas of the network.

Rehabilitation and adaptation form the main influences on our infrastructure networks: the maintenance, repair and replacement of our existing infrastructure under the influences of an ever changing environment. The necessary rehabilitation of an existing network can contribute, to a certain amount, to adapting to a changing environment. But even this small amount should be exploited due to the fact that the rehabilitation has to be carried out anyway and a smaller amount of accompanying measures (e.g. infiltration) has to be constructed and budgeted for. Furthermore, it is important to implement rehabilitation into the examination of future scenarios so as to be able to exploit the possible contributions.

7.2 DISCUSSION AND OUTLOOK

The main point of future research should be the finding, valuing, weighing and implementing of further influences and interdependencies into our idea of rehabilitation management.

I want to start the outlook on future research with a vision: **the transparent infrastructure**. This means an open available data-set for each municipality ranging from the smallest to the largest. This would include the data of all infrastructures and all of the different influencing factors and inter-dependencies. Furthermore, all of these infrastructures are monitored and controlled using calibrated and validated state-of the art models and sensors. The open availability of the date would allow for a comparison between the operators and therefore an interchange of experiences concerning problems and solutions. It would permit the operators of the individual network to operate, maintain and rehabilitate them in an optimal way. This would at the same time enable cooperation with other operators, which are interdependent, to manage the whole infrastructure of a city as a holistic body and find the "best" solutions for occurring problems that may they derive from rehabilitation needs or other influences, which means in this case:

- Maintaining the best possible service quality;
- Minimising infrastructure failures;
- Minimising costs for maintenance and rehabilitation;
- Minimising the disturbance on adjacent infrastructure and the inhabitants.

If we compare this vision to our actual situation we can see the needs for future research as well as for promotion of these ideas. A first important step would be, in the field of urban water infrastructure, the finalisation of a pipe information system for all municipalities, using the available regulations.
This thesis gives some insight into the actual data quality of such pipe information systems and offers ways to deal with the shortcomings. However, it would be advisable to focus future research on the inter-dependencies of infrastructure not only in terms of rehabilitation. Municipal infrastructure is interconnected and so should the decision making processes of the operators be. Research should try to point out these interconnections by interconnecting itself using different areas of expertise: engineering for the technical challenges of the individual networks, economy due to the limitations of budget, legal for the different legislation available as well as for the propositions of new ones, geography for the geographical interconnections which are very important for risk assessment, informatics for the handling of different data sources and providing computer sustained modeling, social sciences because of the effects of changing infrastructure

on the inhabitants as well as the changing effect of inhabitants on the infrastructure. A result could be the necessary data set for addressing all of these challenges.

Of interest in this aspect is the denomination of trigger functions for rehabilitation works. When does the rehabilitation of the street surface trigger rehabilitation of underlying infrastructure or is it the other way round? Is this trigger the same for every municipality or does it depend on the size? It could be that in smaller municipalities the temptation to rehabilitate altogether is higher than in larger ones, where the operator is maybe not the municipality itself. A study about the economic viability of this approach in comparison to a integrated rehabilitation management system would be interesting, maybe resulting in a threshold until which size of municipality which approach is more viable. On the other hand small municipalities could also then maybe profit from unifying the rehabilitation management under the roof of an existing water or waste water association including several municipalities as it is often done for the wastewater treatment plants. Additionally, the economic effects of the integrated approach should be pointed out more clearly. As seen in this thesis the beneficial effects can be assumed, however only a few studies exist on this topic.

In general the economic and organisational side of this topic should be elaborated in following studies. The necessary data management needs a lot of financial investment. The question arises until which size is this investment really justifiable and how high is the willingness of the public to pay for it. Moreover it has to be discussed if it could be paid by adapting water and wastewater prices or from other sources. Different organisational possibilities exist ranging from outsourcing to an engineering company to doing it yourself with existing or newly employed personnel. All of these questions have to addressed for the different scales of operators and for the different starting points. A small operator without data and experience in data management and rehabilitation management could be better off using an external consultant, while a large operator could maybe employ experts.

Another important topic is to do with the technical changes. The widespread usage of trenchless rehabilitation techniques for sewers and water distribution pipes offer new possibilities. These are however seldom implemented into our models. Mainly for deterioration modeling no approaches exist until now, except of treating them as normal pipes or using expert opinion. This means mostly applying a lower life expectancy for them. If this is reasonable, for a technical solid application of these practices for example of inlining on a structural solid pipe, is questionable and should be studied more in

detail.
Another seldom addressed challenge is the fact that in general we only examine a part of our network by ignoring the house connections. These connections form however a large part of our networks. Damages occurring there affect our networks. The main problem (at least in Austria) is the different legislation in the different regions. In this thesis it could be seen that house connection have a higher failure rate in our case studies for water supply. This can be explained to a certain extent by poorer workmanship, however a closer look at this problem, regarding all of the networks would be interesting. Additionally, an application of a deterioration model on house connections alone is shown in this work, but it is one of few existing approaches in this area.
For deterioration a lot of models exist, as shown in this thesis. However the practical application lags behind the manifold approaches. Especially smaller and medium sized operators are skeptical about the usefulness of these models. Moreover, if models are compared to the operators experience differences occur with respect of influencing factors and the expected technical design life. Therefore an evaluation of the models should be made, discussed with the operators and a platform for experiences with these approaches including their shortcomings and data demand should be established. Furthermore, an enhancement of models using a generic network generator to replace unknown historical network growth, which is one problem for deterioration models (e.g. cohort survival models) could be applied. Additionally, approaches using expert knowledge as substitute for fragmentary data can be applied, including a discussion on how far expert knowledge is already biased by existing models and the already occurred failures neglecting the working parts of the network. Furthermore, a discussion, especially for the sewer network, about dividing the models into the four types of condition - hydraulic, structural, environmental and operational - and about which failures really contribute to a model and which are caused by external influences. A lot of the statistical models at the moment are more of an estimation of failure risk, including the possibility of third party damages but at the same time not using any recordings of the adjacent construction sites and/or changes in land use or traffic development on the surface, than really exact models of an aging process. Therefore increased research in the processes and on the influences of these aging processes and by applying more, evaluating and enhancing the physical models could give further insights.
The methodology shown in the annexed papers for prioritisation has focused on street sections as containers for several networks. The four networks implemented (road, water, gas, sewer) are not the only

existing ones. An extension of the model on district heating, electrical and telecommunication and so on should be the next step. However the necessary models could change and their implementation has to be thought of. Furthermore, the street section, which was chosen due to the fact of failure clustering, may not be the best solution. Other approaches should be tested using either defined areas or the pipe level using influencing areas for each pipe.
Rehabilitation aims for the optimum network condition - but what is this in an integrated approach? Performance indicators for this question are necessary, including not only technical but also economical, social and political values due to the fact that decisions for rehabilitation are taken by a variety of stakeholders. Using decision support models (as explained in this work) can only produce a good output when including a lot of decision makers. They could be used for scenario analysis and as a basis for discussion for the stakeholders and decision makers. A higher interaction with operators but also with other decision makers exploring their intentions and motivations, maybe using socioeconomic approaches, could achieve substantial improvements of our models which are often limited to technical reasoning. Any model for infrastructure management and planning however is limited to give suggestions for infrastructure managers about where and when rehabilitation works can be executed.
So finally the future research can be summarised into these questions:

- What are further (other than already addressed in this thesis) interdependencies between the different infrastructures and other influences and how important are they for rehabilitation management? How can they help to explain phenomena like the clustering of pipe bursts?
- Which approaches for rehabilitation management are economically, socially and politically the most viable for which size of applier?
- What is the least expensive and least complicated way to collect the necessary data?
- What are the performance indicators for the optimum infrastructure performance in an integrated view? Are the existing indicators for the individual networks feasible for an integrated view of infrastructure?
- Is it possible to find an applicable physical deterioration model instead of the statistical ones?
- How can our models be enhanced so that they find more application in engineering practice?

- What is an integrated economic view for integrated rehabilitation management? Does the need for an interdisciplinary multi-utility life cycle assessment of our infrastructure arise? Could reclaiming older pipes be more economic in terms of resources (e.g. recycling of metals) than trenchless methods?
- How far can the decision process in rehabilitation management be modeled and what are the intentions and motivations of the involved stakeholders?
- How important are the different factors and stakeholders in the decision making process and how can they be weighted?
- How and how far can rehabilitation assist in the adaptation of our infrastructure to future challenges (not only for the sewer systems which were addressed in this work)? Is the rehabilitation of our networks overtaken by the need to adapt to a changing environment?

BIBLIOGRAPHY

33 U.S.C. §1251 et seq.

1972 *Federal water pollution control act (Clean Water Act)*, http://www2.epa.gov/laws-regulations/summary-clean-water-act.

42 U.S.C. §300f et seq.

1974 *Title XIV of the public health service act safety of public water systems (Safe drinking water act)*, http://www2.epa.gov/laws-regulations/summary-safe-drinking-water-act.

Abrishamchi, Ahmad, Ali Ebrahimian, Massoud Tajrishi and Miguel A. Mariño

2005 "Case study: application of multicriteria decision making to urban water supply", *Journal of Water Resources Planning and Management*, 131 (4), pp. 326–335, ISSN: 1943-5452, DOI: 10.1061/(ASCE)0733-9496(2005)131:4(326).

Agresti, Alan

2002 *Categorical data analysis*, 2nd Edition, Wiley series in probability and statistics, Wiley-Interscience, New York, USA, ISBN: 0-471-36093-7.

Ahmadi, Mehdi, Frédéric Cherqui, Jean-Christophe de Massiac and Pascal Le Gauffre

2013 "Influence of available data on sewer inspection program efficiency", *Urban Water Journal*, 11 (8), pp. 641–656, ISSN: 1744-9006, DOI: 10.1080/1573062X.2013.831910.

2014a "Benefits of using basic, imprecise or uncertain data for elaborating sewer inspection programmes", *Structure and Infrastructure Engineering*, 11 (3), pp. 376–388, ISSN: 1573-2479, DOI: 10.1080/15732479.2014.887122.

2014b "From sewer inspection programmes to rehabilitation needs: research and results related to data quality and availability with the support of numerical experiment", *European Journal of Environmental and Civil Engineering*, 18 (10), pp. 1145–1156, ISSN: 1964-8189, DOI: 10.1080/19648189.2014.893212.

Ahmadi, Mehdi, Frédéric Cherqui, Jean-Baptiste Aubin and Pascal Le Gauffre

2015 "Sewer asset management: impact of sample size and its characteristics on the calibration outcomes of a decision-making multivariate model", *Urban Water Journal*, pp. 1–16, ISSN: 1744-9006, DOI: 10.1080/1573062X.2015.1011668.

