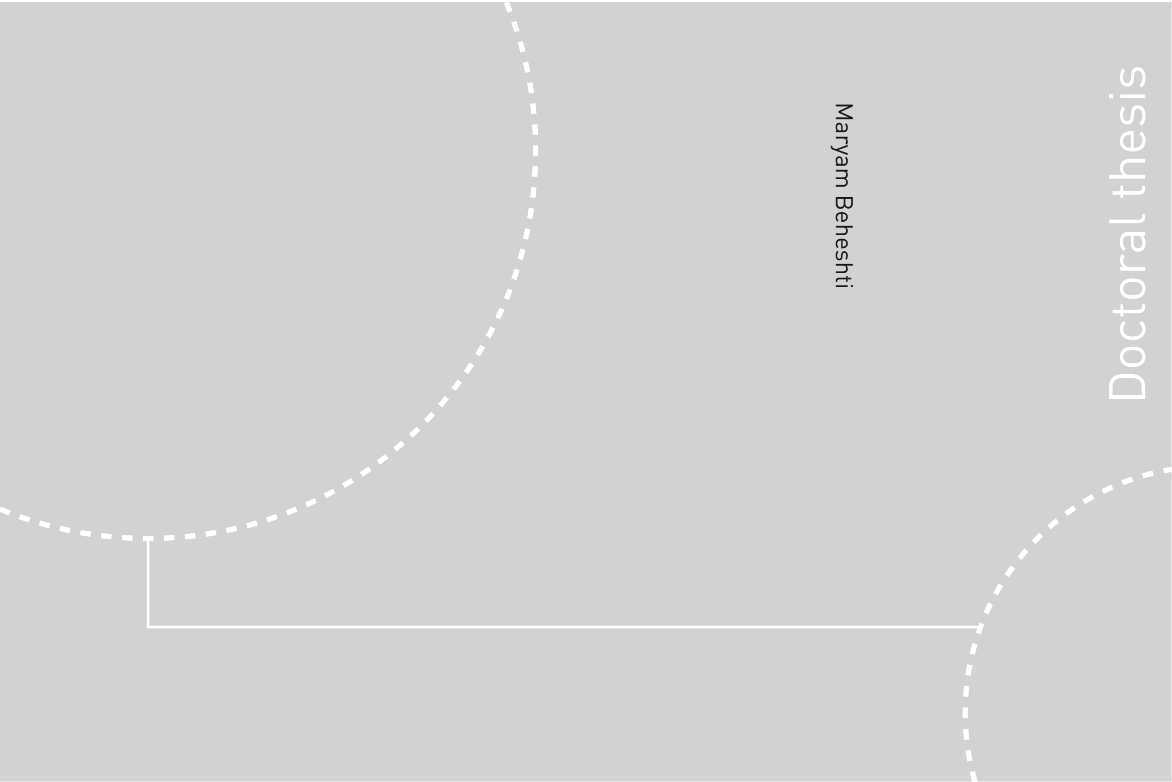

ISBN 978-82-326-3856-7 (printed ver.)
ISBN 978-82-326-3857-4 (electronic ver.)
ISSN 1503-8181

NTNU
Norwegian University of
Science and Technology

Doctoral thesis

Maryam Beheshti

Doctoral theses at NTNU, 2019:129

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Civil and Environmental
Engineering

NTNU

Doctoral theses at NTNU, 2019:129

Maryam Beheshti

Application of Infrastructure Asset Management in Enhancing the Performance of Sewer Networks

Assessment of Infiltration and Inflow of Extraneous Water

NTNU
Norwegian University of
Science and Technology

Maryam Beheshti

Application of Infrastructure Asset Management in Enhancing the Performance of Sewer Networks

Assessment of Infiltration and Inflow of Extraneous Water

Thesis for the Degree of Philosophiae Doctor

Trondheim, June 2019

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the Degree of Philosophiae Doctor

Faculty of Engineering
Department of Civil and Environmental Engineering

ISBN 978-82-326-3856-7 (printed ver.)
ISBN 978-82-326-3857-4 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2019:129

Printed by NTNU Grafisk senter

Abstract

Wastewater transportation systems are one of the main city lifelines and initial prerequisites for urban areas all over the world. Sewer networks represent a high value in water infrastructure assets, and it is important to be preserved, developed and operated by sustainable sewer infrastructure asset management (IAM). Infiltration and inflow (I/I) of unwanted water from different sources—stormwater, groundwater, snowmelt or illicit and faulty connections—in urban sewer systems are significant challenges for sewer IAM and have negative impacts on environmental, public health and economic aspects of sustainable urban wastewater management as well as on chemical and energy resources. In many cities worldwide urban sewer networks are prone to a significant amount of unwanted water ingress from unknown sources due to aging and deterioration in the structure. Therefore, I/I assessment is a prerequisite to evaluate the sewer network performance and restrict unwanted water I/I, which should be considered in strategic long-term rehabilitation planning of sewer IAM.

The overall goal of the presented Ph.D. dissertation is to improve the efficiency and performance of urban sewer systems in the context of sewer IAM with a focus on assessment and detection of unwanted water I/I. Four objectives were defined along with three planning levels of sewer IAM—strategic, tactical and operational—, which are interconnected successively. The first objective was in line with the strategic level planning of "increasing resilience and performance of the sewer system". It discussed the evaluation and improvement of the sewer system efficiency from I/I aspect by strategic maintenance, rehabilitation, and renewal planning in a long-term period. The second objective defined the requirement for investigating and classifying available I/I assessment and detection techniques and finding the most relevant and practical methods for I/I studies at the medium-term tactical level. The last two objectives were in the category of the operational level with a focus on the unwanted water I/I detection and assessment in the short term in order to increase the level of preparedness of the sewer system against I/I of unwanted water in the long term.

The first objective presented the results of a sustainability analysis on the wastewater transport system of Trondheim, Norway, for future planning (2014-2040) from a metabolism-based performance analysis by Dynamic Metabolism Model (DMM) and compared with 'status quo' with constant development of the wastewater network. This work aimed to demonstrate a methodology for comparing different pathways toward sustainable management of wastewater systems. Therefore, four intervention strategies 'infiltration and inflow reduction', 'increasing rehabilitation rate', 'extension of the system regarding population growth', 'energy management' along with different combinations of them were analyzed from environmental, functional and economic aspects.

At the tactical level, intervention priorities, methods, and solutions were defined to reduce the infiltration in critical zones by practical methods in the medium-term period. Therefore, the available commonly used and advanced methods of I/I detection and assessment were classified to quantitative and qualitative techniques and evaluated based on their advantages and limitations by a critical literature review. A combination of these techniques can provide the sewer operators the possibility to compare different technologies and select the relevant ones based on the selection criteria.

In addition to the data collection and analysis in the tactical planning level, I/I simulation by mathematical modeling is a good measure to assess the status of the infiltration and inflow in the sewer network. In the present study, the sewer network of Lykkjbekken catchment in Trondheim was modeled and assessed. The simulation of the sewer flow emphasized on the presence of high rainfall-induced infiltration and inflow during wet weather conditions, whereas the groundwater infiltration during dry weather conditions was insignificant.

The effective reduction of I/I requires information about the location and source of I/I. The third objective of this study focused on I/I detection in the foul sewer network of a catchment in Trondheim during a period without snowmelt or groundwater infiltration. Fiber-optic distributed temperature sensing (DTS) was used for the first time in Norway to detect I/I in tandem with closed-circuit television inspection (CCTV) and smoke testing. The DTS was an accurate and feasible method for I/I detection, though it cannot identify exact types of failure and sources of I/I. Therefore, other complementary methods were used, e.g., CCTV or smoke testing. However, the CCTV was not completely successful in confirming three I/I sources detected by the DTS. This part of the study provides practical insights for the rehabilitation and repair of sewer networks that suffer from the undesirable I/I of extraneous water.

The last objective aimed at accurate quantification of unwanted water I/I from individual sources into a sewer system to assess the status of the sewer network, prioritize problematic parts, and conduct rehabilitation measures. To quantify extraneous water I/I into a sanitary sewer network, the DTS method was applied. The feasibility of DTS method was tested in both experimental discharges and for the rainfall-derived I/I. The achieved results from the monitoring campaign established the promising applicability of the DTS technique in the quantification analysis. Furthermore, the application of this method in quantifying real-life, rainfall-derived I/I into the sewer system was demonstrated and verified during wet weather conditions. This part of the study fills the knowledge gap of availability of reliable and accurate I/I assessment data for having more efficient maintenance and rehabilitation plans.

Preface

This doctoral thesis is submitted to the Norwegian University of Science and Technology (NTNU) as a part of the fulfillment of requirements for the degree of Philosophiae Doctor (Ph.D.).

The work presented in the thesis is the result of a four-year Ph.D. program at the Department of Civil and Environmental Engineering, NTNU, Trondheim. Professor Sveinung Sægrov has been the main supervisor of this study, while Associate Professor Tone Merete Muthanna at NTNU and Professor Paul Thamsen at TU-Berlin have been co-supervisors.

In the current Ph.D. study, 75% of work was dedicated to research and 25% to teaching duty at the department of civil and environmental engineering. This duty work included assisting in TVM4125 Water Supply and Wastewater Engineering, TVM4101 Water and Environment, TVM 4130 Urban Water System, and VM8207 Environmental Engineering Field Course, and supervising master students in their master projects and thesis. NTNU founded this research as a Ph.D. position in the Department of Civil and Environmental Engineering.

Following the guidelines of the Faculty of Engineering, this thesis comprises an introduction to the research that has resulted in four scientific journal papers (listed on page ix). Chapter 1 introduces the topic addressed in the current dissertation. Chapter 2 reviews the research approach that was considered for assessment and management of I/I in sewer networks. Chapter 3 presents the research methodology and experiments conducted to accomplish the current Ph.D. work. Chapter 4 contains data gathering and analysis of the results. Chapter 5-8 contain the five publications that the present thesis is based on. Finally, chapter 9 gives the main conclusions from this dissertation and discusses recommendations for future works.

Acknowledgment

I want to express my sincere gratitude to Professor Sveinung Sægrov for his valuable and endless help, support and encouragement. I am grateful for working with him and having the opportunity to learn a lot and to gain great experiences.

Thanks to Professor Paul Uwe Thamsen and Associate Professor Tone Merete Muthanna for their help and advice during my study.

I would like to thank and acknowledge my colleagues and friends at the department of Civil and Environmental Engineering at NTNU, for all the support, help and good moments.

I am grateful to the Water and Wastewater department of Trondheim Municipality and the personnel of that department, especially Kristin Greiff Johnsen, Birgitte Johannessen and Vidar Figenschou for their valuable support during my study.

I extend my sincere thanks to Professor Valentina Prigiobbe and Ting Liu for all the support and learning opportunity during my stay as an exchange scholor at the department of Civil, Environmental and Ocean Engineering at Stevens Institute of Technology in Hoboken, USA.

Thanks also to Remy Schilperoort, Cornelis de Haan and Erik Liefting at PARTNERS4URBANWATER for their invaluable advice and help during the DTS project.

My parents receive my deepest gratitude and love for their dedication and many years of support, that provided the foundation for this work. Mom, you spent the most beautiful time of your young ages raising and educating me. I will never forget all the good things that you taught me. Dad, you always motivated me to study with providing the best educational facilities. I experienced many amazing things with you and I am so grateful for them. Thanks to my sisters, Narges and Asal, for all amazing moments, laughter, happiness and positive energies that they have given me. Thanks to my parents' in-law, for their kindness. You have supported me always with your good words and encouragements. I am indebted to you because of raising such a great boy who has been my main support during my Ph.D. studies.

The last and biggest 'thank you' goes to my beautiful family. I want to thank my kind husband, Ali Tabeshian, for his patience, understanding, and love during my study. Your precious support and encouragement always enlighten my heart to be brave and go ahead. You defined the pure meaning of equality of men and women with your manner and behavior, and I am so proud of having such a man in my life. I love you so much! Our little princess, Nika, was born in half way of my study in January 2016. You were like a miracle in our life, and with your presence, everything became smoother and more efficient during my study. You were always so supportive with your patience and trust in me, and I feel like the happiest mom in the world for having such a great and wonderful daughter. Thanks to our little prince, who will come to the world soon, for being so calm, kind and supportive during writing this thesis.

Contents

List of publications

I. **Beheshti, M.** & Sægrov, S. (2018) *Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway*, Urban Water Journal, 15:1, 1-8, DOI: 10.1080/1573062X.2017.1363253

II. **Beheshti, M.**, Sægrov, S., Ugarelli, R. (2015) *Infiltration / Inflow Assessment and Detection in Urban Sewer System*, Vann, 01, 2015, 24-34.

III. **Beheshti, M.** & Sægrov, S. (2019) *Detection of extraneous water ingress into the sewer systems using tandem methods- A case Study in Trondheim City*, Water Science and Technology, 2019; DOI:10.2166/wst.2019.057

IV. **Beheshti, M.** & Sægrov, S. (2018) *Quantification assessment of extraneous water infiltration and inflow by analysis of the thermal behavior of the sewer network*, Water, *10*(8), 1070; DOI:10.3390/w10081070

The work in these journal papers are also completed by conference papers, presented at the following international conferences:

- Beheshti, M., Sægrov, S., Muthanna, T.M. (2015) 'Quantification and Detection of Non-Sewer Water Infiltration and Inflow in Urban Sewer Systems,' 17th International Conference on Water Management, May 11-12 2015, Montreal, Canada, p. 1000

- Beheshti, M. & Sægrov, S. (2017) 'Sustainability analysis of the sewer network of Trondheim City in Norway by Dynamic Metabolism Modeling,' LESAM 2017, 20-22 June 2017, Trondheim, Norway

- Beheshti, M., Figenschou, V., Sægrov, S. (2018) 'Assessment of Infiltration and Inflow in urban sewer systems by adaptive methods,' in Proceedings of the IWA World Water Congress, Tokyo, Japan, 16-21 September.