Ahmed, Farzana, John S. Gulliver and John L. Nieber

2015 "Estimating swale performance in volume reduction", in *World Environmental and Water Resources Congress 2015: Floods, droughts, and ecosytems*, ed. by Karen Karvazy and Veronica L. Webster, American Society of Civil Engineers (ASCE), pp. 255–260, ISBN: 978-0-7844-7916-2, DOI: 10.1061/9780784479162.024.

Al-Barqawi, Hassan and Tarek Zayed

2008 "Infrastructure management: integrated AHP/ANN model to evaluate municipal water mains' performance", *Journal of Infrastructure Systems*, 14 (4), pp. 305–318, ISSN: 1076-0342, DOI: 10.1061/(ASCE)1076-0342(2008)14:4(305).

Al-Rashdan, Dina, Bashar Al-Kloub, Angela Dean and Tarik Al-Shemmeri

1999 "Environmental impact assessment and ranking the environmental projects in Jordan", *European Journal of Operational Research*, 118 (1), pp. 30–45, ISSN: 0377-2217, DOI: 10.1016/S0377-2217(97)00079-9.

Alegre, Helena and Sergio T. Coelho

2012 "Infrastructure Asset Management of Urban Water Systems", in *Water Supply System Analysis - Selected Topics*, ed. by Avi Ostfeld, InTech, Rijeka, Croatia, pp. 49–73, ISBN: 978-953-51-0889-4, DOI: 10.5772/52377.

Ana, Eliseo V. Jr.

2009 *Sewer asset management - sewer structural deterioration modeling and multicriteria decision making in sewer rehabilitation projects prioritization*, PhD thesis, Vrije Universiteit Brussel, Brussels, Belgium.

Ana, Eliseo V. Jr. and Willy Bauwens

2010 "Modeling the structural deterioration of urban drainage pipes: the state-of-the-art in statistical methods", *Urban Water Journal*, 7 (1), pp. 47–59, ISSN: 1744-9006, DOI: 10.1080/15730620903447597.

Arbeitshilfen Abwasser 2004/242/D

2012 *Arbeitshilfen Abwasser - Planung, Bau und Betrieb von abwassertechnischen Anlagen in Liegenschaften des Bundes*, Bundesministerium für Verkehr, Bau und Stadtentwicklung, http://www.arbeitshilfen-abwasser.de.

Ariaratnam, Samuel T., Ashraf El-Assaly and Yuqing Yang

2001 "Assessment of Infrastructure Inspection Needs Using Logistic Models", *Journal of Infrastructure Systems*, 7 (4), pp. 160–165, ISSN: 1076-0342, DOI: 10.1061/(ASCE)1076-0342(2001)7:4(160).

Arnbjerg-Nielsen, Karsten

2012 "Quantification of climate change effects on extreme precipitation used for high resolution hydrologic design", *Urban Water Journal*, 9 (2), pp. 57–65, ISSN: 1744-9006, DOI: 10.1080/1573062X.2011.630091.

Ashley, Richard M., David J. Balmforth, Adrian J. Saul and J. D. Blanskby

2005 "Flooding in the future – predicting climate change, risks and responses in urban areas", *Water Science & Technology*, 52 (5), pp. 265–273, ISSN: 0273-1223.

Babovic, Vladan, Jean-Philippe Drécourt, Maarten Keijzer and Peter Friss Hansen

2002 "A data mining approach to modelling of water supply assets", *Urban Water*, 4 (4), pp. 401–414, ISSN: 1462-0758, DOI: 10.1016/S1462-0758(02)00034-1.

Bach, Peter M., Wolfgang Rauch, Peter S. Mikkelsen, David T. McCarthy and Ana Deletic

2014 "A critical review of integrated urban water modelling – Urban drainage and beyond", *Environmental Modelling & Software*, 54, pp. 88–107, ISSN: 1364-8152, DOI: 10.1016/j.envsoft.2013.12.018.

Baker, Dennis, Donald Bridge, Regina Hunter, Gegory Johnson, Joseph Krupa, James Murphy and Ken Sorenson

2001 *Guidebook to decision making methods*, Developed for the Department of Energy, United States of America, WSRC-IM-2002-00002.

Barbosa, Ana E., Joao N. Fernandes and Luís M. David

2012 "Key issues for sustainable urban stormwater management", *Water research*, 46 (20), pp. 6787–6798, ISSN: 0043-1354, DOI: 10.1016/j.watres.2012.05.029.

basemap.at

2015 *basemap.at - Verwaltungsgrundkarte von Österreich*, Stadt Wien und Österreichische Länder bzw. Ämter der Landesregierung, http://www.basemap.at/.

Baur, Rolf

2004 *Einsatz von Zustandsbewertungsprogrammen für Gas- und Wasserversorgungsnetze: KANEW*, Technische Universität Dresden, Beitrag zur Studie an der FH Erfurt im Auftrag des Deutschen Vereins des Gas- und Wasserfaches e.V (DVGW), Dresden, Germany.

Baur, Rolf and Raimund Herz

2002 "Selective inspection planning with ageing forecast for sewer types", *Water Science & Technology*, 46 (6-7), pp. 389–396, ISSN: 0273-1223.

2006 "Multi-Criteria Decision Support", in *Care-S: Computer Aided Rehabilitation of Sewer and Stormwater Networks*, ed. by Sveinung Sægrov, IWA Publishing, chap. 6, pp. 89–110, ISBN: 978-1-8433-9115-9.

Behzadian, Majid, Reza B. Kazemzadeh, Amir Albadvi and Mohammad Aghdasi

2010 "PROMETHEE: A comprehensive literature review on methodologies and applications", *European Journal of Operational Research*, 200 (1), pp. 198–215, ISSN: 0377-2217, DOI: 10.1016/j.ejor.2009.01.021.

Belton, Valerie and Theodor J. Stewart

2002 *Multiple criteria decision analysis: an integrated approach*, 1st Edition, Springer US, ISBN: 978-0-7923-7505-0, DOI: 10.1007/978-1-4615-1495-4.

Benayoun, R., B. Roy and N. Sussman

1966 *Manual de Reference du programme electre*, 25, Direction Scientifique SEMA, Paris, France.

Berardi, Luigi, Orazio Giustolisi, Zoran Kapelan and Dragan A. Savić

2008 "Development of pipe deterioration models for water distribution systems using EPR", *Journal of Hydroinformatics*, 10 (2), pp. 113–126, ISSN: 1464-7141, DOI: 10.2166/hydro.2008.012.

Berardi, Luigi, Orazio Giustolisi, Dragan A. Savić and Zoran Kapelan

2009 "An effective multi-objective approach to prioritisation of sewer pipe inspection", *Water Science & Technology*, 60 (4), p. 841, ISSN: 0273-1223, DOI: 10.2166/wst.2009.432.

Berger, Christian and Christian Falk

2011 "Zustand der Kanalisation in Deutschland - Ergebnisse der DWA Umfrage 2009", *KA - Korrespondenz Abwasser, Abfall*, 1 (11), pp. 26–41, ISSN: 1866-0029, DOI: 10.3242/kae2011/01.001.

BGBl. I Nr. 51

2015 *Bundesgesetz über die Förderung von Maßnahmen in den Bereichen der Wasserwirtschaft, der Umwelt, der Altlastensanierung, zum Schutz der Umwelt im Ausland und über das österreichische JI CDM-Programm für den Klimaschutz (Umweltförderungsgesetz - UFG)*, www.ris.bka.gv.at.

BGBl. I Nr. 54

2014 *Wasserrechtsgesetz: WRG 1959*, www.ris.bka.gv.at.

BGBl. II Nr. 103

2005 *Verordnung des Bundesministers für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft über die Begrenzung von Sickerwasseremissionen aus Abfalldeponien: AEV Deponiesickerwasser*, www.ris.bka.gv.at.

BGBl. II Nr. 359

2012 *Verordnung des Bundesministers für soziale Sicherheit und Generationen über die Qualität von Wasser für den menschlichen Gebrauch (Trinkwasserverordnung - TWV)*, www.ris.bka.gv.at.

BGBl. II Nr. 523

2006 *Verordnung des Bundesministers für Land- und Forstwirtschaft betreffend Abwassereinleitungen in wasserrechtlich bewilligte Kanalisationen (Indirekteinleiterverordnung-IEV)*, www.ris.bka.gv.at.

BGBl. II Nr. 88

2015 *Bundesgesetz über Sicherheitsanforderungen und weitere Anforderungen an Lebensmittel, Gebrauchsgegenstände und kosmetische Mittel zum Schutz der Verbraucherinnen und Verbraucher (Lebensmittelsicherheits und Verbraucherschutzgesetz - LMSVG)*, www.ris.bka.gv.at.

BGBl. Nr. 186

1996 *186. Verordnung des Bundesministers für Land- und Forstwirtschaft über die allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisationen: AAEV*, www.ris.bka.gv.at.

Birgani, Yaser Tahmasebi, Farhad Yazdandoost and Elnaz Dehlavi

2014 "Integrated Approach in Spatial Priority of Urban Areas for Implementation of Urban Drainage Plans Using Analytic Hierarchy Process and GIS for 22nd Municipal District of Tehran, Iran", in *13th International Conference on Urban Drainage (ICUD) - Urban Drainage in the Context of Integrated Urban Water Management: A Bridge Between Developed and Developing Countries*, ed. by Nordin bin Hamdan and Mohamed Roseli bin Zainal Abidin, International Water Association (IWA), Kuching - Sarawak, Malaysia.

Bogetoft, Peter and Peter Pruzan

1997 *Planning With Multiple Criteria: Investigation, Communication, Choice*, 2nd ed., Copenhagen Business School Press, ISBN: 978-8-76300-005-5.

Brans, Jean-Pierre

1982 "L'ingénièrie de la décision; Elaboration d'instruments d'aide à la décision. La méthode PROMETHEE", in *L'aide à la décision: Nature, Instruments et Perspectives d'Avenir*, ed. by R. Nadeau and M. Landry, Presses de l'Université Laval, Québec, Canada, pp. 183–213.

Brans, Jean-Pierre and Philippe Vincke

1985 "A Preference Ranking Organisation Method: The PROMETHEE Method for Multiple Criteria Decision-Making", *Management Science*, 31 (6), pp. 647–656.

Buchanan, John and Daniel Vanderpooten

2007 "Ranking projects for an electricity utility using ELECTRE III", *International Transactions in Operational Research*, 14 (4), pp. 309–323, ISSN: 1475-3995, DOI: 10.1111/j.1475-3995.2007.00589.x.

Büker, Dieter

2000 *Mensch - Kultur - Abwasser: Von der Annehmlichkeit für wenige zur Existenzfrage der Menschheit : der Umgang des Menschen mit Abwässern : ein kulturhistorischer Längsschnitt von den Anfängen bis zum Beginn des 20. Jahrhunderts*, Historie in der Blauen Eule, Die Blaue Eule, Essen, Germany, vol. 9, ISBN: 978-3-89206-980-5.

Burger, Gerhard and Martin Hochedlinger
2008 "Festlegung von Sanierungsprogrammen - Vor- und Nachteile einer Baustellenkoordination anhand von Beispielen", in *Instandhaltung von Trinkwasser- und Abwasserleitungen*, ed. by Harald Kainz, Schriftenreihe zur Wasserwirtschaft: Technische Universität Graz, 54, Verlag der Technischen Universität Graz, Graz, Austria, ISBN: 978-3-85125-021-3.

Burger, Gregor, Robert Sitzenfrei, Manfred Kleidorfer and Wolfgang Rauch
2014 "Parallel flow routing in SWMM 5", *Environmental Modelling & Software*, 53 (0), pp. 27–34, ISSN: 13648152, DOI: 10.1016/j.envsoft.2013.11.002.

Butler, David, P. Jowitt, Richard Ashley, D. Blackwood, J. Davies, C. Oltean-Dumbrava, G. McIlkenny, T. Foxon, D. Gilmour, H. Smith, S. Cavill, M. Leach, P. Pearson, H. Gouda, W. Samson, N. Souter, S. Hendry, J. Moir and F. Bouchart
2003 "SWARD: decision support processes for the UK water industry", *Management of Environmental Quality: An International Journal*, 14 (4), pp. 444–459, ISSN: 1477-7835, DOI: 10.1108/14777830310488676.

Caradot, Nicholas, Hauke Sonnenberg, Andreas Hartmann, Ingo Kropp, Alexander Ringe, Stephane Denhez, Michael Timm and Pascale Rouault
2015 "The influence of data availability on the performance of sewer deterioration modelling", in *Proceedings of the 10th International Conference on Urban Drainage Modelling*, ed. by Thomas Maere, Sovanna Tik, Sophie Duchesne and Peter A. Vanrolleghem, Mont-Sainte-Anne - Québec, Canada, vol. 2, pp. 17–21.

Carey, Brad D. and Jason S. Lueke
2013 "Optimized holistic municipal right-of-way capital improvement planning", *Canadian Journal of Civil Engineering*, 40 (12), pp. 1244–1251, ISSN: 0315-1468, DOI: 10.1139/cjce-2012-0183.

Carriço, Nelson, Dídia I.C. Covas, Maria do Céu Almeida, João P. Leitão and Helena Alegre
2012 "Prioritization of rehabilitation interventions for urban water assets using multiple criteria decision-aid methods", *Water Science & Technology*, 66 (5), pp. 1007–1014, ISSN: 0273-1223, DOI: 10.2166/wst.2012.274.

Cashman, Adrian and Richard Ashley

2008 "Costing the long-term demand for water sector infrastructure", *foresight*, 10 (3), pp. 9–26, ISSN: 1463-6689, DOI: 10.1108/14636680810883099.

Cheng, Steven, Christine W. Chan and Guo H. Huang

2002 "Using multiple criteria decision analysis for supporting decisions of solid waste management", *Journal of Environmental Science and Health, Part A*, 37 (6), pp. 975–990, DOI: 10.1081/ESE-120004517.

Churchman, Charles West, Russell L. Ackoff and Nicholas M. Smith Jr.

1954 "An Approximate Measure of Value", *Journal of the Operations Research Society of America*, 2 (2), pp. 172–187, ISSN: 0096-3984, http://www.jstor.org/stable/166603.

Çınlar, Erhan

2011 *Probability and stochastics*, 1st ed., Graduate texts in mathematics, Springer-Verlag New York, New York, USA, vol. 261, ISBN: 978-0-387-87858-4, DOI: 10.1007/978-0-387-87859-1.

Coutinho-Rodrigues, João, Ana Simão and Carlos Henggeler Antunes

2011 "A GIS-based multicriteria spatial decision support system for planning urban infrastructures", *Decision Support Systems*, 51 (3), pp. 720–726, ISSN: 0167-9236, DOI: 10.1016/j.dss.2011.02.010.

Cox, David R.

1972 "Regression Models and Life-Tables", English, *Journal of the Royal Statistical Society. Series B (Methodological)*, 34 (2), pp. 187–220, ISSN: 0035-9246, http://www.jstor.org/stable/2985181.

Dandy, Graeme C. and Mark O. Engelhardt

2006 "Multi-Objective Trade-Offs between Cost and Reliability in the Replacement of Water Mains", *Journal of Water Resources Planning and Management*, 132 (2), pp. 79–88, DOI: 10.1061/(ASCE)0733-9496(2006)132:2(79).

data.gv.at

2015 *data.gv.at - offene Daten Österreichs*, Bundeskanzleramt Österreich, https://www.data.gv.at/.

Datla, Suresh V. and Mahesh D. Pandey

2005 *Estimation of life expectancy of engineering components from inspection data*, UNENE Technical Report UTR-01, Waterloo, Canada.

Davies, Joel P., B. A. Clarke, J. T. Whiter, R. J. Cunningham and A. Leidi

2001 "The structural condition of rigid sewer pipes: a statistical investigation", *Urban Water*, 3 (4), pp. 277–286, ISSN: 1462-0758, DOI: 10.1016/S1462-0758(01)00036-X.

De Oliveira, Daniel P., Daniel B. Neill, James H. Garrett and Lucio Soibelman

2011 "Detection of Patterns in Water Distribution Pipe Breakage Using Spatial Scan Statistics for Point Events in a Physical Network", *Journal of Computing in Civil Engineering*, 25 (1), pp. 21–30, ISSN: 0887-3801, DOI: 10.1061/(ASCE)CP.1943-5487.0000079.

De Feo, Giovanni, George Antoniou, Hilal Fardin, Fatma El-Gohary, Xiao Zheng, Ieva Reklaityte, David Butler, Stavros Yannopoulos and Andreas Angelakis

2014 "The Historical Development of Sewers Worldwide", *Sustainability*, 6 (6), pp. 3936–3974, ISSN: 2071-1050, DOI: 10.3390/su6063936.

De Haan, Fjalar J., Briony C. Ferguson, Rebekah R. Brown and Ana Deletic

2011 "A Workbench for Societal Transitions in Water Sensitive Cities", in *12th International Conference on Urban Drainage (ICUD)*, ed. by International Water Association (IWA).

Di Sivo, Michele and Daniela Ladiana

2011 "Decision-support tools for municipal infrastructure maintenance management", *Procedia Computer Science - World Conference on Information Technology*, 3 (0), pp. 36–41, ISSN: 1877-0509, DOI: 10.1016/j.procs.2010.12.007.

Directive 2007/2/EC

2007 *Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)*, OJL 108/1, http://eur-lex.europa.eu/.

Dirksen, Jojanneke and Francois Clemens

2008 "Probabilistic modeling of sewer deterioration using inspection data", *Water Science & Technology*, 57 (10), pp. 1635–1641, ISSN: 0273-1223, DOI: 10.2166/wst.2008.308.

Dirksen, Jojanneke, Francois Clemens, Hans Korving, Frédéric Cherqui, Pascal Le Gauffre, Thomas Ertl, Hanns Plihal, Karsten Müller and C. T.M. Snaterse

2013 "The consistency of visual sewer inspection data", *Structure and Infrastructure Engineering*, 9 (3), pp. 214–228, ISSN: 1573-2479, DOI: 10.1080/15732479.2010.541265.

Dorini, Gianluca, Zoran Kapelan and Adisa Azapagic

2011 "Managing uncertainty in multiple-criteria decision making related to sustainability assessment", English, *Clean Technologies and Environmental Policy*, 13 (1), pp. 133–139, ISSN: 1618-954X, DOI: 10.1007/s10098-010-0291-7.

DVGW G 402

2011 *Netz- und Schadenstatistik - Erfassung und Auswertung von Daten zum Aufbau von Instandhaltungsstrategien für Gasverteilungsnetze*, Deutscher Verein des Gas- und Wasserfaches e.V., Bonn, Germany.

DVGW G 403

2011 *Entscheidungshilfen für die Instandhaltung von Gasverteilungsnetzen*, Deutscher Verein des Gas- und Wasserfaches e.V., Bonn, Germany.

DVGW W 402

2010 *Netz- und Schadenstatistik - Erfassung und Auswertung von Daten zur Instandhaltung von Wasserrohrnetzen*, Deutscher Verein des Gas- und Wasserfaches e.V., Bonn, Germany.

DWA-M 149-3

2007 *Zustandserfassung und -beurteilung von Entwässerungssystemen außerhalb von Gebäuden - Teil 3: Zustandsklassifizierung und -bewertung*, Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.

Egger, Christoph, Andreas Scheidegger, Peter Reichert and Max Maurer

2013 "Sewer deterioration modeling with condition data lacking historical records", *Water Research*, 47 (17), pp. 6762–6779, ISSN: 0043-1354, DOI: 10.1016/j.watres.2013.09.010.

Egger, Patrick

2015 *Comparison of multi-criteria decision support methods for integrated rehabilitation management of urban infrastructure networks*, Master Thesis, University of Innsbruck, Unit of Environmental Engineering, Innsbruck, Austria.

EN 13508-2

2011 *Investigation and assessment of drain and sewer systems outside buildings - Part 2: Visual inspection coding system*, European Committee for Standardization, https://www.cen.eu/.

EN 1610

1998 *Construction and testing of drains and sewers*, European Committee for Standardization, https://www.cen.eu/.

EN 752

2008 *Drain and sewer systems outside buildings*, European Committee for Standardization, https://www.cen.eu/.

EN 805

2000 *Water supply - Requirements for systems and components outside buildings*, European Committee for Standardization, https://www.cen.eu/.

Engelhardt, Mark O., Peter J. Skipworth, Dragan A. Savić, Adrian J. Saul and Godfrey A. Walters

2000 "Rehabilitation strategies for water distribution networks: a literature review with a UK perspective", *Urban Water*, 2 (2), pp. 153–170, ISSN: 1462-0758, DOI: 10.1016/S1462-0758(00)00053-4.

Ertl, Thomas

2007 *Entwicklung einer Methode für den technischwirtschaftlichen Vergleich von Kanalisationsunternehmen als Grundlage zur Optimierung ihrer Betriebsführung*, PhD thesis, Universität für Bodenkultur Wien, Institut für Siedlungswasserbau, Industriewasserwirtschaft und Gewässerschutz, Vienna, Austria.

Feizizadeh, Bakhtiar, Piotr Jankowski and Thomas Blaschke

2013 "A Spatially Explicit Approach for Sensitivity and Uncertainty Analysis of GIS-Multicriteria Landslide Susceptibility Mapping", in *GI_Forum 2013 - Creating the GISociety*, ed. by Thomas Jekel, Adrijana Car, Josef Strobl and Gerald Griesebner, ÖAW Verlag, Vienna, Austria, pp. 157–164, ISBN: 978-3-7001-7438-7, DOI: 10.1553/giscience2013s157.