- Liu T., Beheshti M., Su X., Prigiobbe V. (2018) 'Sewer-Groundwater Interaction in Urban Coastal Areas.' in Urban Drainage Modelling (UDM) 2018, Palermo, Italy, 23-26 September. Published in New Trends in Urban Drainage Modelling. UDM 2018. Green Energy and Technology. Springer, Cham, pp. 771-776, DOI: https://doi.org/10.1007/978-3-319-99867-1_133

This Ph.D. research has been presented in the above conferences, in addition to several national and international contexts, including:

- Beheshti, M. & Sægrov, S., (2015). Assessment of infiltration and inflow in urban sewer systems by novel methods, EURO SAM workshop, Amsterdam, Jun 4th and 5th 2015
- EURO SAM workshop (Strasbourg, Jun 2016)
- EURO SAM workshop (Innsbruck, Jun 11th and 12th 2018)
- SPN 8, 31Aug-2 Sep 2016, Rotterdam, Netherlands

- Beheshti, M. & Sægrov, S., (2017). 'Sustainability analysis of the sewer network of Trondheim City in Norway by Dynamic Metabolism Modeling,' LESAM 2017 Conference, 20-22 June 2017, Trondheim, Norway
- Beheshti, M., Sægrov, S., (2017). 'Innovative Methods for measuring infiltration and ingress into sewers,' VA-Yngre Seminar, 25-26 April 2017, Kristiansand, Norway. (In Norwegian)
- Beheshti, M., Sægrov, S., (2017). 'Detection of infiltration points in the sewer systems,' Tekna Conference of Wastewater management in Norway, 12-13 January 2017, Trondheim, Norway. (In Norwegian)
- Beheshti, M., Sægrov, S., (2016). 'Methods of infiltration measurements in sewer systems,' Norwegian Water Annual Conference (Norsk Vanns årskonferanse), 6-7 September 2016, Trondheim, Norway. (In Norwegian)
- Beheshti, M., Sægrov, S., Schilperoort, R., (2016). 'The Application of DTS in Detection of Extraneous Water Infiltration and Inflow into the Sewer Systems,' 8th Sewer Processes and Networks Conference (SPN 8), Rotterdam, Netherlands, (poster presentation)
- Beheshti, M., Sægrov, S., Muthanna, T.M., (2015). 'Quantification and Detection of Non-Sewer Water Infiltration and Inflow in Urban Sewer Systems,' 17th International Conference on Water Management, May 2015, Montreal, Canada

The Ph.D. program was combined with teaching and supervisions:

- August-September 2018 –Teacher assistant for TVM4125- Water Supply and Wastewater Engineering, third-year course (bachelor level) for civil engineering students
- 2014-2018 –Teacher assistant for four semesters in TVM4101- Water and Environment,1st-year course (bachelor level) for all civil engineering students at NTNU (200 students).
- February 2018- Guest lecturer in Stormwater and Climate subject for one lecture in TVM4101- Water and Environment, 1st-year course (bachelor level) for all civil engineering students at NTNU (200 students).
- August 2017 – Guest lecturer for one lecture in the advanced course in TVM 4130- Urban Water System, 4th-year course (master level) NTNU (25 students).
- September 2016 – Guest lecturer for one lecture in the advanced course in TVM 4130- Urban Water System, 4th-year course (master level) at NTNU (25 students).
- October 2016 – lecturer for one lecture in urban water systems technical solutions in Water Week at NTNU, Trondheim.
- May 2016 – Demonstration of some hydrological instrumentations in VM8207- Environmental Engineering Field Course, Doctoral degree level course at NTNU (25 students).
- Master student supervision at NTNU: Fall 2014 (Master project- Hans Magnus Johnsen), Spring 2015 (Master thesis-Hans Magnus Johnsen), Fall 2016 (Master project- Lars Solberg & Pauli Nordvåg), Spring 2017 (Master thesis- Lars Solberg & Pauli Nordvåg), Autumn 2018 (Master project- Birgitte Taugbøl Kragset), Spring 2019 (Master thesis- Birgitte Taugbøl Kragset).

Nomenclature

Notations

Symbol	Description
‘a’	Intervention of Reduction of Infiltration and inflow
‘b’	Intervention of Improvement of rehabilitation rate
‘c’	Intervention of Extension of wastewater transport network
‘d’	Intervention of Energy management

Abbreviations

CIPP	Cured-In-Place-Pipe
CSO	Combined sewer overflow
CSS	Combined sewer systems
DEM	Digital elevation model
DMM	Dynamic Metabolism Model
DTS	Distributed Temperature Sensing
ERA	Environmental Risk Assessment
GHG	Greenhouse Gases
GIS	Geographic information system
I/I	Infiltration and Inflow into the sewer system
IAM	Infrastructure asset management
IOT	Internet of things
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
NSE	Nash-Sutcliffe efficiency
NOK	Norwegian Krone
O & M	Operation and Maintenance
PDCA	Plan-do-check-act
PE	PolyEthylene
PVC	Polyvinyl Chloride
SAM	Sewer asset management

SWMM	Stormwater management model
UWS	Urban Water Systems
WM2	WaterMet2 Model
WW	Wastewater
WWTP	Wastewater Treatment Plant

List of Figures

List of Tables

1. INTRODUCTION

1.1 Background

Water is one of the most important substances to all life, and its absence vanishes the existence. Access to clean drinking water is one of the essential human needs, as well as safe transportation of wastewater from urban areas. Urban water systems (UWS), *i.e.* water distribution and wastewater transportation systems, are one of the initial prerequisites for cities all over the world. Urban sewer systems are considered as one of the main city lifelines, transporting sewage and stormwater to wastewater treatment plants (WWTP). Urban water and wastewater infrastructure in industrialized cities are representing a high asset value while encountering asset deterioration after decades of operation (Kracht and Gujer, 2006; Rehan *et al.*, 2014). Moreover, the underground position of the pipelines makes their monitoring and preservation challenging. Functional efficiency and structural quality of sewer systems ensure conveying urban and industrial wastewater to WWTP without infiltration and exfiltration (J. B. Ellis *et al.*, 2005).

Infiltration and inflow (I/I) of unwanted water in urban sewer systems are significant challenges for urban water management and sewer infrastructure asset management (IAM). I/I have negative impacts on environmental, social, and economic aspects of sustainable urban wastewater management as well as on chemical and energy resources. Moreover, this unwanted water leads to overloading the sewer system—*i.e.* sewer pipelines, pumping stations and WWTPs—, increasing the risk of sanitary sewer overflow in urban areas, and increasing the pumping cost and energy consumption for transporting and purification. Therefore, I/I assessment is important in evaluating the sewer network performance and should be considered in the strategic long-term planning of urban sewer system IAM.

Climate change has been tangible and perceptible in the recent decades and has already had observable effects on global warming, ocean temperature increasing, ice/snow melting, and sea level rising (IPCC, 2007; Schneider *et al.*, 2013). Additionally, extreme weather events such as heatwaves, heavy rain- and snow storms, flooding, drought, and inundation influence the hydrological cycle and functionality of urban infrastructure. The climate models predict increase in temperature, and winter precipitation and decrease in summer precipitation for the northern hemisphere (IPCC, 2007), including Norway (Sundt-Hansen; *et al.*, 2017). Changing precipitation pattern, rising temperature, and abrupt snow melting may have determined effects on infiltration and inflow of stormwater and groundwater into separate sewer networks.

The concept of sustainability with its triangle bottom line of environment, social and economy is expanding to all aspects of human life. UWS are likewise not deprived of sustainability issue and are connected to various dimensions of it. Utilities usually have a vigorous effort on the quality of water, treatment efficiencies, and cost-effectiveness; nonetheless, in the course of recent years more focus has been devoted to broader sustainability features, such as greenhouse gas (GHG) emissions and life cycle environmental consequences (Ashley *et al.*, 2008; Slagstad and Brattebø, 2014). GHGs are emitted incessantly throughout the pipelines installation, operation and maintenance, and rehabilitation phases. However, more than 80% of these emissions happen during fabrication of pipelines (Strutt *et al.*, 2008; Venkatesh, Hammervold and Brattebø, 2009). Therefore, to reduce the amount of GHG emissions it is wise to keep current pipelines in the network by proper maintenance and rehabilitation plans, which is the main outcome of efficient sustainable infrastructure management.

1.2 Infrastructure asset management

Integrated urban water IAM is the framework of balancing performance, cost and risk of the system infrastructure in the long term. This can be achieved by three main competencies of management, engineering and information in utilities, while coordinating system activities at different planning and decision levels of strategic, tactical and operational (Alegre and Coelho, 2012). Figure 1.1 illustrates a holistic view of IAM in different dimensions of analysis, competence and planning levels. IAM planning and decision levels are introduced in Figure 1.2, where the strategic and operational levels are respectively the highest and lowest planning levels.

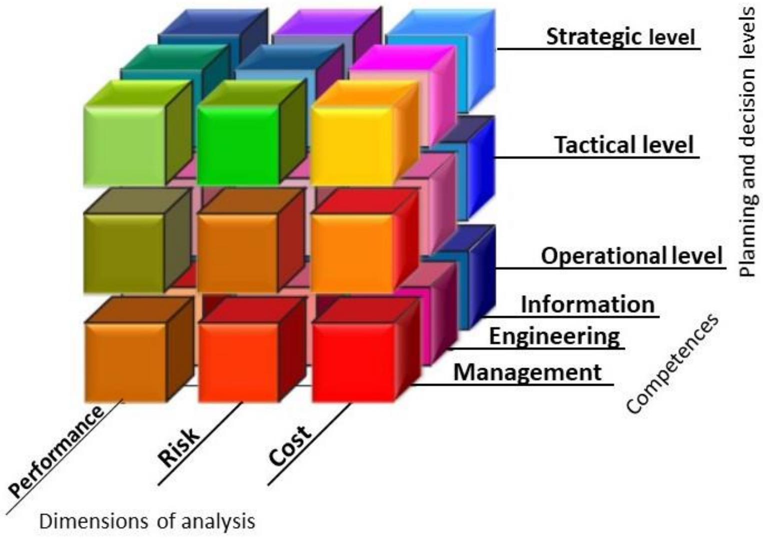

Figure 1.1 Infrastructure asset management approach (Alegre and Coelho, 2012)

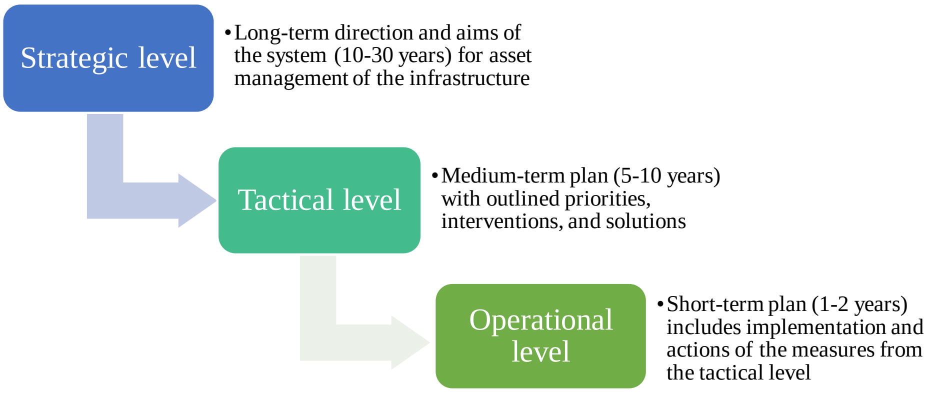

Figure 1.2 Different planning and decision levels in infrastructure asset management

The *ISO 2451x series* 2007 suggests the application of a plan-do-check-act (PDCA) principle at each decision levels —described in Figure 1.2—for continuous improvement of the IAM process, which is set of activities connected on a consecutive way. Figure 1.3 illustrates the proposed PDCA-inspired planning process for each IAM planning level by Alegre and Coelho (2012). The process at each planning level —strategic, tactical and operational from top to down—, consists of (i) set the objectives, assessment criteria, metrics and goals which come from the higher planning level, (ii) perform diagnosis of the system regarding to the selected objectives and metrics, (iii) produce plan consists of identification, evaluation, and alternative solutions, (iv) implementation of the plan; and (v) monitoring and reviewing the plan (Alegre and Coelho, 2012). It should be noted that the documentation and communication are essential during each level. The results are used as the input for the lower planning level.

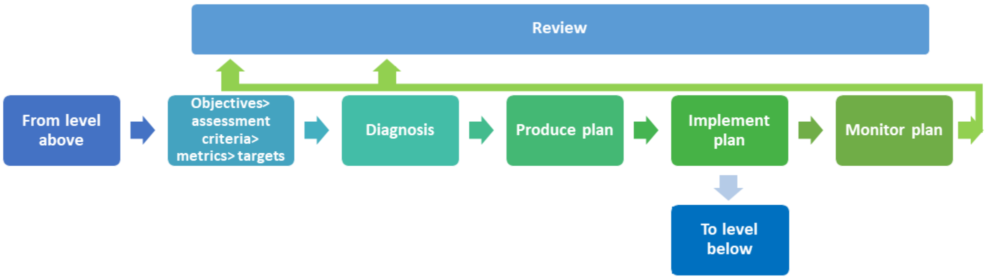

Figure 1.3 Illustration of the planning process at each planning and decision level

In IAM of urban water systems, planning levels are consecutively connected, while applying the PDCA cycle. The strategic level planning starts with defining objectives and targets driven by the water utility strategies. At the tactical level, intervention priorities, and solutions are defined at the medium-term period, which follows by actions in the short term in the operational level. The final goal is to balance the performance, cost, and risk of the system assets in a multidisciplinary structure. This is the framework of our research and is further explained in chapter 2.

1.3 Sewer networks

There are different types of sewer systems for conveying wastewater and stormwater in urban areas, i.e., combined and separate networks. Most European and industrialized cities rely on combined sewer systems (CSS), the common way of draining wastewater and stormwater to WWTP. CSS representing a high asset value, while some old components of these systems—built over 100 years ago—are still in use (Sægrov, 2013). Replacement cost for all CSS in Europe was estimated up to total one trillion Euros, which is not cost-effective and affordable under the current and forecasted economic capabilities of European cities (Sægrov, 2013). Hydraulic overloading of the CSS in extreme rain events can trigger to flooding of urban areas. Flooding events have become more frequent in urban areas in the last decades, which can cause health, social and environmental problems. In addition, I/I of extraneous water in sewer systems can increase operational time of combined sewer overflows (CSO). Specific health and environmental problems are associated with CSO, due to the discharge of contaminated and untreated wastewater to water recipients. Moreover, transportation, pumping, and treatment of stormwater—mixed with wastewater—are not efficient from energy and economic point of views.

Separate sewers have been introduced as a cost-effective solution to convey wastewater and stormwater separately, and disconnect impervious areas from combined sewers for reducing CSO emissions and hydraulic overloading of sewer systems (Langeveld *et al.*, 2012). The major limitation of separate sewer systems is the occurrence of illicit and faulty cross-connections between stormwater outlets and wastewater systems (Hoes *et al.*, 2009; Schilperoort *et al.*, 2013), which results in unwanted water inflow. Unwanted water inflow has negative impacts on the sewer systems performance, and its efficient reduction and removal is very important.

Sewer systems in most industrialized cities are deteriorated due to age. Moreover, as a result of insufficient maintenance, and inappropriate investment and rehabilitation strategies, many sewer systems across Europe are not watertight and suffer from significant infiltration and exfiltration. Bad construction quality of the sewer networks—due to the poor quality of pipe material, bad laying conditions, omission or underestimation of geotechnical effects and road traffic conditions— population growth, climate change, and new standards and requirements are some other reasons that sewer networks are not completely satisfactory.

Significant investment and resources are needed to construct, renew, rehabilitate and upgrade urban sewer systems (B. Ellis *et al.*, 2005). Sewer network renovation is costly, difficult, and energy demanding due to digging up the soil and installing new pipelines. However, rehabilitation of existing pipelines with renewal strategies, such as cured-in-place pipe (CIPP) technology, is more practical, cost-effective and environmentally friendly. In small-scale rehabilitation plans, point-repair can be a good alternative (Sægrov, 2014). Moreover, the majority of GHG emissions happens during fabrication and installation of pipelines, and therefore it is necessary to keep these underground assets by sufficient maintenance and rehabilitation plans.

1.4 Infiltration and inflow in the sewer network

Infiltration and inflow (I/I) of unwanted water are from extraneous sources and illicit connections. Extraneous water is defined as unwanted water I/I in separate sanitary networks from stormwater, groundwater, drainage water, or leakages from drinking water networks through defective pipes, pipe joints, or manhole walls (Hoes *et al.*, 2009). Faulty and illicit connections are intended or unintended sewer cross-connections between stormwater and wastewater separate pipelines, which result in discharging contaminated water in storm sewers, and unpolluted water in foul sewers (Hoes *et al.*, 2009). Unwanted water can enter the sewer networks from defective parts in both private and public properties. Figure 1.4 demonstrates one of the I/I sources in separate sewers from a combined manhole for both stormwater and wastewater. Faulty cross-connected foundation drains and downspouts, leaky sewer pipes, uncapped cleanouts, and root intrusions are examples of I/I sources in private properties, which allow unwanted water, stormwater and groundwater enter the sewer networks. In public premises, I/I sources can be wrong street drain cross-connections, cracked manholes or pipes, leaky manhole covers, leaky pipe connection, and manhole cross-connections.

Figure 1.4 Combined manhole can be a source of unwanted water I/I in separate sewers.

Climate change, extreme events, and seasonal groundwater fluctuations affect I/I level in the sewer network. Groundwater level is a dominant factor affecting the infiltration and exfiltration into the sewer system. When the groundwater table is higher than the sewer network level, the sewer infrastructure defects, *i.e.*, cracks and root intrusions, behave as infiltration sources. On the other hand, in low groundwater tables, sewer defects act as exfiltration points, which allow the leakages of the wastewater resulting in the contamination of the surrounding areas as well as groundwater. During wet seasons with rain and snowmelt, the soil moisture increases and the rain-induced infiltration seeps into the sewer network through defective parts.

Moreover, significant leakages from drinking water pipes increase the groundwater table and subsequently, infiltration in leaky sewers can occur through joints, cracks, and holes. Misconnected downspouts and foundation drains in wastewater networks due to poor plumbing have a high contribution in unwanted water inflow into sewer systems. Besides, climate change and extreme events increase the risk of flooding, which amplifies the probability of overloading separate wastewater networks.

Detection and efficient removal of I/I in sewer systems have several advantages:

I. Restrict hydraulic overload in sewer pipelines, which leads to less flooding in residential areas or sanitary sewer overflows (SSO).

II. Reduce CSO operation time and contamination of surface water bodies.

III. Decrease pollutant discharge from illicit connections in storm sewers and water recipients.

IV. Lessen the risk of public health hazards and environmental contamination issues.

V. Decrease entry of sediments, which leads to lower maintenance requirements.

VI. Reduce pumping costs and energy consumption for conveying the unwanted water to WWTP.

VII. Remove unwanted water feeding of WWTP and lessen energy and chemical usage for wastewater treatment.

VIII. Increase the efficiency of the wastewater treatment process and resource recovery due to less diluted wastewater.

IX. Decrease the level of GHG emission due to less energy consumption in both pumping station and WWTP.

Efficient curbing and reduction of I/I in separate sewers require comprehensive and detailed understanding about the location and magnitude of any unwanted water ingress and illicit connection (Schilperoort *et al.*, 2013). Approximately, in separate sanitary sewers ~50% of the wastewater, which is delivered to WWTP, is I/I from extraneous water (Peters *et al.*, 2002; Langeveld *et al.*, 2012), which can even exceed the wastewater volume in deteriorated networks (Kracht and Gujer, 2006; Ellis and Bertrand-Krajewski, 2010).

I/I play a critical role in sustainable wastewater management. Achieving enhanced knowledge about the location and magnitude of unwanted water in sewer networks during wet and dry weather conditions enables the possibility to define the status of the sewer network from I/I feature and prioritize problematic parts of the network. Furthermore, the effect of I/I on the sewer system efficiency can be improved by strategic maintenance, rehabilitation, and renewal planning in the long term.

The undesirable outcomes of I/I can be tackled by a combination of I/I measurement methods along with the sewer network rehabilitation and improvement. Investigating the household connections and disconnecting the illicit connections may reduce I/I drastically. Local stormwater management affects the I/I level by reducing stormwater inflow to sewer networks and treatment facilities. Moreover, the leakage reduction in deteriorated water networks may affect I/I level in the sewer network. Smart technologies and solutions for water management such as digitalization and internet of things (IOT) will provide better monitoring and faster diagnosis of the problems in urban water and wastewater infrastructure systems. For instance, warning systems connecting to ubiquitous sensor network is a fast and effective way to detect I/I sources.

1.5 Infiltration and inflow modeling

I/I detection and measurement impose high expenses to municipalities. Many sewer pipelines are under the state of deterioration and suffer from I/I problems due to insufficient investments on I/I projects. Therefore, simulating the infiltration and inflow in the sewer networks can be a good measure to give a holistic view about the status of I/I in the network. Mathematical modeling can be used for simulating the wastewater performance from I/I point of view. Geographic information system (GIS) can be applied in combination with hydrological models like stormwater management model (SWMM) to dynamically simulate rainfall-runoff-subsurface routing and analyze infiltration and inflow in the sewer network. To simulate I/I with this method in dry and wet situations, comprehensive and detailed data about characteristics of the catchment and sewer network are needed, e.g., morphology, soil profile, land use, sewer geometry, groundwater level, air temperature, precipitation, and wastewater flow measurement. The simulation results can be used for pinopinting the problematic parts of the network in addition to proofing the presence of unwanted water in the sewer system and convincing the decision-makers in water utilities to implement some preventive measures for I/I management in the sewer networks.

1.6 Aims, objectives and scope

This study was conducted in the context of sewer IAM, with a focus on assessment of unwanted water I/I in separate sewer networks. The work presented in the thesis have aimed at achieving a deeper understanding and improving the efficiency and functionality of the urban sewer systems by unwanted water assessment and reduction by strategic rehabilitation planning and preventive methods. The following research objectives were defined to clarify the research path:

Objective 1: Establish a procedure to analyze the current situation of sewer pipelines, predict future and decrease unwanted water I/I into the sewer system by long-term strategic maintenance and rehabilitation plans in the context of sustainability. This can be conducted by methodology of life cycle analysis (LCA) and material flow analysis (MFA).

Objective 2: Establish a methodology for I/I detection and measurement by different techniques. Classify the existing I/I assessment methods to quantitative and qualitative techniques and assess their advantages and limitations.

Objective 3: Detect different sources of unwanted water I/I in separate sewer systems—*e.g.*, stormwater inflow, rainfall-induced infiltration, snowmelt infiltration, groundwater infiltration, or illicit and faulty connections—and develop reliable and accurate results by applying different techniques.

Objective 4: Quantify precisely the level of unwanted water I/I from individual sources in the sanitary sewer system in dry and wet weather conditions.

The city of Trondheim was considered as the main case study in this Ph.D. and the research was accomplished mainly in collaboration with Trondheim municipality. Field measurements were performed in order to assess and detect I/I by different methods and achieve reliable results. I/I assessment studies and measurement campaigns were conducted in Lykkjbekken catchment in Trondheim city, which is located in a highly strategic position beside the main drinking water source of the city. Data analysis and sewer I/I simulation were performed for Lykkjbekken catchment to assess the I/I status of the network from different sources in dry and wet weather conditions.

2. RESEARCH APPROACH

The achievement of each objective of the current Ph.D. study relies on applying methods, which are relevant for the specific objective. Figure 2.1 demonstrates how different objectives, defined in section 1.6, are related to each other. Research objectives defined and organized in the typology of IAM planning levels (Figure 2.1).

Objective 1 discusses the research need for evaluating and improving the sewer system efficiency from I/I aspect by strategic maintenance, rehabilitation, and renewal planning in the long term. Restriction and management of I/I in urban sewer systems are required in the long term to obtain good performance, which are prerequisites for water infrastructural asset management and have significant environmental, social and economic impacts on future cities.

Objective 2 defines the requirement for establishing a methodology for I/I assessment by different techniques. It is important to investigate and classify different I/I assessment and detection techniques and find the most relevant and practical ones. The effectiveness of the available I/I detection methods and their advantages and limitations can be evaluated by critical literature review. Moreover, I/I assessment can be done by data analysis and I/I modeling as a cost-effective way to analyze the status of the network.

Objectives 3 and **4** refer to the identified needs to assess unwanted water I/I in sewer systems and distinguish between different sources, e.g., stormwater, groundwater, snowmelt or illicit and faulty connections. Achieving enhanced knowledge about the location and magnitude of unwanted water in sanitary sewers during wet and dry weather conditions enables the possibility for defining the status of the I/I in sewer networks, and prioritizes problematic parts of the network. Furthermore, it fills the knowledge gap of availability of reliable and accurate I/I assessment data to have more efficient maintenance and rehabilitation plans.

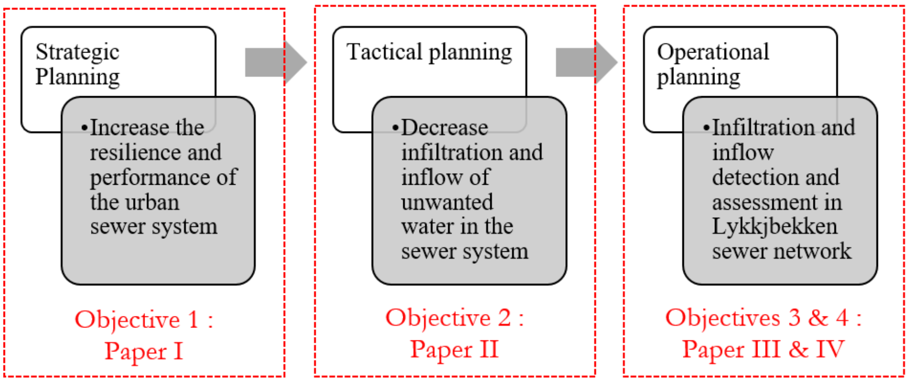

Figure 2.1 Research objectives defined and organized in the typology of sewer IAM planning levels.

The three planning levels of IAM are interconnected on a successive flow. In this study, the strategic level planning started with “increasing resilience and performance of the sewer system”. At the tactical level, intervention priorities, methods, and solutions were defined, i.e., reduction of infiltration and inflow in critical catchments by practical methods at the medium-term period. In the operational level, operation and maintenance solutions were carried out at the short-term period in order to increase the level of preparedness of the system against I/I of unwanted water in the long term.