Feizizadeh, Bakhtiar, Khalil Omrani, Fereidon Babaei Aghdam, Bakhtiar Feizizadeh, Piotr Jankowski and Thomas Blaschke

2015 "Fuzzy Analytical Hierarchical Process and Spatially Explicit Uncertainty Analysis Approach for Multiple Forest Fire Risk Mapping", *GI_Forum 2015 - Geospatial Minds for Society*, 1, ed. by Thomas Jekel, Adrijana Car, Josef Strobl and Gerald Griesebner, pp. 72–80, ISSN: 2308-1708, DOI: 10.1553/giscience2015s72.

Fenner, R.A

2000 "Approaches to sewer maintenance: a review", *Urban Water*, 2 (4), pp. 343–356, ISSN: 1462-0758, DOI: 10.1016/S1462-0758(00)00065-0.

Friedl, Franz

2014 *Vergleich von statistischen und physikalischen Modellen zur Berechnung der Auftrittswahrscheinlichkeit von Schadensarten auf Trinkwasser-Haupt- und Zubringerleitungen*, PhD-Thesis, TU Graz, Institut für Siedlungswasserwirtschaft und Landschaftswasserbau, Graz, Austria.

Friedl, Franz, Michael Möderl, Wolfgang Rauch, Q. Liu, S. Schrotter and Daniela Fuchs-Hanusch

2012 "Failure Propagation for Large-Diameter Transmission Water Mains Using Dynamic Failure Risk Index", in *World Environmental And Water Resources Congress 2012*, ed. by Eric D. Loucks, American Society of Civil Engineers (ASCE), pp. 3082–3095, DOI: 10.1061/9780784412312.310.

Fritsch, Peter, Werner Knaus, Gerhard Merkl, Erwin Preininger, Joachim Rautenberg, Matthias Weiss and Burkhard Wricke

2011 *Mutschmann/Stimmelmayr - Taschenbuch der Wasserversorgung*, 15., vollständig überarbeitete und aktualisierte Auflage, Vieweg+Teubner Verlag / Springer Fachmedien, Wiesbaden, Germany, ISBN: 978-383480951-3.

Fuchs, Daniela

2001 *Decision Support Systeme für die Rehabilitationsplanung von Wasserrohrnetzen*, PhD-Thesis, TU Graz, Institut für Siedlungswasserwirtschaft und Landschaftswasserbau, Graz, Austria.

Fuchs-Hanusch, Daniela, Birgit Kornberger, Gerald Gangl, Johannes Hofrichter and Peter Kauch

2007 "Entwicklung eines Entscheidungshilfesystems für die Rehabilitationsplanung von Wasserrohrnetzen", *Österreichische Wasser- und Abfallwirtschaft*, 59 (9), pp. 111–116, ISSN: 0945-358X, DOI: 10.1007/s00506-007-0127-9.

Fuchs-Hanusch, Daniela, Franz Weyrer, Wolfgang Hanusch, Doris Kasess, Franz Friedl and Rosa Sulzbacher

2009 "Wasserverluste und Schadensraten als Qualitätsparameter für Trinkwassernetze", in *Wasserverluste in Trinkwassernetzen*, ed. by Harald Kainz and Jörg Kölbl, Schriftenreihe zur Wasserwirtschaft, Verlag der TU Graz, Graz, vol. 57, G1–G16, ISBN: 978-3-85125-056-5.

Fuchs-Hanusch, Daniela, Franz Friedl, Michael Möderl, Werner Sprung, Hanns Plihal, Florian Kretschmer and Thomas Ertl

2012 "Risk and Performance Oriented Sewer Inspection Prioritization", in *World Environmental And Water Resources Congress 2012*, ed. by Eric D. Loucks, American Society of Civil Engineers (ASCE), pp. 3711–3723, DOI: 10.1061/9780784412312.373.

Fuchs-Hanusch, Daniela, David Steffelbauer, Markus Günther and Dirk Muschalla

2015 "Systematic material and crack type specific pipe burst outflow simulations by means of EPANET2", *Urban Water Journal*, pp. 1–11, ISSN: 1744-9006, DOI: 10.1080/1573062X.2014.994006.

Gangl, Gerald

2008 *Rehabilitationsplanung von Trinkwassernetzen*, Schriftenreihe zur Wasserwirtschaft, Verlag der TU Graz, Graz, Austria, vol. 53, ISBN: 978-3-85125-007-7.

Garbrecht, Günther

1988 "Mensch und Wasser im Altertum", in *Die Wasserversorgung antiker Städte*, ed. by Frontinus Gesellschaft e.V., Geschichte der Wasserversorgung, Verlag Philipp von Zabern, vol. 3, chap. 1, pp. 13–40, ISBN: 3-8053-0984-8.

Gervásio, Helena and Luis Simões da Silva

2012 "A probabilistic decision-making approach for the sustainable assessment of infrastructures", *Expert systems with applications*, 39 (8), pp. 7121–7131, DOI: 10.1016/j.eswa.2012.01.032.

Gironás, Jorge, Larry A. Roesner, Lewis A. Rossman and Jennifer Davis

2010 "A new applications manual for the Storm Water Management Model (SWMM)", *Environmental Modelling & Software*, 25 (6), pp. 813–814, ISSN: 1364-8152, DOI: 10.1016/j.envsoft.2009.11.009.

Giustolisi, Orazio, Daniele Laucelli and Dragan A. Savić

2006 "Development of rehabilitation plans for water mains replacement considering risk and cost-benefit assessment", *Civil Engineering and Environmental Systems*, 23 (3), pp. 175–190, ISSN: 1028-6608, DOI: 10.1080/10286600600789375.

Grewe, Klaus

1991 "Wasserversorgung und -entsorgung im Mittelalter", in *Die Wasserversorgung im Mittelalter*, ed. by Frontinus Gesellschaft e.V., Geschichte der Wasserversorgung, Verlag Philipp von Zabern, vol. 4, chap. 1, pp. 11–81, ISBN: 3-8053-1157-5.

Großmann, Katrin, Marco Bontje, Annegret Haase and Vlad Mykhnenko

2013 "Shrinking cities: Notes for the further research agenda", *Cities*, 35, pp. 221–225, ISSN: 0264-2751, DOI: 10.1016/j.cities.2013.07.007.

Haider, Husnain, Rehan Sadiq and Solomon Tesfamariam

2014 "Selecting performance indicators for small and medium sized water utilities: Multi-criteria analysis using ELECTRE method", *Urban Water Journal*, 12 (4), pp. 305–327, ISSN: 1744-9006, DOI: 10.1080/1573062X.2014.900089.

Halfawy, Mahmoud R., Leila Dridi and Samar Baker

2008 "Integrated Decision Support System for Optimal Renewal Planning of Sewer Networks", *Journal of Computing in Civil Engineering*, 22 (6), pp. 360–372, ISSN: 0887-3801, DOI: 10.1061/(ASCE)0887-3801(2008)22:6(360).

Herz, Raimund

1998 "Exploring rehabilitation needs and strategies for water distribution networks", *Aqua*, 47 (6), pp. 275–283.

2002 "Developing Rehab Strategies For Drinking Water Networks", in *9th International Conference on Durability of Building Materials and Components*, ed. by Stewart Burn.

Herz, Raimund and Roland Krug

2000 "Sanierungsbedarf und Sanierungsstrategien für Abwassernetze", in *11. Leipziger Bau-Seminar: Thema: öffentliche und industrielle Wasserwirtschaft im Umbruch*, ed. by Verein der Freunde der technischen Fachbereiche der Universität Leipzig e.V.

Hörold, Stefan and Rolf Baur

1999 "Modelling sewer deterioration for selective inspection planning - case study Dresden", in *Proceedings of the 13th European Junior Scientist Workshop*, ed. by Technische Universität Dresden.

Huang, Ivy B., Jeffrey Keisler and Igor Linkov

2011 "Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends", *Science of The Total Environment*, 409 (19), pp. 3578–3594, ISSN: 0048-9697, DOI: 10.1016/j.scitotenv.2011.06.022.

Huang, Jih-Jeng, Gwo-Hshiung Tzeng and Hsiang-Hsi Liu
2009 "A Revised VIKOR Model for Multiple Criteria Decision Making - The Perspective of Regret Theory", in *Cutting-edge research topics on multiple criteria decision making*, ed. by Yong Shi, Shouyang Wang, Yi Peng, Jianping Li and Yong Zeng, Communications in computer and information science, Springer-Verlag Berlin Heidelberg, Berlin and Heidelberg, Germany, vol. 35, pp. 761–768, ISBN: 978-3-642-02297-5, DOI: 10.1007/978-3-642-02298-2.

Hwang, Ching-Lai and Kwangsun Yoon
1981 *Multiple Attribute Decision Making: Methods and Applications - A State-of-the-Art Survey*, Lecture Notes in Economics and Mathematical Systems, Springer-Verlag Berlin Heidelberg, Berlin and Heidelberg, Germany, vol. 186, ISBN: 978-3-540-10558-9, DOI: 10.1007/978-3-642-48318-9.

Jomehpour, Mahmoud
2009 "Qanat irrigation systems as important and ingenious agricultural heritage: case study of the qanats of Kashan, Iran", *International Journal of Environmental Studies*, 66 (3), pp. 297–315, ISSN: 0020-7233, DOI: 10.1080/00207230902752629.

Kabir, Golam
2014 "Consultant selection for quality management using VIKOR method under fuzzy environment", *International Journal of Multicriteria Decision Making*, 4 (2), pp. 96–113, DOI: 10.1504/IJMCDM.2014.060423.

Kabir, Golam, Rehan Sadiq and Solomon Tesfamariam
2014 "A review of multi-criteria decision-making methods for infrastructure management", *Structure and Infrastructure Engineering*, 10 (9), pp. 1176–1210, ISSN: 1573-2479, DOI: 10.1080/15732479.2013.795978.

Kiker, Gregory A., Todd S. Bridges, Arun Varghese, Thomas P. Seager and Igor Linkov
2005 "Application of multicriteria decision analysis in environmental decision making", *Integrated environmental assessment and management*, 1 (2), pp. 95–108, ISSN: 1551-3777, DOI: 10.1897/IEAM\textunderscore2004a-015.1.

Kleiber, Christian and Achim Zeileis
2008 *Applied econometrics with R*, Use R!, Springer-Verlag New York, New York, USA, ISBN: 978-0-387-77316-2, DOI: 10.1007/978-0-387-77318-6.

Kleidorfer, Manfred, Michael Möderl, Robert Sitzenfrei, Christian Urich and Wolfgang Rauch

2009 "A case independent approach on the impact of climate change effects on combined sewer system performance", *Water Science & Technology*, 60 (6), p. 1555, ISSN: 0273-1223, DOI: 10.2166/wst.2009.520.