2.1 Strategic planning (Paper I)

Sustainability assessment of the water and wastewater infrastructure in strategic long-term UWS plans leads to economic and environmental accomplishments for society. Nevertheless, this essential topic has not been considered deeply so far, and just a few studies have been conducted on social and environmental features of sustainability on UWS (Ludzia, Larsson and Aguayo, 2014). Moreover, the wastewater transport system has not been evaluated individualy in previous sustainability studies.

The sustainability analysis of Trondheim wastewater transport system using a dynamic metabolism model (DMM) is presented in **chapter 5** (Publication I). For this purpose, a methodology was introduced for comparing different pathways toward sustainable management of wastewater systems. In order to decrease the flaws and deficiencies and improve the current system, some possible actions inside the wastewater transport system were considered by defining different scenarios and interventions. Each of these scenarios involved a broad range of changes in economic and technological factors. The environmental, functional and economic aspects of sustainability were analyzed and evaluated. The historical data of 2000–2013 were used as the database of this study and predictions were made for the period 2014–2040.

2.2 Tactical planning (Paper II)

Identifying the problematic zones of the network and selection of methods and projects for correction and improvement of the sewer network are in the context of tactical planning in the integrated urban water IAM. I/I of extraneous water in separate sewer systems are serious concerns for sustainable urban water management and water infrastructural asset management, which have environmental, social and economic impacts on cities and sewer systems. Quantification and detection of unwanted water I/I in critical areas of the network should be considered for efficient curbing and reduction of I/I. **Chapter 6** presents a systematic method to assess unwanted water in the sewer systems as well as a general overview and classification of the available I/I detection and assessment techniques.

Also, assessing the status of the sewer network by mathematical modeling and I/I simulation is a cost-effective and efficient measure, which can be used in the tactical planning level to obtain a general view about the I/I status of the sewer network. Chapter 4 presents historical data analysis and I/I modelling for sewer network of Lykkjbekken catchment in Trondheim, Norway. This chapter demonstrates the applicability of I/I modeling in the assessment of the sewer network performance by a combination of GIS and SWMM models.

2.3 Operational planning (Paper III and IV)

Corresponding measures and operations to effectively restrict the amount of unwanted water I/I in the sewer network is in the context of operational planning. To reach this aim, comprehensive and accurate information about the location and magnitude of any excess water ingress and the illicit connections are needed. In this study, I/I detection and assessment were carried out in the separate wastewater network of a catchment in Trondheim. A combination of various I/I detection techniques was applied in tandem to decrease uncertainties and gain more reliable results, *i.e.*, fiber-optic distributed temperature sensing (DTS), closed-circuit television inspection (CCTV), and smoke testing. **Chapter 7** presents the details and results out of this study, which is in line with the fourth objective. This part provides practical insights for the rehabilitation and repair of sewer networks that suffer from the undesirable I/I of extraneous water.

After detection of I/I sources, the severity of them should be quantified to assess the sewer network status, prioritize the problematic sections, and implement rehabilitation measures. In this study, the DTS method was applied for the first time in Norway to monitor the sewer network from I/I aspect. The feasibility of DTS method was tested in both experimental and real-life rainfall-derived I/I to assess unwanted water I/I into the sewer network. Detailed description and results of this research are presented in paper IV in **chapter 8.** This part of the study fills the knowledge gap of availability of reliable and accurate I/I assessment data for having more efficient maintenance and rehabilitation plans.

3. MATERIALS AND METHODS

3.1 Infiltration and inflow assessment methodology

Unwanted water I/I in separate foul sewers affect the functionality of the sewer system negatively. Therefore, rehabilitation is required in the presence of I/I sources and illicit connections in the sewer systems. Achieving enhanced knowledge about extraneous water I/I sources in separate sewer systems enables detecting the problematic parts of the sewer networks and taking decisions for rehabilitation and renewal planning in the long term. The systematic process for the assessment of unwanted water in catchments with different properties is proposed in Fig 3.1.

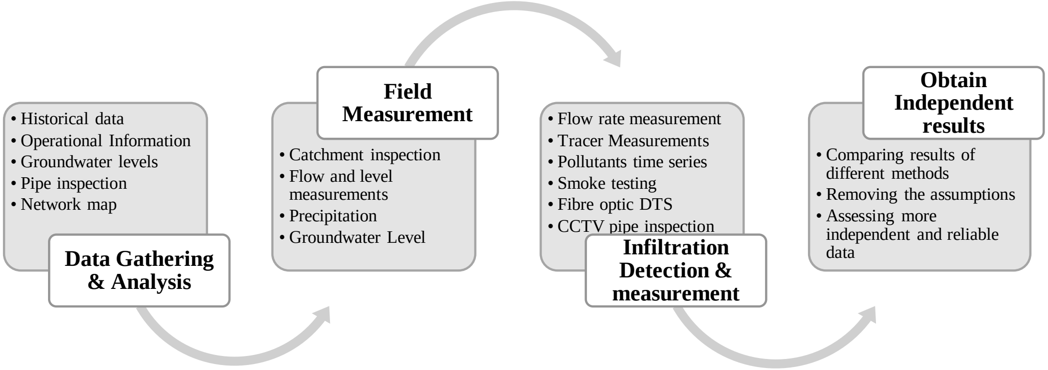

Figure 3.1 Systematic method for detecting unwanted water in the sewer system (Beheshti, Sægrov and Ugarelli, 2015).

As it is demonstrated in Fig 3.1 the process of I/I assessment in the sewer network is primarily dependent on the analysis of historical hydrological variables, operational information, pipe inspection, and network map. Afterward, it is very important to invest properly on the catchment inspection and hydrological variables measurement—i.e., flow data, precipitation, and groundwater—by right instrumentation and sufficient timing and resource. The next step, after proofing the presence of unwanted water in the sewer system is to assess and detect I/I sources by a combination of available techniques and finally gain accurate and reliable results by comparing the results from different methods.

3.2 Case study

Trondheim city with a population of 193 500 residents in 2018 is the third largest town in Norway by population (Statistics Norway, 2018). The main water source of Trondheim is Lake Jonsvatnet, which is a large lake in the eastern part of Trondheim city (Fig 3.2). Vikelvdalen (VIVA) is the water treatment plant of Trondheim and the surface water from Jonsvatnet is treated in this treatment plant, and then the drinking water is distributed to households and consumers with almost 100% coverage of the town. The urban water cycle path in Trondheim city is completed downstream by transporting the stormwater and wastewater from consumers such as households and industries through the wastewater transport system to two wastewater treatment plants of Høvringen (HØRA) and Ladehammeren (LARA) in the northern parts of Trondheim. In Trondheim, 50% of wastewater production is from households, which correlates to water consumption, and the rest is from industry (Slagstad and Brattebø, 2014).

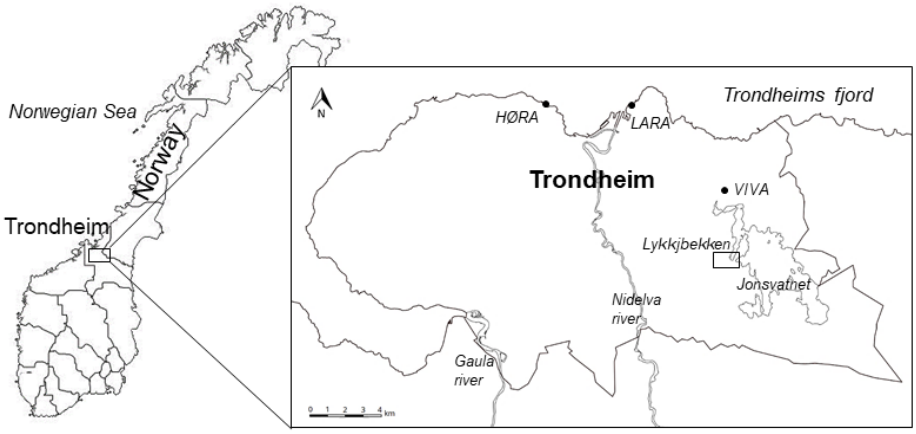

Figure 3.2 The case study area location (Beheshti and Sægrov, 2018c).

The sewer network of Trondheim with the average age of 30 years is about 1200 km in public and municipal sections, consists of combined and separate sewer pipelines for transporting wastewater and stormwater. In Trondheim 52% of the total length of the wastewater network is separate, and the rest is combined. The length of the separate stormwater network in Trondheim at the end of the year 2013 was 40% of the whole wastewater transport network. Moreover, there are currently 54 pumping stations in the wastewater transport system of Trondheim, of which three are for stormwater, 24 for foul sewer, and 27 for the combined system (Trondheim Municipality, 2013). WWTPs of Trondheim are encountering a high volume of unwanted water I/I in dry weather condition. The water balance of Trondheim sewer system in years 2009-2011 is illustrated in Figure 3.3. It should be mentioned that the reason for presenting data of 2013 is using them as the database of this study.

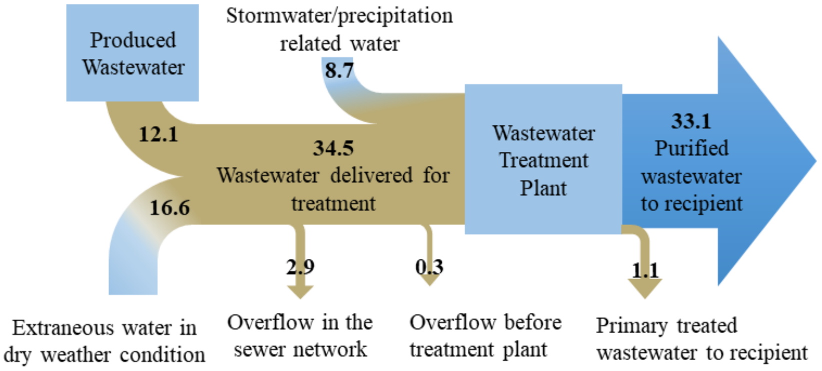

Figure 3.3 Trondheim water balance 2009–2011 (million m^3/year) (Trondheim Municipality, 2013).

According to Trondheim water balance 2009-2011, I/I of unwanted water in Trondheim sewer system was about 46% of the water, which was delivered to WWTPs for purification before releasing to Trondheim Fjord, and it is a priority in Trondheim municipality to manage this high amount of extraneous water.

3.3 Infiltration and inflow methods

There are several conventional and innovative methods available for I/I assessment and detection in the sewer systems, *e.g.*, flow-rate measurement, tracer methods, DTS technology. New measurement methods have been developed to assess I/I into sewer systems more accurate and with little environmental risk, *e.g.*, DTS and electro scan.

I/I methods can be divided into two groups of quantitative and qualitative. Quantitative methods are for assessment of magnitude, volume, and discharge of I/I, and qualitative methods detect the I/I sources. Each of these methods is based on some assumptions and has its limitations and advantages. A combination of these methods based on the selection criterias enables the sewer operators to compare different techniques and obtain reliable and accurate I/I data, which are essential for rehabilitation plans. A description of available I/I assessment methods is presented in Tables 3.1 and 3.2. These tables are updated version of Table 1 in chapter 6 with more techniques such as water level measurement and water temperature measurement in quantitative methods and electro-scan for both quantitative and qualitative methods.

Table 3.1 presents the quantitative methods and their advantages and limitations for I/I assessment and measurement in sewer networks, while Table 3.2 describes the qualitative methods for detection of problematic sections and I/I sources. Some of these methods, such as DTS and electro scan are classified in both qualitative and quantitative methods, and they can be applied for both detection and measurement of I/I sources.

Table 3.1 Quantitative methods in assessing I/I in sewer systems and their advantages and limitations.

Quantitative methods			
Method	**Method Description**	**Advantages**	**Limitations / Restrictions**
Flow rate measurement	A conventional infiltration assessment method in sewer systems, based on analyzing the water balance and diurnal flow rate in the dry weather conditions. In this method, the minimum night-time flow is addressing as I/I related flow, with the simple assumption of constant infiltration of groundwater in daily dry weather flows (DWF) without precipitation and snowmelt (Kracht *et al.* 2007; Zhang *et al.* 2018).	-Simple method. -Widely used method. -Give a rough overview of the sewer network form I/I aspect.	-Based on simplified assumptions such as having no flow during nighttime, omission of sewer network exfiltration from sewer networks. -An accurate flowmeter is needed. -Rather inaccurate results due to the sewer overflow in overloaded systems (Zhang *et al.*, 2018). -Unreliable method in shallow wastewater flows due to flowmeter instrumental errors.
Stable isotopes method	Stable isotopes δ^{18}O and δ^{2}H of water act as a direct natural tracer and provide a reliable tool to quantify the infiltration of unwanted water in sewer systems (Kracht, Gresch and Gujer, 2007). This method is based on different isotopic signatures of main water from a distant hydrological source and infiltrating water from groundwater and local precipitation, and the infiltration fraction calculation is based on the concentration of different isotopes as tracers (Ellis and Bertrand-Krajewski, 2010).	- Not adding radioactive or chemical contaminants into the environment (Koeniger *et al.*, 2009). -Cause less disturbance and environmental impact than tritium, salts or dye tracers (Koeniger *et al.*, 2009).	-Professional and expensive water isotope analyzer instrument is needed. -Drinking water and groundwater should have homogenous but distinct isotopic signatures (Ellis and Bertrand-Krajewski, 2010). -Components of drinking water and groundwater sources should interact (Ellis and Bertrand-Krajewski, 2010). -Inhomogeneity of the local groundwater or other origins of parasitic waters is crucial (Ellis and Bertrand-Krajewski, 2010). -Comprehensive hydrologic and hydrogeological investigation (Ellis and Bertrand-Krajewski, 2010). -Definable, accessible for sampling, and precise statistically describable ‘infiltration main source’ (Ellis and Bertrand-Krajewski, 2010).
Pollutant time series method	This method quantifies infiltration fraction by analyzing time-series of pollutant concentrations and wastewater flows. Automatically operating in-line devices are applied in this method to obtain time-series of pollutant concentrations with a high temporal resolution. Based on the time-series of the wastewater flows, a modeled time-series of pollutant concentration is calculated, and by fitting this model series to the measured data, a set of parameters, which define infiltration discharge can be estimated (Ellis and Bertrand-Krajewski, 2010).	-Flexible infiltration measurements (Ellis and Bertrand-Krajewski, 2010). -Wide practical applicability with considering natural storage and interflow phenomena (Ellis and Bertrand-Krajewski, 2010). -Simplifying measurements in rainy seasons, when infiltration increases due to elevated groundwater (Ellis and Bertrand-Krajewski, 2010).	-Preparation of the experimental team (Ellis and Bertrand-Krajewski, 2010). -Local boundary conditions at the investigation site (flow condition, accessibility) (Ellis and Bertrand-Krajewski, 2010). - Automatically-operating in-line devices for obtaining pollutant concentration (Ellis and Bertrand-Krajewski, 2010). - In the case of using submersible UV-VIS spectrometer, bias-, and drift-free operation is required (Ellis and Bertrand-Krajewski, 2010). - Time-consuming and expert-oriented measurement.

DTS method	Distributed temperature sensing (DTS) is a high-tech technique for detection and measurement of unwanted water I/I in sewer networks. The principle of this method is based on temperature measurement along a fiber-optic cable installed in the sewer network, which sends the data to a DTS monitoring unit at the end of the cable for data collection and process. Unwanted water I/I can be detected and assessed by analyzing the thermal behavior of the wastewater, so long as I/I water differs in temperature (Schilperoort, 2011; de Jong *et al.* 2015). I/I ratio can be driven by the help of laws of conservation of mass and energy and with knowing the temperature of unwanted water I/I and wastewater before and after mixing with it (Schilperoort, 2011).	-Unwanted water ratio can be measured exactly from individual sources (Beheshti and Sægrov, 2018b). - Takes place in the public part of the system and without the residents of the area involved (Schilperoort and Clemens, 2009). - Accurate I/I measurement results compared to more traditional research. - Large areas –up to several kilometers- can be examined and monitored simultaneously. -Use of single instrument in an easy and safe location.	-High initial cost of instrumentation and installation. - High probability of sewer blockage in low flows and therefore maintenance is needed (frequent flushing of the sewer in low flows). - Almost new technique with low experience in sewer systems. - Results are by nature not-easily-reproducible (Vosse *et al.*, 2013). - Precipitation and air temperature measurement is needed. - Expert-oriented method. - Time-consuming method.
Electro scan	Electro scan is a new technique in pipeline monitoring based on measuring the electrical resistance of the non-conductive pipe wall. In this method, an electro scan probe travels in a pipeline and scan the pipe wall by sending a low voltage high-frequency electric current. The principle behind this method is that a defect in the pipe that leaks water will also leak electrical current, and electricity flows through pipe defects, and the electrical resistance pinpoints water leakages (Harris & Dobson 2006; Tuccillo *et al.* 2011). In addition to identifying leak locations, Electro Scan indicates the size as well. The bigger the electrical flow, the bigger the defect, the bigger the leak potential. Therefore, this method is in both I/I classifications of quantification and qualification. Moreover, type of defect—joint, tap, or crack—is shown by the pattern of the electric current with different marks. This method is a straightforward technique, and the results can be used directly in a minute without expert interpretation. This method is applicable in non-conductive pipes and is not applicable in metallic pipelines.	- Accurate leak location and size. - Repeatable data results. - Defining the type of defect. - Reporting in Minutes, not days. - No data interpretation.	- Rather expensive method. - Cannot find leaks in metallic pipelines. - Cannot find I/I from all sources, e.g. misconnected roofs.

Water level measurement	Water level measurement is the method of monitoring the water level in different manholes in a catchment to detect the most problematic manholes and sewer pipes from I/I aspect. After finding the most problematic manhole, further inspections can be conducted for finding the I/I sources in the manhole or upstream sewer with relevant methods. This method consists of electrode sensors on different levels (*e.g.,* 25% and 50%) above the normal water surface. Electrode sensors record the numbers that water rises and touches them. The normal water level (consumption water) is the water level after 2 days with dry weather or in cold periods. A combination of the data from water level sensor with precipitation data can give the possibility to find most problematic places in wastewater networks. After finding the most frequent water rise manholes, measures that are more detailed can be implemented for finding the problematic sources upstream.	- Low operation cost in installation and data generation. - Provide general overview of each manhole from I/I aspect. - Occurs in public parts of the system without any need to entrance to private premises.	- Costly method in large catchments with many manholes. - Disable in defining the failure source and type. - Do not provide information about presence of small infiltration and inflows. - Results are by nature not-easily-reproducible. - The method is dependent on the presence of rainfall and high groundwater table. - Another measures are needed for monitoring the network. - Time-consuming method.
Water temperature measurement	This method was introduced by HOFER *et al.,* 2014 for monitoring CSO chambers. However, this method is applicable in sewer networks for monitoring water level fluctuations in manholes. The principle of this method is close to water level measurement, but in this method, thermometers monitor the water level fluctuations in each manhole. By putting thermometers in different levels in and above the normal wastewater level and monitoring thermal changes, the most problematic parts of the network from I/I point of view can be detected.	- Easy and practical method in detecting defective sewer parts. - Cost-effective I/I detection method. - Low operation cost in installation and data generation. - Provide the general overview of each manhole from I/I aspect. - Occurs in public parts of the system without any need to entrance to private premises.	- Precipitation measurement is needed simultaneously. - Disable in defining the failure source and type. - Another measures are needed for monitoring the network. - The method is dependent on the presence of rainfall and high groundwater table. - Results are by nature not-easily-reproducible. - Time-consuming method.

Table 3.2 Qualitative I/I detection methods in sewer systems and their advantages and limitations.

	Qualitative methods		
Method	**Method Description**	**Advantages**	**Limitations / Restrictions**
Smoke Testing	A practical engineering method to detect, identify and classify potential sources of I/I in a wastewater network, especially in detecting misconnected stormwater drains, downspouts and foundation outlets in separate foul sewers (Hoes *et al.* 2009). In this method, vegetable-based smoke, produced by a smoke generator, is injected into isolated parts of the sewer network, where I/I is suspected. The smoke, which tends to escape through openings and vents, pinpoints I/I sources in the separate sewer network (Hoes *et al.*, 2009).	- Inexpensive method. - Relatively easy method. - Environment-friendly method. - No need to restricted space entry.	- Not a very accurate method (Schwindamann, 2008). - Don't find all the infiltration points (Schwindamann, 2008). - Coordination with the local fire station and the connected households is needed. - A television camera is needed for monitoring the network (Schwindamann, 2008). - Smoke testing cannot pass through water seal traps.
Dye Testing	A tracing method for detecting the path of the flow with tracking dye and determining illicit connections existing in sewer systems. In this method, a non-toxic fluorescent dye is added to a water or wastewater source, which is suspected as an I/I source into the separate sewer system. For example, the dye is placed and flushed in plumbing fixtures, and an illicit connection will be detected in the case of finding the dye in a location other than a sewer system. In another way, a period of heavy rainfall is simulated by flooding the stormwater system with pumped water from a large tank. Dyes of different colors are applied to different places. The sewer system is monitored simultaneously by a television camera (CCTV), and infiltration of stormwater is confirmed by finding dye in the sewer system.	- Inexpensive method. - Relatively easy method. - Points to a specific source.	- Difficult to see dye in high-flow or turbid conditions. - Time-consuming in low flows. - Entering a facility is necessary. - Rather labor-intensive. - Require entrance onto private premises.
CCTV method	CCTV is a common method in sewer maintenance to inspect and assess the status of the wastewater network. In this method, a remote control, closed-circuit video camera is inserted into the sewer network through a manhole and moves inside the sewer network by a small robot, allowing the operator to inspect the network and detect problematic parts via real-time visual inspection.	- Provides live footage of the sewer network. - Effective method in inspection of active taps.	- Ineffective if inactive taps convey illicit discharges (Tuomari and Thompson, 2003). - Time-consuming to interpret results (Tuomari and Thompson, 2003). - Possibility of over- or under-estimating the status of the network due to operator errors and invisible defects in the pipeline. - Depending on the presence of rainfall or high groundwater table in I/I detection in foul sewers.

DTS Method	Distributed temperature sensing (DTS) is a high-tech monitoring technique for detecting I/I sources from illicit connections and extraneous water in sewer networks (Pazhepurackel 2009; Schilperoort & Clemens 2009). This method is based on continuous temperature measurement along the fiber-optic cable in the wastewater network, up to several kilometers. Potential I/I sources can be located precisely by monitoring and analyzing the thermal behavior of sewage, so long as I/I water differs in temperature (Schilperoort, 2011; de Jong *et al.* 2015).	- Source of unwanted water localized exactly (Schilperoort and Clemens, 2009; Langeveld *et al.*, 2012). - Takes place in the public part of the system and without the residents of the area involved (Schilperoort and Clemens, 2009). - Safer results compared to more traditional research (Schilperoort and Clemens, 2009; Langeveld *et al.*, 2012). - Large areas –up to several kilometers- can be examined and monitored simultaneously. - Use of single instrument in an easy and safe location.	- High initial cost of instrumentation and installation. - Expert-oriented method in non-automated process (Vosse *et al.*, 2013). - High probability of sewer blockage in low flows and therefore maintenance is needed (frequent flushing of the sewer in low flows). - Results are by nature not-easily-reproducible (Vosse *et al.*, 2013). - Almost new technique with low experience in sewer systems. - Time-consuming method. - Rather expensive method.
Electro scan	A new technique in sewer monitoring based on measuring the electrical resistance of the pipe wall. In this method an electro scan probe travels in a pipeline and scan the pipe wall by sending a low voltage high-frequency electric current. The principle behind this method is that a defect in the pipe that leaks water will also leak electrical current, and electricity flows through the defects and the electrical resistance indicates water leakages (Harris & Dobson 2006; Tuccillo *et al.* 2011). In addition to identifying leak locations, Electro Scan indicates the size, too. The bigger the electrical flow, the bigger the defect, the bigger the leak potential. Moreover, type of defect – joint, tap, or crack– is shown by the pattern of the electric current by different marks.	- Accurate leak location and size. - Repeatable data results. - Defining the type of defect. - Reporting in Minutes, not days. - No data interpretation.	- Cannot find leaks in metallic pipelines.

3.4. Measurement campaign

Lykkjbekken catchment is located on the western part of Jonsvatnet lake, the main water source of Trondheim city, and therefore is an important strategic location (Figure 3.4). The catchment is a rural region, and the studied sewer section covers an area of around 10 km^2 with around 200 inhabitants. The wastewater from households conveys through separate sanitary sewers to the Lykkjbekken pumping station and then to the LARA wastewater treatment plant. The pumping station faces the water level rise in wet weather conditions, which increases the risk of overloading the sewer network and pumping station, and sanitary sewer overflow near the drinking water source.

The wastewater system of the catchment consists of a pumping station and small PVC pipelines (160 mm internal diameter), which was installed in 1996. However, even after less than two decades of operation, the wastewater network of this catchment was prone to high amount of extraneous water I/I from unknown sources, which were not detected in CCTV inspection.

A rain gauge and a flow meter were installed in the catchment to monitor and evaluate the status of the Lykkjbekken sewer network on the wet and dry weather conditions (Figure 3.5). A tipping bucket rain gauge with the standard resolution of 0.2 mm was installed in the catchment to record the precipitation during the monitoring campaign, together with an ultrasonic Doppler flowmeter in the sewer network.

Lykkjbekken pumping station provided another database for wastewater flow measurement of the whole catchment (Fig 3.6). Groundwater table was monitored simultaneously in the closest available groundwater well located in the southern part of the lake Jonsvatnet. The location of the groundwater well was outside of the Lykkjbekken catchment but because of having the same catchment characteristics—i.e., land use, soil type, bedrock, and morphology—the data was used to monitor the behavior of the wastewater flow from groundwater infiltration in Lykkjbekken catchment. Moreover, the lake Jonsvantnet surface level was applied as a dominant variable in verification of the groundwater data fluctuations in Lykkjbekken catchment and investigation of its impacts on the wastewater flow.

Figure 3.4 Aerial photo (left) (Wikipedia, 2018), and a closer capture (right) of Jonsvatnet lake.

Figure 3.5 Flow meter (left) and rain gauge (right) in Lykkjbekken catchment.

Figure 3.6 Groundwater well (left) and pumping station (right) in Lykkjbekken catchment.

3.5 Infiltration and inflow assessment in Lykkjbekken

In separate foul sewer network of Lykkjbekken catchment, a combination of DTS, smoke testing and CCTV was applied to qualify and quantify I/I of unwanted water.

3.5.1 Distributed Temperature Sensing (DTS)

The DTS is a new technology in monitoring sewer networks and detecting I/I sources over the past decade. The principle of this method is based on monitoring the wastewater temperature along the fiber-optic cable installed in the sewer pipeline. The DTS monitoring device—contains a computer, an optoelectronic device and a laser instrument— which is located at the end of the fiber-optic cable sends laser pulses, receives and collects them. Afterwards, the collected information can be interpreted into readable temperature data. By analyzing the thermal behavior of the sewer network, the locations of I/I sources can be detected, as long as I/I water differs in temperature (Schilperoort, 2011; de Jong *et al*. 2015). Moreover, this method is applicable in measuring the ratio of unwanted water entering to the sewer network and assessing the severity of I/I sources.