Kleidorfer, Manfred, Michael Möderl, Franz Tscheikner-Gratl, Max Hammerer, Heiko Kinzel and Wolfgang Rauch

2013 "Integrated planning of rehabilitation strategies for sewers", *Water Science & Technology*, 68 (1), pp. 176–182, ISSN: 0273-1223, DOI: 10.2166/wst.2013.223.

Kleidorfer, Manfred, Ulrich Tschiesche, Franz Tscheikner-Gratl, Robert Sitzenfrei, Florian Kretschmer, Dirk Muschalla, Thomas Ertl and Wolfgang Rauch

2014 "Von den Daten zum Modell: Anforderungen an hydraulische Entwässerungsmodelle in kleinen und mittleren Gemeinden", in *Kanalmanagement 2014*, ed. by Thomas Ertl, Wiener Mitteilungen, Universität für Bodenkultur Wien, Institut für Siedlungswasserbau, Industriewasserwirtschaft und Gewässerschutz, Vienna, Austria, vol. 231, ISBN: 978-3-85234-125-5.

Kleiner, Yehuda

2001 "Scheduling Inspection and Renewal of Large Infrastructure Assets", *Journal of Infrastructure Systems*, 7 (4), pp. 136–143, ISSN: 1076-0342, DOI: 10.1061/(ASCE)1076-0342(2001)7:4(136).

Kleiner, Yehuda and Balvant Rajani

2001 "Comprehensive review of structural deterioration of water mains: statistical models", *Urban Water*, 3 (3), pp. 131–150, ISSN: 1462-0758, DOI: 10.1016/S1462-0758(01)00033-4.

Kleiner, Yehuda, Amir Nafi and Balvant Rajani

2010 "Planning renewal of water mains while considering deterioration, economies of scale and adjacent infrastructure", *Water Science & Technology: Water Supply*, 10 (6), p. 897, DOI: 10.2166/ws.2010.571.

KPC

2013 *Ergebnisse der Investitionskostenerhebung Siedlungswasserwirtschaft 2012*, Kommunalkredit Public Consulting GmbH.

2014 *Bericht 2014 zu den Umweltförderungen gemäß UFG und zur Schutzwasserwirtschaft gemäß WBFG*, Kommunalkredit Public Consulting GmbH, http://www.umweltfoerderung.at.

Krabina, Bernhard, Thomas Prorok and Brigitte Lutz

2011 *Open Government Vorgehensmodell - Umsetzung von Open Government*, KDZ - Zentrum für Verwaltungsforschung, https://www.kdz.eu/.

Krainz, Kathrin

2003 *Eine Investitionskostenschätzung für die österreichische Siedlungswasserwirtschaft*, MA thesis, University of Graz, Institute of Economics.

Land Tirol

2014 *Leitfaden Oberbaukatalog*, Abteilung Verkehr und Straße, https://www.tirol.gv.at.

2015 *Open Government Data*, Sachgebiet Verwaltungsentwicklung, https://www.tirol.gv.at/data/.

Langeveld, Jeroen, Remy Schilperoort and S. R. Weijers

2013 "Climate change and urban wastewater infrastructure: There is more to explore", *Journal of Hydrology*, 476 (0), pp. 112–119, ISSN: 00221694, DOI: 10.1016/j.jhydrol.2012.10.021.

LAWA

2005 *Leitlinien zur Durchführung dynamischer Kostenvergleichsrechnungen (KVR-Leitlinien)*, 7., überarbeitete Auflage, Empfehlungen Wasserwirtschaftliche Grundlagen, Länderarbeitsgemeinschaft Wasser (LAWA), Kulturbuchverlag, Berlin, Germany, ISBN: 3-88961-240-7.

LB-SW05

2005 *Standardisierte Leistungsbeschreibung LB-Siedlungswasserbau LB-SW, Version 05*, Arbeitskreis Leistungsbeschreibung Siedlungswasserbau.

Le Gat, Yves

2008 "Modelling the deterioration process of drainage pipelines", *Urban Water Journal*, 5 (2), pp. 97–106, ISSN: 1744-9006, DOI: 10.1080/15730620801939398.

Le Gauffre, Pascal, Hatem Haidar, David Poinard, Katia Laffréchine, Rolf Baur and Marcello Schiatti

2007 "A Multicriteria Decision Support Methodology for Annual Rehabilitation Programs of Water Networks", *Computer-Aided Civil and Infrastructure Engineering*, 22 (7), pp. 478–488, ISSN: 1093-9687, DOI: 10.1111/j.1467-8667.2007.00504.x.

Leandro, Jorge, Albert S. Chen, Slobodan Djordjević and Dragan A. Savić

2009 "Comparison of 1D/1D and 1D/2D Coupled (Sewer/Surface) Hydraulic Models for Urban Flood Simulation", *Journal of Hydraulic Engineering*, 135 (6), pp. 495–504, DOI: 10.1061/(ASCE)HY.1943-7900.0000037.

Lee, Jung Ho, Chun Woo Baek, Joong Hoon Kim, Hwan Don Jun and Deok Jun Jo

2009 "Development of a Decision Making Support System for Efficient Rehabilitation of Sewer Systems", *Water Resources Management*, 23 (9), pp. 1725–1742, ISSN: 0920-4741, DOI: 10.1007/s11269-008-9349-2.

Lei, Jianhua and Sveinung Sægrov

1998 "Statistical approach for describing failures and lifetimes of water mains", *Water Quality International '98 Selected Proceedings of the 19th Biennial Conference of the International Association on Water Quality*, 38 (6), pp. 209–217, ISSN: 0273-1223, DOI: 10.1016/S0273-1223(98)00582-4.

Lerer, Sara Maria, Karsten Arnbjerg-Nielsen and Peter Steen Mikkelsen

2015 "A Mapping of Tools for Informing Water Sensitive Urban Design Planning Decisions - Questions, Aspects and Context Sensitivity", *Water*, 7 (3), p. 993, ISSN: 2073-4441, DOI: 10.3390/w7030993.

LGBl. Nr.130

2013 *Gesetz vom 8. November 2000 über öffentliche Kanalisationen (Tiroler Kanalisationsgesetz 2000 - TiKG 2000)*, www.ris.bka.gv.at.

Liu, Zheng, Yehuda Kleiner, Balvant Rajani, Lili Wang and Wendy Condit

2012 *Condition Assessment Technologies for Water Transmission and Distribution Systems*, EPA/600/R-12/017, Environmental Protection Agency (EPA), National Risk Management Research Laboratory, Cincinnati, USA.

Løken, Espen

2007 "Use of multicriteria decision analysis methods for energy planning problems", *Renewable and Sustainable Energy Reviews*, 11 (7), pp. 1584 –1595, ISSN: 1364-0321, DOI: 10.1016/j.rser.2005.11.005.

Macharis, Cathy, Johan Springael, Klaas De Brucker and Alain Verbeke

2004 "PROMETHEE and AHP: The design of operational synergies in multicriteria analysis.: Strengthening PROMETHEE with ideas of AHP", *European Journal of Operational Research*, 153 (2), pp. 307–317, ISSN: 0377-2217, DOI: 10.1016/S0377-2217(03)00153-X.

Mair, Michael, Robert Sitzenfrei, Manfred Kleidorfer, Michael Möderl and Wolfgang Rauch

2012 "GIS-based applications of sensitivity analysis for sewer models", *Water Science & Technology*, 65 (7), p. 1215, ISSN: 0273-1223, DOI: 10.2166/wst.2012.954.

Malm, Annika, Olle Ljunggren, Olof Bergstedt, Thomas J.R. Pettersson and Gregory M. Morrison

2012 "Replacement predictions for drinking water networks through historical data", *Water Research*, 46 (7), pp. 2149–2158, ISSN: 0043-1354, DOI: 10.1016/j.watres.2012.01.036.

Mareschal, Bertrand

1988 "Weight stability intervals in multicriteria decision aid", *European Journal of Operational Research*, 33 (1), pp. 54–64, ISSN: 0377-2217, DOI: 10.1016/0377-2217(88)90254-8.

Marlow, David, Simon Heart, Stewart Burn, Antony Urquhart, Scott Gould, Max Anderson, Steve Cook, Michael Ambrose, Belinda Madin and Andrew Fitzgerald

2007 *Condition assessment strategies and protocols for water and wastewater utility assets*, 03-CTS-20CO, Water Environmental Research Foundation (WERF), American Water Works Association Research Foundation (AwwaRF), United States Environmental Protection Agency (U.S. EPA), London, UK.

Martin, C., Y. Ruperd and Michel Legret

2007 "Urban stormwater drainage management: The development of a multicriteria decision aid approach for best management practices", *European Journal of Operational Research*, 181 (1), pp. 338–349, ISSN: 0377-2217, DOI: 10.1016/j.ejor.2006.06.019.

Marzouk, Mohamed and Magdy Omar

2013 "Multiobjective optimisation algorithm for sewer network rehabilitation", *Structure and Infrastructure Engineering*, 9 (11), pp. 1094–1102, ISSN: 1573-2479, DOI: 10.1080/15732479.2012.666254.

Marzouk, Mohamed and Ahmed Osama

2015 "Fuzzy approach for optimum replacement time of mixed infrastructures", *Civil Engineering and Environmental Systems*, pp. 1–12, ISSN: 1028-6608, DOI: 10.1080/10286608.2014.1002715.

Matzinger, Andreas, Marco Schmidt, Mathias Riechel, Andreas Hein, Juliane Bräcker, Clemens Strehl, Darla Nickel, Jens Libbe, Heiko Sieker, Matthias Pallasch, Manfred Köhler, Daniel Kaiser, Stefan Brückmann, Constantin Möller, Björn Büter, Günter Gross, Robert Günther, Ina Säumel, Thomas Taute, Hella Schwarzmüller, Hartmut Bartel, Stefan Heise, Christian Remy, Hauke Sonnenberg, Theo Schmitt, Bernd Heinzmann, Kay Joswig, Matthias Rehfeld-Klein, Brigitte Reichmann and Pascale Rouault

2014 "Quantifying the effects of urban stormwater management – towards a novel approach for integrated planning", in *13th International Conference on Urban Drainage (ICUD) - Urban Drainage in the Context of Integrated Urban Water Management: A Bridge Between Developed and Developing Countries*, ed. by Nordin bin Hamdan and Mohamed Roseli bin Zainal Abidin, International Water Association (IWA), Kuching - Sarawak, Malaysia.

Maurer, Max, Martin Wolfram and Anja Herlyn

2010 "Factors affecting economies of scale in combined sewer systems", *Water Science & Technology*, 62 (1), p. 36, ISSN: 0273-1223, DOI: 10.2166/wst.2010.241.

Mikovits, Christian, Wolfgang Rauch and Manfred Kleidorfer

2014 "Dynamics in Urban Development, Population Growth and their Influences on Urban Water Infrastructure", *Procedia Engineering*, 70, 12th International Conference on Computing and Control for the Water Industry (CCWI 2013), pp. 1147–1156, ISSN: 1877-7058, DOI: 10.1016/j.proeng.2014.02.127.

2015 "A dynamic urban development model designed for purposes in the field of urban water management", *Journal of Hydroinformatics*, 17 (3), pp. 390–403, ISSN: 1464-7141, DOI: 10.2166/hydro.2014.015.

Milojković, Ivan and Sinisa Andrić

2009 "Vikor method for asset management in Serbian Belgrade Wastewater Services", in *Proceedings of the Tenth International Conference on Computing and Control for the Water Industry, CCWI 2009 - Integrating Water Systems*, ed. by J. Boxall and C. Maksimović, pp. 741–747, ISBN: 978-0-415-54851-9.

Mitchell, V. Grace

2006 "Applying Integrated Urban Water Management Concepts: A Review of Australian Experience", *Environmental Management*, 37 (5), pp. 589–605, ISSN: 0364-152X, DOI: 10.1007/s00267-004-0252-1.

Mithen, Steven

2010 "The domestication of water: water management in the ancient world and its prehistoric origins in the Jordan Valley", *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 368 (1931), pp. 5249–5274, ISSN: 1364-503X, DOI: 10.1098/rsta.2010.0191.

Möderl, Michael

2009 *Modelltechnische Analyse von Netzwerksystemen der Siedlungswasserwirtschaft*, PhD thesis, Leopold-Franzens-Universität Innsbruck, Innsbruck, Austria.

Möderl, Michael, Manfred Kleidorfer, Robert Sitzenfrei and Wolfgang Rauch

2009 "Identifying weak points of urban drainage systems by means of VulNetUD", *Water Science & Technology*, 60 (10), pp. 2507–2513, ISSN: 0273-1223, DOI: 10.2166/wst.2009.664.

Morais, Danielle C. and Adiel T. Almeida

2007 "Water supply system decision making using multicriteria analysis", *Water SA*, 32 (2), pp. 229–236, ISSN: 0378-4738, DOI: 10.4314/wsa.v32i2.5247.

Moura, P. M., M. B. Baptista and S. Barraud

2006 "Comparison between two methodologies for urban drainage decision aid", *Water Science & Technology*, 54 (6-7), p. 493, ISSN: 0273-1223, DOI: 10.2166/wst.2006.612.

Nafi, Amir and Yehuda Kleiner

2010 "Scheduling Renewal of Water Pipes While Considering Adjacency of Infrastructure Works and Economies of Scale", *Journal of Water Resources Planning and Management*, 136 (5), pp. 519–530, ISSN: 0733-9496, DOI: 10.1061/(ASCE)WR.1943-5452.0000062.

Neunteufel, Roman, Thomas Ertl, André Spindler, Aditya Lukas, Reinhard Perfler, Dominik Schwarz, Matthias Zessner and Raimund Haberl

2012 *Technische Herausforderungen in der Siedlungswasserwirtschaft*, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Sektion VII Wasser, Vienna, Austria.

Nicklow, John, Patrick Reed, Dragan A. Savic, Tibebe Dessalegne, Laura Harrell, Amy Chan-Hilton, Mohammad Karamouz, Barbara Minsker, Avi Ostfeld, Abhishek Singh and Emily Zechman

2010 "State of the Art for Genetic Algorithms and Beyond in Water Resources Planning and Management", *Journal of Water Resources Planning and Management*, 136 (4), pp. 412–432, DOI: 10.1061/(ASCE)WR.1943-5452.0000053.

Ochs, Christian-Peter

2012 *Multikriterielle Optimierung der Sanierungsplanung von Entwässerungsnetzen*, PhD thesis, Universität Kaiserslautern, Kaiserslautern, Germany.

ÖNORM B 2503

2009 *Kanalanlagen - Ergänzende Bestimmungen für die Planung, Ausführung und Prüfung*, Österreichisches Normungsinstitut, https://www.austrian-standards.at/.

ÖNORM B 2533

2004 *Koordinierung unterirdischer Einbauten - Planungsrichtlinien*, Österreichisches Normungsinstitut, https://www.austrian-standards.at/.

ÖNORM B 2538

2002 *Transport-, Versorgungs- und Anschlussleitungen von Wasserversorgungsanlagen - Ergänzende Bestimmungen zu ÖNORM EN 805*, Österreichisches Normungsinstitut, https://www.austrian-standards.at/.

OpenStreetMap

2015 *OpenStreetMap*, OpenStreetMap Foundation, https://www.openstreetmap.org/.

Opricovic, Serafim

1998 *Multicriteria optimization of civil engineering systems*, PhD thesis, Faculty of Civil Engineering University of Belgrade.

Opricovic, Serafim and Gwo-hshiung Tzeng

2004 "Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS", *European Journal of Operational Research*, 156 (2), pp. 445–455, ISSN: 0377-2217, DOI: 10.1016/S0377-2217(03)00020-1.

Osman, Hesham

2015 "Coordination of urban infrastructure reconstruction projects", *Structure and Infrastructure Engineering*, pp. 1–14, ISSN: 1573-2479, DOI: 10.1080/15732479.2014.995677.

Osman, Hesham and Kevin Bainbridge

2011 "Comparison of Statistical Deterioration Models for Water Distribution Networks", *Journal of Performance of Constructed Facilities*, 25 (3), pp. 259–266, ISSN: 0887-3828, DOI: 10.1061/(ASCE)CF.1943-5509.0000157.

ÖVGW W 100

2007 *Wasserverteilleitungen -Betrieb und Instandhaltung*, ÖVGW Österreichische Vereinigung für das Gas- und Wasserfach, Vienna, Austria.

ÖVGW W 105

2011 *Schadensstatistik - Erfassung und Verarbeitung von Schadensereignissen*, ÖVGW Österreichische Vereinigung für das Gas- und Wasserfach, Vienna, Austria.

ÖVGW W 62

2013 *Kalkulation zur Ermittlung des Wassertarifes*, ÖVGW Österreichische Vereinigung für das Gas- und Wasserfach, Vienna, Austria.

ÖVGW W 63

2009 *Wasserverluste in Trinkwasserversorgungssystemen*, ÖVGW Österreichische Vereinigung für das Gas- und Wasserfach, Vienna, Austria.

ÖWAV-RB 11

2009 *Abwassertechnische Berechnung und Dimensionierung von Abwasserkanälen*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 19

2007 *Richtlinien für die Bemessung von Mischwasserentlastungen*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 22

2015 *Betrieb von Kanalisationsanlagen*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 28

2007 *Unterirdische Kanalsanierung*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 35

2003 *Behandlung von Niederschlagswässern*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 40
2010 *Leitungsinformationssystem - Wasser und Abwasser*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 42
2011 *Unterirdische Kanalsanierung - Hauskanäle*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

ÖWAV-RB 43
2013 *Optische Kanalinspektion*, Österreichischer Wasser- und Abfallwirtschaftsverband, Vienna, Austria.

Park, Suwan, Hwan Don Jun, Bong Jae Kim and G. C. Im
2008 "Modeling of Water Main Failure Rates Using the Log-linear ROCOF and the Power Law Process", *Water Resources Management*, 22 (9), pp. 1311–1324, ISSN: 0920-4741, DOI: 10.1007/s11269-007-9227-3.

Park, Suwan, Hwan Don Jun, Newland Agbenowosi, Bong Jae Kim and Kiyoung Lim
2011 "The Proportional Hazards Modeling of Water Main Failure Data Incorporating the Time-dependent Effects of Covariates", *Water Resources Management*, 25 (1), pp. 1–19, ISSN: 0920-4741, DOI: 10.1007/s11269-010-9684-y.

Pires, Ana, Ni-Bin Chang and Graça Martinho
2011 "An AHP-based fuzzy interval TOPSIS assessment for sustainable expansion of the solid waste management system in Setúbal Peninsula, Portugal", *Resources, Conservation and Recycling*, 56 (1), pp. 7–21, ISSN: 0921-3449, DOI: 10.1016/j.resconrec.2011.08.004.

Plihal, Hanns
2013 "Zustandsdatenanalyse nach Schadensursache, Entstehungsphase und Schutzziel zur Optimierung der Kanalinstandhaltung", in *Kanalmanagement 2013*, ed. by Thomas Ertl, Wiener Mitteilungen, Universität für Bodenkultur Wien, Institut für Siedlungswasserbau, Industriewasserwirtschaft und Gewässerschutz, Vienna, Austria, vol. 229, ISBN: 978-3-85234-122-4.

Quantum GIS Development Team
2015 *Quantum GIS: Open Source Geospatial Foundation Project*, Quantum GIS Development Team, http://qgis.osgeo.org/de/site/.

R Development Core Team
2008 *R: A Language and Environment for Statistical Computing*, ISBN 3-900051-07-0, R Foundation for Statistical Computing, Vienna, Austria, http://www.R-project.org.

Rajani, Balvant and Yehuda Kleiner

2001 “Comprehensive review of structural deterioration of water mains: physically based models”, *Urban Water*, 3 (3), pp. 151–164, ISSN: 1462-0758, DOI: 10.1016/S1462-0758(01)00032-2.

Rinaldi, Steven M., James P. Peerenboom and Terrence K. Kelly

2001 “Identifying, understanding, and analyzing critical infrastructure interdependencies”, *IEEE Control Systems Magazine*, 21 (6), pp. 11–25, ISSN: 0272-1708, DOI: 10.1109/37.969131.

Roscher, Harald

2000 *Zustandsbewertung städtischer Wasserrohrleitungen zur Vorbereitung der Rehabilitation*, ROHRBAU-Kongress 2000 in Weimar, FITR - Forschungsinstitut für Tief- und Rohrleitungsbau Weimar e.V.

Rossman, Lewis A.

2000 *EPANET 2: Users Manual*, EPA/600/R-00/057, U.S. Environmental Protection Agency, Cincinnati, USA.

2010 *Storm Water Management Model User's Manual Version 5.0*, EPA/600/R-05/040, U.S. Environmental Protection Agency, Cincinnati, USA.

Røstum, Jon

2000 *Statistical modelling of pipe failures in water networks*, PhD thesis, Norwegian University of Science and Technology NTNU, Trondheim, Norway.

Roy, B.

1978 “ELECTRE III: Un algorithme de classements fondé sur une représentation floue des préf érences en présence de critéres multiples”, *Cahiers du Centre d'Etudes de Recherche Opérationnelle*, 20, pp. 3 –24.