This method in this study was applied for the first time in Norway to detect and assess unwanted water I/I in the sewer network. Besides the advantageous and limitations of this method, the DTS installation is quite expert demanding. Figure 3.7 shows the installation of the DTS monitoring campaign in Lykkjbekken catchment in August 2015. More details about the DTS method in addition to results out of its monitoring campaign are presented in chapters 7 and 8.

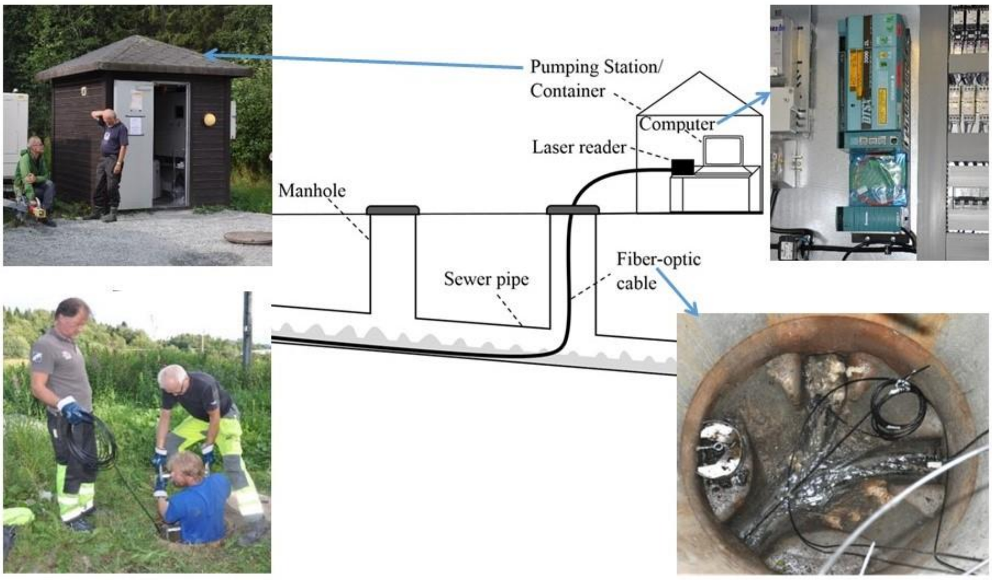

Figure 3.7 Schematic outline of the DTS method in a sewer network (Beheshti & Sægrov 2018a), with pictures of different stages of DTS installation in Lykkjbekken catchment in August 2015.

3.5.2 Smoke testing

Smoke testing is an engineering surveying method for I/I detection in sewer networks. This method is a practical method for finding the illicit connections in foul sewers, especially misconnections from stormwater outlets, *e.g.*, downspouts and gutters. In this method, a vegetable-based smoke, produced by a smoke generator, is injected into isolated parts of the sewer network, where I/I is suspected. The smoke, which tends to escape through openings and vents, pinpoints I/I sources in the separate sewer network (Hoes *et al.*, 2009). However, this method is not working in the presence of water seal traps in the misconnected drainpipes. These traps are curved pipes (bends) designed to let the wastewater flow and block the passages of sewer gasses by the retained water to go back into the building. Figure 3.8 demonstrates the application of this method in finding misconnected roof downspouts in the separate sewer network of Lykkjbekken catchments. These spots were detected by DTS monitoring, and smoke testing was used to detect, identify and classify the potential I/I sources.

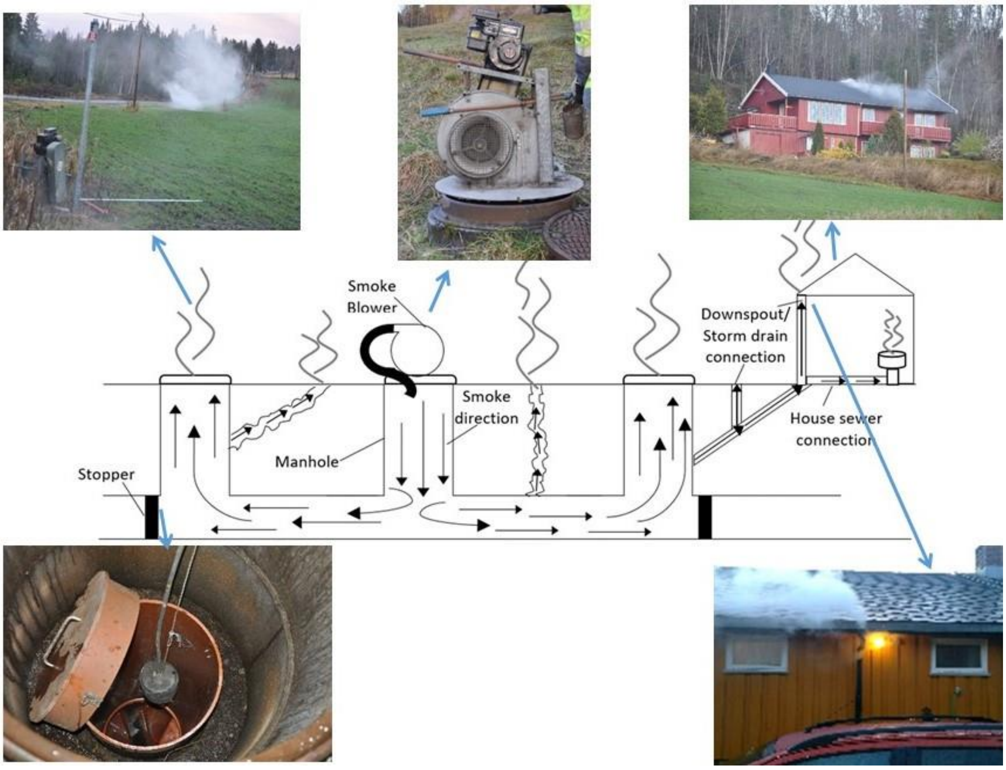

Figure 3.8 Smoke testing process for finding potential sources of infiltration and inflow into a foul sewer system (Beheshti et al. 2015); with photographs of smoke testing in Lykkjbekken catchment in November 2015.

3.5.3 CCTV

Closed-circuit television inspection (CCTV) is one of the most common ways of inspecting sewer pipelines. The operator evaluates the status of the sewer network by looking into a live footage while the CCTV camera moves into the pipeline on a remote-control tractor. In Lykkjbekken catchment, CCTV was used for inspecting the sewer network before and during DTS project. Figure 3.9 demonstrates some CCTV inspection pictures in the Lykkjbekken separate foul sewer before DTS installation. In this case the CCTV operators did not report any major problem in the network before fiber-optic DTS installation. However, as it is shown in the left picture in the Figure 3.9, high amount of clean-water inflows from a house connection, which can be corresponded to I/I from stormwater or groundwater. The CCTV inspection was conducted on 13 April 2015, which was a rainy day. Therefore, this water could be a rainfall-derived inflow from a misconnected storm drain, which was confirmed later by DTS monitoring and smoke testing in the location x=3964 m (see chapter 7). By the time of the inspection, the operator underestimated the sewer failure in this location with considering it as an inflow from the house connection.

Figure 3.9 CCTV inspection photos in PVC sewer network of Lykkjbekken catchment in April (left) and May (right) 2015

In CCTV inspection, the status of the sewer network can be defined by grading each pipeline failure from 1 to 4. After evaluating the failure score for each section of the network between two manholes, the condition of the network can be classified in a 5-level scale, which S1 is very good and S5 is the useless condition. The condition classes of 1 and 2 do not require any improvements, while 3 needs more assessments for improvement, and pipelines in condition levels of 4 and 5 should be prioritized for rapid improvement measures. The CCTV inspections of Lykkjbekken network classified that the network was in condition class 1 and 2. Figure 3.9 demonstrates CCTV inspection pictures of two different pipe section in Lykkjbekken network with condition class 2.

4. DATA ANALYSIS AND I/I MODELING

4.1 Historical data analysis

Analyzing the available historical data, *e.g.* hydrological, geological, hydrogeological, and flow, in the sewer network is the preliminary step to evaluate the I/I in sewer networks and obtaining information about the presence of any extraneous water ingress in the sewer system.

By analyzing the geology and morphology of the catchment soil in GIS, *i.e.* type, depth, and size of the soil material, the probability of infiltration from groundwater can be estimated. The coarser the soil material is, the higher is the permeability, and the easier is the groundwater movement and infiltration. In Lykkjbekken catchment, there are large portions of areas with thick oceanic deposits, glacial drifts, peat and marsh, and smaller areas with glacial stream deposits and weather corrosion materials. As it is demonstrated in Figure 4.1, soil classification analysis in Arc GIS software around the Lake Jonsvatnet and Lykkjbekken catchment demonstrates the variety of groundwater infiltration capacity in different parts of the sewer network.

To further investigate the sewer system I/I of the Lykkjbekken catchment, the available historical data of hydrological and hydrogeological cycle was analyzed. Therefore, recorded wastewater flow, groundwater table, lake water level, and precipitation were evaluated simultaneously. Figure 4.2 illustrates the sewer network in Lykkjbekken catchment in addition to the location of the flowmeter, pumping station, and rain gauge. The location of the nearest groundwater well to the Lykkjbekken catchment is indicated in Figure 4.1, which is in the southeast of the study area. Due to similar geology and soil classification in major parts of both catchments, it was assumed that the fluctuations of groundwater level and seasonal variations could follow the same pattern in both catchments. Figures 4.3 and 4.4 demonstrate the relationship between wastewater flow and other hydrological and hydrogeological variables in Lykkjbekken catchment in wet and dry weather conditions respectively.

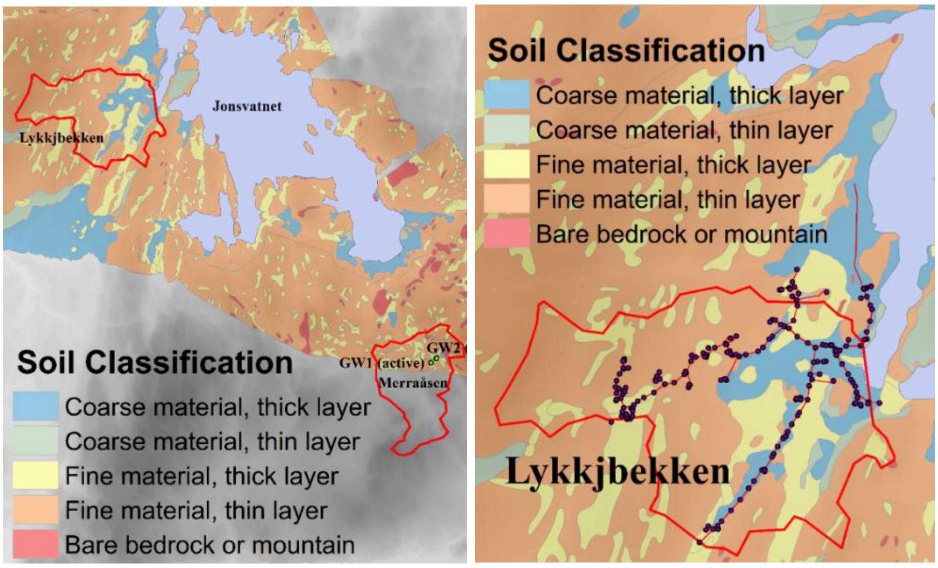

Figure 4.1 Soil classification analysis in Arc GIS around the Lake Jonsvatnet (left), and Lykkjbekken catchment (right) (data from Geological Survey of Norway).

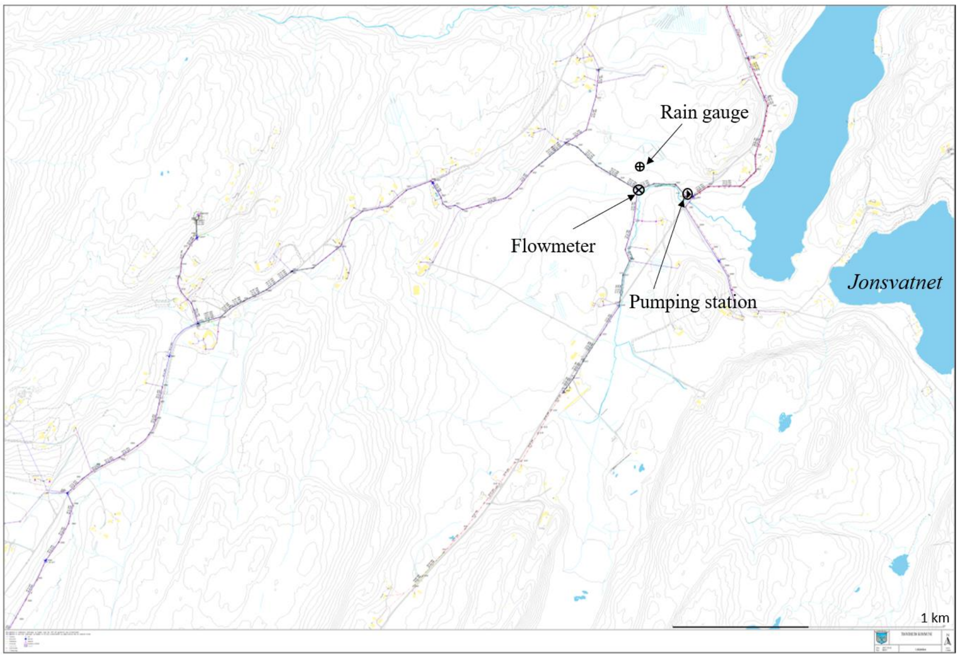

Figure 4.2 Wastewater network in Lykkjbekken catchment with location of rain gauge, flowmeter, and pumping station (Trondheim Municipality, 2013).