Ruth, Matthias, Clark Bernier, Nigel Jollands and Nancy Golubiewski

2007 “Adaptation of urban water supply infrastructure to impacts from climate and socioeconomic changes: The case of Hamilton, New Zealand”, *Water Resources Management*, 21 (6), pp. 1031–1045, ISSN: 0920-4741, DOI: 10.1007/s11269-006-9071-x.

Saaty, R. W.

1987 “The analytic hierarchy process—what it is and how it is used”, *Mathematical Modelling*, 9 (3–5), pp. 161–176, ISSN: 0270-0255, DOI: 10.1016/0270-0255(87)90473-8.

Saaty, Thomas L.

1980 *The Analytic Hierarchy Process: Planning, Piority Setting, Resource Allocation*, McGraw-Hill, New York, USA, ISBN: 978-0-07054-371-3.

Sabzi, Hamed Zamani and James Phillip King

2015 "Numerical Comparison of Multi-criteria Decision-making Techniques: A Simulation on Flood Management Multi-criteria Systems", in *World Environmental and Water Resources Congress 2015: Floods, droughts, and ecosytems*, ed. by Karen Karvazy and Veronica L. Webster, American Society of Civil Engineers (ASCE), pp. 359–373, ISBN: 978-0-7844-7916-2, DOI: 10.1061/9780784479162.035.

Sægrov, Sveinung

2005 (ed.), *Care-W: Computer Aided Rehabilitation of Water Networks*, IWA Publishing, London, UK, ISBN: 978-1-84339-091-6.

2006 (ed.), *Care-S: Computer Aided Rehabilitation of Sewer and Stormwater Networks*, IWA Publishing, London, UK, ISBN: 978-1-84339-115-9.

Sægrov, Sveinung and Wolfgang Schilling

2002 "Computer aided rehabilitation of sewer and storm water networks", in *Global Solutions for Urban Drainage*, ed. by Eric W. Strecker and Wayne C. Huber, American Society of Civil Engineers (ASCE), pp. 1–15, ISBN: 978-0-78440-644-1.

Scheidegger, Andreas, T. Hug, Jörg Rieckermann and Max Maurer

2011 "Network condition simulator for benchmarking sewer deterioration models", *Water Research*, 45 (16), pp. 4983–4994, ISSN: 0043-1354, DOI: 10.1016/j.watres.2011.07.008.

Scheidegger, Andreas, Lisa Scholten, Max Maurer and Peter Reichert

2013 "Extension of pipe failure models to consider the absence of data from replaced pipes", *Water Research*, 47 (11), pp. 3696–3705, ISSN: 0043-1354, DOI: 10.1016/j.watres.2013.04.017.

Scholten, Lisa, Andreas Scheidegger, Peter Reichert and Max Maurer

2013 "Combining expert knowledge and local data for improved service life modeling of water supply networks", *Environmental Modelling & Software*, 42, pp. 1–16, ISSN: 1364-8152, DOI: 10.1016/j.envsoft.2012.11.013.

Semadeni-Davies, Annette, Claes Hernebring, Gilbert Svensson and Lars-Göran Gustafsson

2008 "The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system", *Journal of Hydrology*, 350 (1–2), pp. 100–113, ISSN: 0022-1694, DOI: 10.1016/j.jhydrol.2007.05.028.

Shamir, Uri and Charles Howard

1979 "An Analytical Approach to Scheduling Pipe Replacement", *Journal-American Water Works Association*, 71 (5), pp. 248–258.

Sitzenfrei, Robert and Wolfgang Rauch

2014 "Investigating Transitions of Centralized Water Infrastructure to Decentralized Solutions – An Integrated Approach", *Procedia Engineering*, 70, 12th International Conference on Computing and Control for the Water Industry (CCWI 2013), pp. 1549–1557, ISSN: 1877-7058, DOI: 10.1016/j.proeng.2014.02.171.

Sitzenfrei, Robert, Michael Mair, Franz Tscheikner-Gratl, B. Hupfauf and Wolfgang Rauch

2015 "What can we learn from historical water network transition?", in *World Environmental and Water Resources Congress 2015: Floods, droughts, and ecosytems*, ed. by Karen Karvazy and Veronica L. Webster, American Society of Civil Engineers (ASCE), pp. 907–916, ISBN: 978-0-7844-7916-2, DOI: 10.1061/9780784479162.086.

Smith, Ben R.

2009 "Re-thinking wastewater landscapes: combining innovative strategies to address tomorrow's urban wastewater treatment challenges", *Water Science & Technology*, 60 (6), pp. 1465–1473, ISSN: 0273-1223, DOI: 10.2166/wst.2009.473.

Solecka, Katarzyna

2014 "Electre III method in assessment of variants of integrated urban public transport system in Cracow", *Transport Problems*, 9 (4), pp. 83 –95, ISSN: 1896-0596.

Sorge, Christian

2006 *Technische Zustandsbewertung metallischer Wasserversorgungsleitungen als Beitrag zur Rehabilitationsplanung*, PhD thesis, Bauhaus Universität Weimar, Weimar, Germany.

Stanić, Nikola, Jeroen Langeveld and Francois Clemens

2012 "Identification of the information needs for sewer asset management by assessing failure mechanisms", in *9th International Conference on Urban Drainage Modelling*, ed. by Dusan Prodanovic and Jasna Plavsic.

Statistik Austria

2015 *Gemeindegrößenklassen mit Einwohnerzahl 2015*, Bundesanstalt Statistik Österreich, http://www.statistik.at.

Stibernitz, Christina

2014 *Rehabilitierungsplanung alternder Infrastruktur anhand eines konkreten Fallbeispiels*, Bachelor thesis, Universität Innsbruck, Innsbruck, Austria.

Stone, Steve J., Emil J. Dzuray, Deborah Meisegeier, Anna S. Dahlborg and Manuela Erickson

2002 *Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems*, EPA/600/R-02/029, U.S. Environmental Protection Agency (EPA), Edison, USA.

Strommenger, Eva

1980 *Habuba Kabira: Eine Stadt vor 5000 Jahren: Ausgrabungen der Deutschen Orient-Gesellschaft am Euphrat in Habuba Kabira - Syrien*, Verlag Philipp von Zabern, ISBN: 3-8053-0449-8.

Theuretzbacher-Fritz, Heimo, Roman Neunteufel, Jörg Kölbl, Reinhard Perfler, Mario Unterwainig and Rafael Krendelsberger

2006 *Benchmarking und Best Practices in der österreichischen Wasserversorgung – Stufe B. – Öffentlicher Abschlussbericht zum ÖVGW-Projekt 2005/06*, Graz-Wien-Wiener Neustadt, Austria.

Tran, Dang Hoa, Anne W. M. Ng, Kerry J. Mcmanus and Stewart Burn

2008 "Prediction models for serviceability deterioration of stormwater pipes", *Structure and Infrastructure Engineering*, 4 (4), pp. 287–295, ISSN: 1573-2479, DOI: 10.1080/15732470600792236.

Tran, H. D., Perera, B. J. C. and Anne W. M. Ng

2010 "Markov and Neural Network Models for Prediction of Structural Deterioration of Storm-Water Pipe Assets", *Journal of Infrastructure Systems*, 16 (2), pp. 167–171, ISSN: 1076-0342, DOI: 10.1061/(ASCE)IS.1943-555X.0000025.

Triantaphyllou, Evangelos and Alfonso Sánchez

1997 "A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods", *Decision Sciences*, 28 (1), pp. 151–194, ISSN: 0011-7315, DOI: 10.1111/j.1540-5915.1997.tb01306.x.

Trojan, Flavio and Danielle C. Morais

2012 "Prioritising alternatives for maintenance of water distribution networks: A group decision approach", *Water SA*, 38 (4), ISSN: 0378-4738, DOI: 10.4314/wsa.v38i4.11.

Tscheikner-Gratl, Franz, Christian Mikovits, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer

2013a "Chancen und Herausforderungen für eine ganzheitliche Sanierungsplanung von Kanalisationen", in *Kanalmanagement 2013*, ed. by Thomas Ertl, Wiener Mitteilungen, Univ. für Bodenkultur Wien, Inst. für Siedlungswasserbau, Industriewasserwirtschaft und Gewässerschutz, Vienna, Austria, vol. 229, pp. C1–C26, ISBN: 978-3-85234-122-4.

Tscheikner-Gratl, Franz, Christian Mikovits, Michael Möderl, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer

2013b "Integrated Rehabilitation Management for Different Infrastructure Sectors", *gwf-Wasser-Abwasser*, 154 (Special 1/2013), pp. 50–56, https://www.di-verlag.de/de/Zeitschriften/gwf-Wasser-Abwasser/2013/sp1/Integrated-Rehabilitation-Management-for-Different-Infrastructure-Sectors.

Tscheikner-Gratl, Franz, Christian Mikovits, Wolfgang Rauch and Manfred Kleidorfer

2014a "Adaptation of sewer networks using integrated rehabilitation management", *Water Science & Technology*, 70 (11), pp. 1847–1856, ISSN: 0273-1223, DOI: 10.2166/wst.2014.353.

Tscheikner-Gratl, Franz, Christian Mikovits, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer

2014b "Deterioration of our sewer infrastructure as an opportunity for adaptation", in *Conference Proceedings of CeoCor 2014*, ed. by Luigi Di Biase, Max Hammerer and Markus Büchler, European Committee for the study of corrosion and protection of pipe and pipeline systems, Weimar, Germany.

Tscheikner-Gratl, Franz, Robert Sitzenfrei, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer

2014c "Prioritization of Rehabilitation Areas for Urban Water Infrastructure. A Case Study", *Procedia Engineering*, 89, 16th Water Distribution System Analysis Conference, WDSA2014 Urban Water Hydroinformatics and Strategic Planning, pp. 811–816, ISSN: 1877-7058, DOI: 10.1016/j.proeng.2014.11.511.

Tscheikner-Gratl, Franz, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer

2015a "Enhancement of limited water supply network data for deterioration modelling and determination of rehabilitation rate", *Structure and Infrastructure Engineering*, pp. 1–15, ISSN: 1573-2479, DOI: 10.1080/15732479.2015.1017730.

Tscheikner-Gratl, Franz, Christian Mikovits, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer

2015b "GIS-Anwendung in der integrierten Rehabilitierungsplanung von urbaner Wasserinfrastruktur", *AGIT - Journal für Angewandte Geoinformatik*, 1, pp. 308–314, DOI: 10.14627/537557043.

Tscheikner-Gratl, Franz, Robert Sitzenfrei, Christina Stibernitz, Wolfgang Rauch and Manfred Kleidorfer

2015c "Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities", in *World Environmental and Water Resources Congress 2015: Floods, droughts, and ecosytems*, ed. by Karen Karvazy and Veronica L. Webster, American Society of Civil Engineers (ASCE), pp. 2045–2057, ISBN: 978-0-7844-7916-2, DOI: 10.1061/9780784479162.201.