As it is demonstrated in Figure 4.3, Lykkjbekken wastewater flow (from both flowmeter and pumping station) follows the same trend with recorded precipitation and lake water level especially in wet weather conditions. Groundwater data with one day delay demonstrated better correlation with the precipitation and flow data. This can be due to the dominant type of the soil in southeast parts of the catchment with high impermeability and low infiltration capacity. However, lake water level fluctuations in wet conditions can be an indicator of groundwater fluctuations in the areas with coarse soil and high permeability.

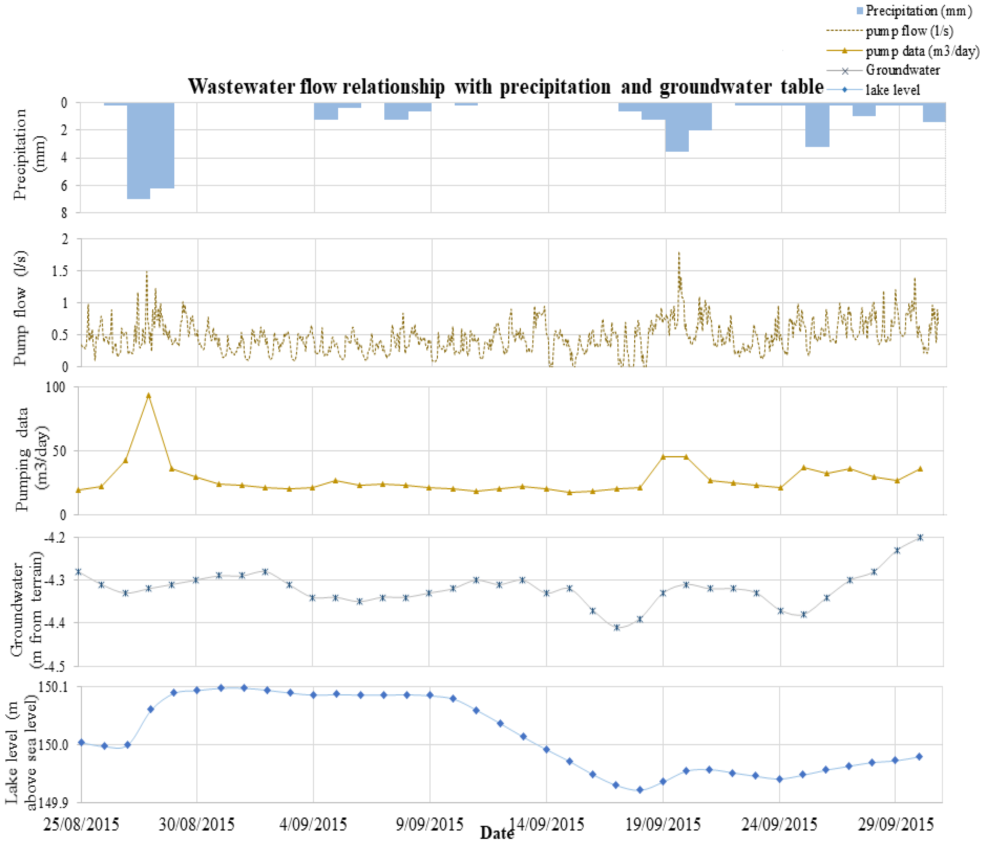

Figure 4.3 Wastewater flow relationship with precipitation and groundwater table in wet weather condition in Lykkjbekken catchment.

Figure 4.4 illustrates the relationship between the lake water level, groundwater and pumped wastewater flow in a dry weather condition without precipitation and snowmelt. The data analysis emphasizes the presence of I/I from unknown stormwater and groundwater sources to the sewer network in Lykkjbekken catchment and validates the results out of the soil classification results in Figure 4.1. The analysis of historical data in Lykkjbekken catchment highlights the need for detection and reduction of unwanted water by relevant and effective I/I detection and rehabilitation methods.

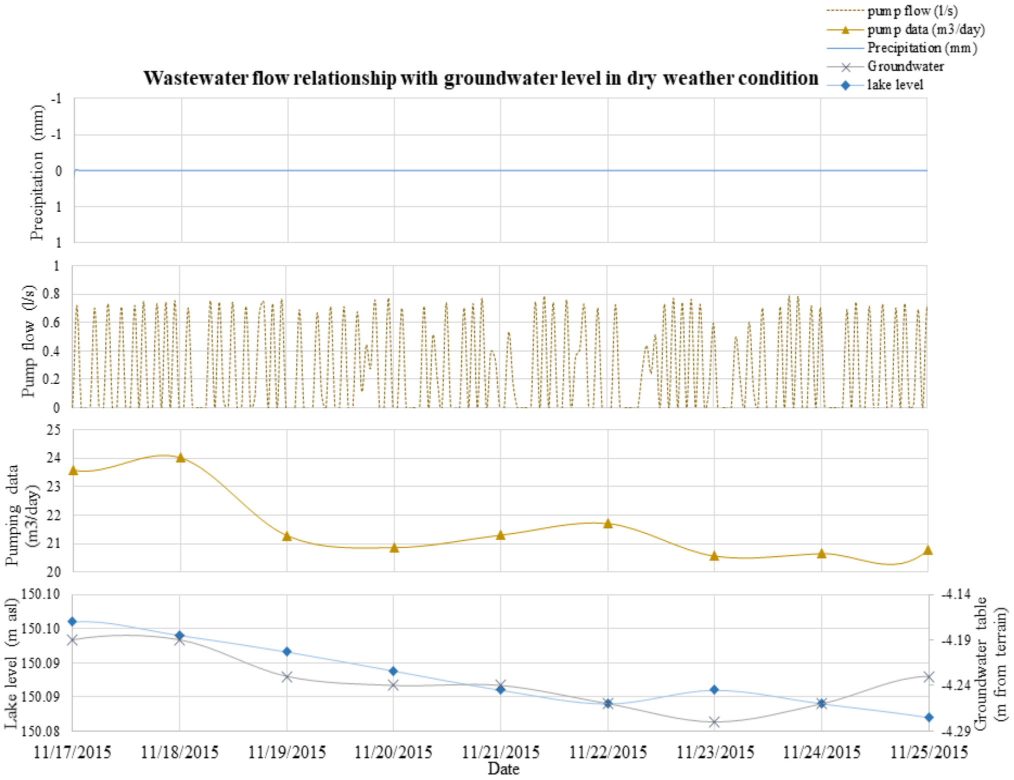

Figure 4.4 Wastewater flow relationship with the groundwater table in dry weather condition in Lykkjbekken catchment.

The groundwater data was applied from Sagelva, which is a neighbor catchment to Lykkjbekken. The size of the wetlands and areas with coarse soil material in Lykkjbekken is larger than the corresponding wetlands in Sagelva. Therefore, the response time of the groundwater in Lykkjbekken is faster than Sagelva. The correlation between the flow and groundwater data with a one-day delay can be used to see the groundwater impacts on the flow in the Lykkjbekken pumping station. Figures 4.5, 4.6 and 4.7 illustrate respectively the cross-correlation analysis between flow at Lykkjbekken pumping station with precipitation, and groundwater level in wet and dry weather conditions.

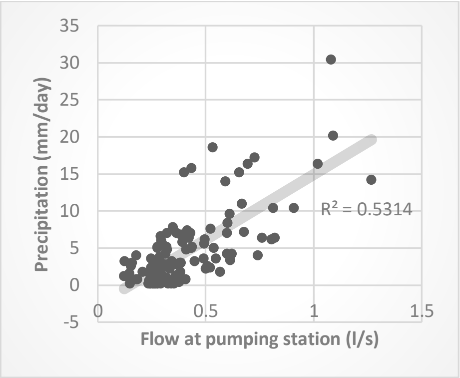

Figure 4.5 Cross-correlation analysis between flow at the pumping station and precipitation in Lykkjbekken catchment.

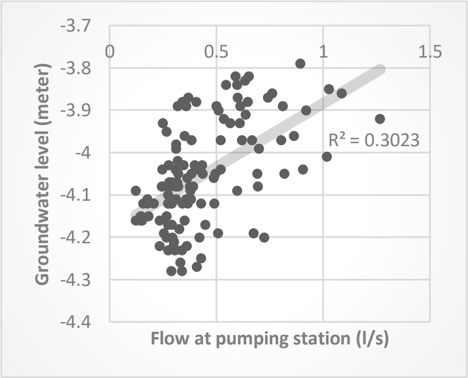

Figure 4.6 Cross-correlation analysis between flow at the pumping station and groundwater level in wet weather conditions in Lykkjbekken catchment.

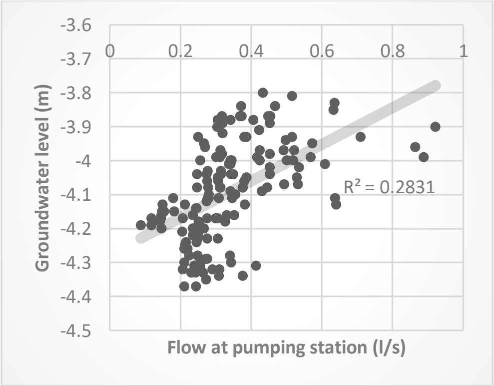

Figure 4.7 Cross-correlation analysis between flow at the pumping station and groundwater level in dry weather conditions in Lykkjbekken catchment.

The cross-correlation between precipitation and wastewater flow in Figure 4.5 shows the presence of extraneous water inflow in the sewer network in some wet periods as it is demonstrated in Figure 4.3. However, as it is demonstrated in Figures 4.6 and 4.7, the poor R^2 between groundwater level and wastewater flow in the pumping station in both dry and wet periods can be due to the soil type and high impermeability of the catchment. Therefore, the separate sewer network in Lykkjbekken is not significantly affected by infiltration from groundwater.

4.2 I/I modeling

After analyzing the historical data, sewer I/I can be simulated in Lykkjbekken catchment. Therefore, the GIS software can be applied in combination with the SWMM software to analyze I/I in the sewer network. The SWMM is a software developed by the US Environmental Protection Agency (EPA), which dynamically simulates rainfall-runoff-subsurface routing and analyzes various hydrological processes. This software is applicable for analysis, planning, and design applications of different hydrological processes such as rainfall-runoff, flooding, sewer overflow, and pollution control. In the current study, the SWMM modeling was applied in assessing I/I in the separate sanitary sewer of Lykkjbekken catchment during various weather conditions.

Trondheim municipality provided the data of Lykkjbekken catchment, the sewer network (*e.g.*, conduits, manholes, and their attribute data), and pumping station from Gemini VA database (a database for water and wastewater system in Norway). To build the model in SWMM, the data should be analyzed and processed in the GIS tool of the ArcMap software. Therefore, the digital elevation model (DEM) was downloaded from ”Geonorge.no”, and groundwater and geological data were obtained from the Geological Survey of Norway (NGU.no). The precipitation was measured in Lykkjbekken catchment, and temperature data was gained from the Norwegian meteorological institute. The I/I were modeled during dry and wet weather conditions and Lykkjbekken pumping data was used for model calibration and validation, see Figure 4.8.

In a study together with Birgitte Taugbøl Kragset (2018), the sewer infiltration simulation of Lykkjbekken catchment was conducted for three weather conditions; dry with low and high groundwater table, and wet weather condition. The model was calibrated against the measured flow at Lykkjbekken pumping station.

Calibration is the process of matching the bahaviour of the model with the observed data by changing the model parameters, which is essential for the performance of the model (Gupta, Sorooshian and Yapo, 1999). The I/I calibration was carried out for two periods of dry weather condition with infiltration unrelated to precipitation and wet weather condition with infiltration related to precipitation. For the dry weather condition, the model was calibrated by considering the estimated baseflow from the households. In simulation of rainfall derived I/I (RDII), precipitation time-series was considered as model input. In SWMM modelling, the RDII can be estimated by unit hydrographs with short-term, medium-term and long-term responses

(Rossman, 2015). Each unit hydrograph is defined by RTK parameters (Figure 4.9), where R is the ratio of precipitation volume that enters the sewer network, T is the time from the start of the rainfall to the peak of the hydrograph, and K is the ratio of recession time from the hydrograph peack to the end (Kragset, 2018).

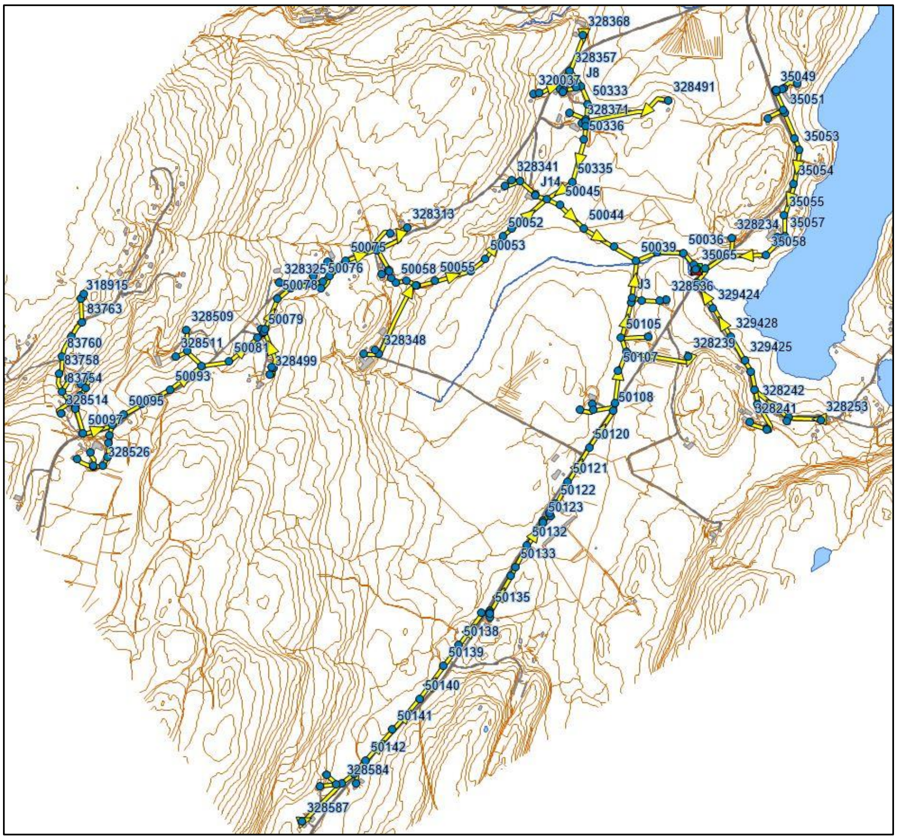

Figure 4.8 Sewer modeling of Lykkjbekken catchment in EPA-SWMM software (Kragset, 2018).