Tscheikner-Gratl, Franz, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer

2015d "Integrated rehabilitation planning of urban infrastructure systems using a street section priority model", *Urban Water Journal*, pp. 1–13, ISSN: 1744-9006, DOI: 10.1080/1573062X.2015.1057174.

Tscheikner-Gratl, Franz, Tanja Vonach, Wolfgang Rauch and Manfred Kleidorfer

2015e "Verwendete Materialien in der Wasserversorgung bei Betreibern von Versorgungsnetzen kleinerer und mittlerer Größe", *Bauingenieur*, 90 (02-2015), pp. 81–87, http://www.bauingenieur.de/bauing/article.php?data[article_id]=83058.

Tzeng, Gwo-Hshiung and Jih-Jeng Huang

2011 *Multiple attribute decision making: Methods and appliations*, A Chapman & Hall book, CRC Press, Boca Raton, USA, ISBN: 978-1-43986-157-8.

2013 *Fuzzy multiple objective decision making*, A Chapman & Hall book, CRC Press, Boca Raton, USA, ISBN: 978-1-46655-461-0.

Urban, Dieter and Jochen Mayerl

2011 *Regressionsanalyse: Theorie, Technik und Anwendung*, 4., überarbeitete und erweiterte Auflage, Studienskripten zur Soziologie, VS, Verlag für Sozialwissenschaften, Wiesbaden, ISBN: 978-3-531-17345-0.

Urich, Christian and Wolfgang Rauch

2014 "Modelling the urban water cycle as an integrated part of the city: a review", *Water Science & Technology*, 70 (11), pp. 1857–1872, ISSN: 0273-1223, DOI: 10.2166/wst.2014.363.

van Riel, Wouter, Jeroen Langeveld, Paulien Herder and Francois Clemens

2014 "Intuition and information in decision-making for sewer asset management", *Urban Water Journal*, 11 (6), pp. 506–518, ISSN: 1744-9006, DOI: 10.1080/1573062X.2014.904903.

Voinov, Alexey and Herman H. Shugart

2013 "'Integronsters', integral and integrated modeling", *Environmental Modelling & Software*, 39, pp. 149–158, ISSN: 1364-8152, DOI: 10.1016/j.envsoft.2012.05.014.

Wade, Rebecca, Lian Lundy, Neil Berwick, Fiona Fordyce, Chris Jefferies and Eduardo Garcia

2014 "Maximising Multiple Benefits From Sustainable Drainage Systems: Identification and Decision Support", in *13th International Conference on Urban Drainage (ICUD) - Urban Drainage in the Context of Integrated Urban Water Management: A Bridge Between Developed and Developing Countries*, ed. by Nordin bin Hamdan and Mohamed Roseli bin Zainal Abidin, International Water Association (IWA), Kuching - Sarawak, Malaysia.

Walski, Thomas M., Donald V. Chase, Dragan A. Savić, Walter Grayman, Stephanus Beckwith and E. Koelle

2003 *Advanced water distribution modeling and management*, 1st ed, Bentley Institute Press, Exton, USA, ISBN: 978-1-93449-301-4.

Ward, Ben and Dragan A. Savić

2012 "A multi-objective optimisation model for sewer rehabilitation considering critical risk of failure", *Water Science & Technology*, 66 (11), pp. 2410–2417, ISSN: 0273-1223, DOI: 10.2166/wst.2012.393.

Water Framework Directive 2000/60/EC

2000 *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*, OJL 327, http://eur-lex.europa.eu.

Weber, Karl and Michael Obermeier

2012 *Rechtliche Grundlagen und Haftungsfragen in der Siedlungswasserwirtschaft*, Forum Umwelttechnik und Wasserbau, iup, Innsbruck, vol. 12, ISBN: 978-3902811-48-6.

Wildt, Stefan

2013 "Tirol im Fokus: Ergebnisse der Investitionskostenerhebung 2012", in *ÖWAV - Seminar: Sanierung und Anpassung von Entwässerungsmaßnahmen*, ed. by Wolfgang Rauch, Österreichischer Wasser- und Abfallwirtschaftsverband, ISBN: 978-3-902810-66-3.

Willi, Anton, Josef Hörnler and Markus Federspiel

1992 *Zustand der Tiroler Abwasserkanäle*, ed. by Erich Wenzl, Amt der Tiroler Landesregierung Abteilung IIIg, Innsbruck, Austria.

Wolf, Martin

2006 *Untersuchungen zu Sanierungsstrategien von Abwasserkanalnetzen und deren Auswirkungen auf Wertentwicklung und Abwassergebühren*, Mitteilungen / Institut für Wasserwesen, Oldenbourg-Industrieverlag, Munich, Germany, vol. 95, ISBN: 3-8356-3117-9.

Wolf, Martin, Stefan Braunschmidt, Thomas Rabe and Klaus-Jochen Sympher

2005 *KANSAS Verbundvorhaben - Entwicklung einer ganzheitlichen Kanalsanierungsstrategie für Stadtentwässerungsnetze Deutschlands: Leitfaden*, Förderkennzeichen : 02WK0147 - 02WK0149, Bundesministerium für Bildung und Forschung, Munich, Germany.

Wong, Tony H. F. and Rebekah R. Brown

2009 "The water sensitive city: principles for practice", *Water Science & Technology*, 60 (3), pp. 673–682, ISSN: 0273-1223, DOI: 10.2166/wst.2009.436.

Yang, Bo and Shujuan Li

2013 "Green Infrastructure Design for Stormwater Runoff and Water Quality: Empirical Evidence from Large Watershed-Scale Community Developments", *Water*, 5 (4), pp. 2038–2057, ISSN: 2073-4441, DOI: 10.3390/w5042038.

Yang, Jidong

2004 *Road Crack Condition Performance Modeling Using Recurrent Markov Chains And Artificial Neural Networks*, PhD-Thesis, University of South Florida, Tampa, USA.

Yang, Ming-Der, Tung-Ching Su and Yi-Ping Chen

2005 "Priority Evaluation of Sewerage Rehabilitation by AHP", in *Proceedings of the Pipeline Division Specialty Conference 2005*, ed. by C. Vipulanandan and R. Ortega, pp. 523–537, DOI: 10.1061/40800(180)41.

Young, Kevin D., Tamim Younos, Randel L. Dymond, David F. Kibler and David H. Lee

2010 "Application of the analytic hierarchy process for selecting and modeling stormwater best management practices", *Journal of Contemporary Water Research & Education*, 146 (1), pp. 50–63, ISSN: 1936-704X, DOI: 10.1111/j.1936-704X.2010.00391.x.

Younis, Rizwan and Mark A. Knight

2010a "A probability model for investigating the trend of structural deterioration of wastewater pipelines", *Tunnelling and Underground Space Technology*, 25 (6), pp. 670–680, ISSN: 0886-7798, DOI: 10.1016/j.tust.2010.05.007.

2010b "Continuation ratio model for the performance behavior of wastewater collection networks", *Tunnelling and Underground Space Technology*, 25 (6), pp. 660–669, ISSN: 0886-7798, DOI: 10.1016/j.tust.2010.06.003.

Zeleny, M.

1973 "Compromise Programming", in *Multiple Criteria Decision Making*, ed. by J. Cochrane and M. Zeleny, University of South Carolina Press, Columbia, pp. 262–301.

Zhao, Jack Q. and Balvant Rajani

2002 *Construction and rehabilitation costs for buried pipe with a focus on trenchless technologies*, Research Report No. 101, Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario.

Zischg, Jonathan, Michael Mair, Wolfgang Rauch and Robert Sitzenfrei

2015 "Stochastic performance assessment and optimization strategies of the water supply network transition of Kiruna during city relocation", in *World Environmental and Water Resources Congress 2015: Floods, droughts, and ecosytems*, ed. by Karen Karvazy and Veronica L. Webster, American Society of Civil Engineers (ASCE), pp. 2045–2057, ISBN: 978-0-7844-7916-2, DOI: 10.1061/9780784479162.080.

Part II

Publications

8 PAPER I

Integrated rehabilitation planning of urban infrastructure systems using a street section priority model

Authors: **Franz Tscheikner-Gratl**, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer

Date: 2015
Place: Urban Water Journal
Type: Journal publication

9 PAPER II

Integrated rehabilitation management by prioritization of rehabilitation areas for small and medium sized municipalities

Authors: **Franz Tscheikner-Gratl**, Robert Sitzenfrei, Christina Stibernitz, Wolfgang Rauch and Manfred Kleidorfer
Date: 2015
Place: World Environmental and Water Resources Congress 2015
Type: Proceedings paper

10 | PAPER III

Prioritization of Rehabilitation Areas for Urban Water Infrastructure. A Case Study

Authors: **Franz Tscheikner-Gratl**, Robert Sitzenfrei, Max Hammerer, Wolfgang Rauch and Manfred Kleidorfer
Date: 2014
Place: Procedia Engineering
Type: Journal publication

11 PAPER IV

Integrated planning of rehabilitation strategies for sewers

`Authors:` Manfred Kleidorfer, Michael Möderl, **Franz Tscheikner-Gratl**, Max Hammerer, Heiko Kinzel and Wolfgang Rauch
`Date:` 2013
`Place:` Water Science & Technology
`Type:` Journal publication

12 | PAPER V

Integrated Rehabilitation Management for Different Infrastructure Sectors

Authors: **Franz Tscheikner-Gratl**, Max Hammerer, Wolfgang Rauch, Christian Mikovits and Manfred Kleidorfer

Date: 2013
Place: gwf Wasser-Abwasser
Type: Journal publication

13 | PAPER VI

Enhancement of limited water supply network data for deterioration modelling and determination of rehabilitation rate

Authors: **Franz Tscheikner-Gratl**, Robert Sitzenfrei, Wolfgang Rauch and Manfred Kleidorfer
Date: 2015
Place: Structure and Infrastructure Engineering
Type: Journal publication

14 PAPER VII

Verwendete Materialien in der Wasserversorgung bei Betreibern von Versorgungsnetzen kleinerer und mittlerer Größe

Authors: **Franz Tscheikner-Gratl**, Tanja Vonach, Wolfgang Rauch and Manfred Kleidorfer
Date: 2015
Place: Bauingenieur
Type: Journal publication

15 | PAPER VIII

What can we learn from historical water network transition?

`Authors:` Robert Sitzenfrei, Michael Mair, **Franz Tscheikner-Gratl**, Bernhard Hupfauf and Wolfgang Rauch
`Date:` 2015
`Place:` World Environmental and Water Resources Congress 2015
`Type:` Proceedings paper

16 | PAPER IX

Adaptation of sewer networks using integrated rehabilitation management

Authors: **Franz Tscheikner-Gratl**, Christian Mikovits, Wolfgang Rauch and Manfred Kleidorfer

Date: 2014
Place: Water Science & Technology
Type: Journal publication