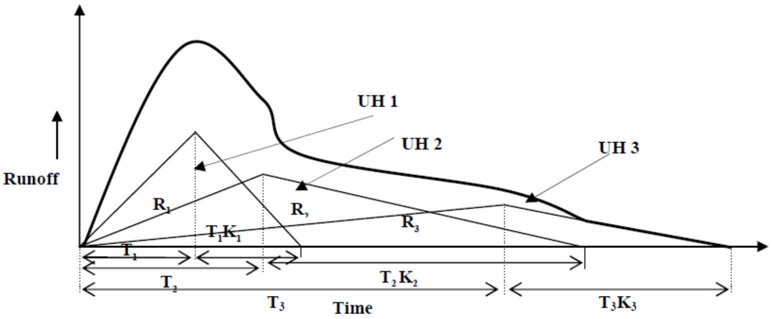

Figure 4.9 RTK parameters in unit-hydrographs (Muleta and Boulos, 2008).

To exclude the affect of direct I/I, the period between December 2014 and February 2015 with low snowmelting and groundwater table was chosen. Moreover, the days with rainfall and holidays were extracted from the time series to give a better and more reliable dry weather simulation. For simulation of dry weather with high groundwater table, the period between 27 April to 21 May 2015 was chosen. For simulating the RDII in wet weather condition, a period with low groundwater table and intense rainfall in summer was chosen. Therefore, the period of 27-28 August 2015 with low groundwater table and 46 mm precipitation during 14 hours was considered. Table 4.1 presents the calibration results for the three various weather conditions.

Table 4.1 Statistical analysis of the simulated flow and observed flow in Lykkjbekken pumping station.

	Dry weather with low groundwater table	**Dry weather with high groundwater table**	**Wet weather condition**
Correlation (R^2)	0.69	0.67	0.65
Nash-Sutcliffe efficiency (NSE)*	0.64	0.59	0.55
Relative error in flow volume**	7.36%	7.78%	28.5%

*NSE = 1 - (sum(($Q_{observation}$ - $Q_{simulation}$)^2) / sum((Q_{obs} - mean(Q_{obs}))^2)

** Relative error in volume of flow = ($V_{simulation}$-$V_{observation}$)*100 / $V_{observation}$

The results from simulation of the wastewater in dry weather condition with both low and high groundwater table demonstrated insignificant extraneous water I/I in the sewer network. The correspondance R^2 between the measured flow and simulated dry weather conditions with low and high groundwater tables were respectively 0.69 and 0.67, while NSE were 0.64 and 0.59. Moreover, the relative volume error of the total simulated flow from the measured flow is insignificant (~ 7%), see Table 4.1. Simulation of the wastewater in wet weather condition was more complicated and done by defining the best set of RTK parameters for unit hydrographs. The model simulated the flow with 0.65 R^2 and NSE of 0.55 (Figure 4.10). The results demonstrated that rainfall-derived I/I was around 68% of the total wastewater volume in the storm event on 27-28 August 2015 with 46 mm precipitation. The simulated graph is smoother than the flow due to the fluctuations of the measured flow in the pumping station.

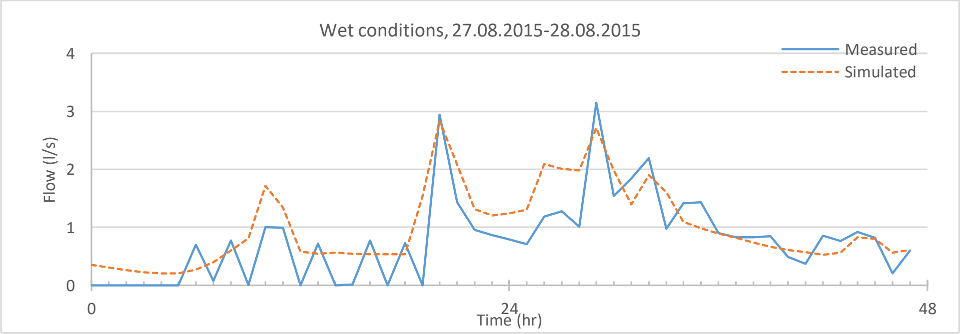

Figure 4.10 Simulated and measured flow during wet weather conditions (Kragset, 2018).

The results from the sewer and I/I modeling in SWMM software indicated the presence of rainfall-derived I/I in the sewer network, however, no significant groundwater infiltration was detected in both low and high ground water table. The reason for the same trend in pumping station flow and groundwater table in dry weather condition in Figure 4.4, can be due to previous rainfalls that gradually affected sewer flow by rainfall-induced infiltration. The low infiltration capacity of the large area in the Lykkjbekken catchment can be a good explanation for this behaviour of the system. The modeling of I/I in the sewer network of Lykkjbekken highlighted the need for restriction of rainfall-induced sources of extraneous water I/I in the sewer network by rehabilitation planning.

The model validation results follow the same trend as the flow data but were less satisfactory than the calibration. This can be due to fluctuations in the recorded pumping data, that was used as the observation data for calibration and validation, and cannot be modeled as the catchment continues flow. The accuracy of defining proper unit hydrograph parametrs is another source of uncertainty, which can cause failure in model validation. Moreover, uncertainties in accuracy of the model physical parameters, such as depth and height of the manhole nodes can be another source of error in validation.

5. STRATEGIC PLANNING (PUBLICATION I)

The following publication *Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway*, written by Maryam Beheshti and Sveinung Sægrov, was published in 2018 in Urban Water Journal, Volume 15, Issue 1, pages 1–8, DOI: https://doi.org/10.1080/1573062X.2017.1363253

Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway

Maryam Beheshti and Sveinung Sægrov

Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Abstract: Sewer networks represent high value in water infrastructure assets and it is important to develop and operate them by specified sustainable management. This paper presents the results of a sustainability analysis on the wastewater transport system of Trondheim, Norway, for future planning (2014–2040) from a metabolism-based performance analysis by the Dynamic Metabolism Model (DMM). The aim of this work is to demonstrate a methodology for comparing different pathways toward a sustainable management of wastewater systems. For this purpose, four intervention strategies ‘infiltration and inflow reduction’, ‘increasing rehabilitation rate’, ‘extension of system regarding population growth’, ‘energy management’ along with different combinations of them have been analysed. The results of this study may give some support to decision-makers in wastewater departments. In practice, to achieve strategic level planning of sustainable sewer asset management, it is vital to assess different aspects of sustainability and manage them in a comprehensive system.

Keywords: Sustainability, Urban Water Systems (UWS), sewer infrastructure asset management, Dynamic Metabolism Model (DMM)

Introduction

Urban water systems (UWS) are related to different aspects of sustainability such as social, economic, and environmental dimensions, which are ‘triple bottom line’ of the sustainability concept. Utilities usually have robust concepts of water quality, treatment efficiencies and cost-effectiveness; nevertheless, in recent years more attention has been given to broader sustainability aspects such as greenhouse gas emissions and life cycle environmental effects (Ashley *et al.*, 2008; Slagstad and Brattebø, 2014). Moreover, with regard to asset investments, the ‘triple bottom line’ approach of sustainability should be considered (Ashley *et al.*, 2008). The aim of this work is to demonstrate a methodology for comparing different pathways toward sustainable management of wastewater transport systems, which represent a high value in water infrastructure assets.

Urban water and wastewater infrastructure assets are undergoing aging and deterioration (Ana and Bauwens, 2010), due to lack of sufficient municipal investments in maintenance and rehabilitation (Rehan *et al.*, 2014). Functional efficiency and structural quality of sewer systems are the principal factors that ensure urban and industrial wastewater transport to treatment plants without infiltration and exfiltration (J. B. Ellis *et al.*, 2005). Management of infiltration and exfiltration in the urban sewer system is crucial in the long term to achieve good performance, which is a prerequisite for water infrastructural asset management and has significant environmental, social and economic impacts on cities (Beheshti, Sægrov and Ugarelli, 2015). Moreover, the sustainable management of the water infrastructure should be considered in strategic long-term planning of UWS, which leads to economic and environmental achievements for society. These infrastructures present a high asset value and future generations will inherit the consequences of today's investments decisions (Marlow *et al.*, 2013). Unfortunately, this important issue in general has not been considered seriously until now and there are only few studies which have been carried out on social and environmental aspects of sustainability on UWS (Ludzia, Larsson and Aguayo, 2014).

Greenhouse gases (GHG) are released continuously during the installation phase, operation and maintenance phase and rehabilitation phase. However, more than 80% of these emissions happen during fabrication of pipelines (Strutt *et al.*, 2008; Venkatesh, Hammervold and Brattebø, 2009). Therefore, to reduce the amount of GHG emissions it is wise to keep current pipelines in the network by proper maintenance and rehabilitation plans, which is the main outcome of an efficient sustainable infrastructure management. There are different methodologies available for estimating the environmental impacts of water and wastewater systems, such as Strategic Environmental Assessments (SEA), Cost-Benefit Analysis (CBA), Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Environmental or Ecological Risk Assessment (ERA) (Finnveden *et al.*, 2009; Chen, Ngo and Guo, 2012).

SEA is a tool for integrated assessment of environmental aspects at a strategic level (Lee and Walsh, 1992; Salhofer, Wassermann and Binner, 2007). This method is defined as the structured and holistic procedure of assessing the environmental consequences in the initial phase of policies, plans and programs to assure they are properly addressed and are in line with economic and social concerns of decision-making (Nilsson *et al.*, 2005; Salhofer, Wassermann and Binner, 2007; Garfi *et al.*, 2011). The CBA method evaluates an urban system quantitatively from integrated economic and environmental aspects (Salhofer, Wassermann and Binner, 2007; Villarroel Walker *et al.*, 2014), with consideration of internal costs and external environmental and social impacts (Chen, Ngo and Guo, 2012). In this method, the flux of material, resource and energy into the system can be estimated as monetary revenue and expenditure changes (Villarroel Walker *et al.*, 2014). MFA is based on understanding and quantitative analysis of the flows, transformation and stocks of materials, energy and resources in a system specified in scope and time (Brunner and Helmut, 2004; Garcia-Montiel *et al.*, 2014). In UWS, MFA deals with the inflow of materials and energy to the water and wastewater networks, i.e. due to addition of pipelines and the rehabilitation rate. MFA is an effective initial monitoring method in UWS and its outcomes are a leading consideration for evaluating a system (Brunner and Helmut, 2004; Chen, Ngo and Guo, 2012). LCA is applied for evaluating the life cycle environmental impacts of the flows into a system, and has proven to be feasible in sustainability assessment of UWS in the last 20 years (Loubet *et al.*, 2014). Furthermore, ERA is a method for assessing the adverse impacts of environmental pollutions arising from human activities with a known uncertainty level (Oost, Beyer and Vermeulen, 2003). This method mainly evaluates site-specific chemical hazards in UWS (Chen, Ngo and Guo, 2012).

UWS can be analysed from a sustainability point of view by metabolism-based models. The approach is to assess and analyse the flow, conversion and process of resources in the concept of material, money and energy into the UWS to accomplish the mandatory requirements of the system in terms of water supply and sanitary transport at the required quantity and quality stages (Venkatesh, Sægrov and Brattebø, 2014). WaterMet^2 (WM2) developed at Exeter in the UK (Behzadian *et al.*, 2014), and the Dynamic Metabolism Model (DMM) developed at the Norwegian University of Science and Technology (Venkatesh, Sægrov and Brattebø, 2014) are two metabolism-based models for sustainability modelling and analysis of UWS, which are developed on the basis of MFA and LCA (Venkatesh *et al.*, 2017). These two mass-balanced-based models have been tested for analysis of energy consumption, emissions, costs and environmental impact of UWS in Oslo as a case study (Venkatesh *et al.*, 2017). UWS metabolism like other urban metabolic systems, is in interaction with other domains such as social, economic and environmental criteria (Behzadian and Kapelan, 2015), and these metabolism-based models give the opportunity to quantitatively investigate and document metabolism of UWS as a basis for sustainability analysis under different strategic scenarios and interventions for long-term planning.

In the current study, a sustainability analysis by DMM has been conducted on the wastewater transport system of Trondheim. The system consists of combined and separate sewer pipelines for transporting foul sewer and stormwater in addition to pumping stations. Other components of the wastewater system such as wastewater treatment plants (WWTP) are excluded from this study. This will require detailed analysis of the wastewater system hydraulic performance and respective detailed information of components in WWTP. They are therefore the subject of separate studies.

Methodology

The wastewater transport system has not been considered alone in previous sustainability studies. In this study, the metabolism of the wastewater transport system of the city of Trondheim in Norway has been investigated and assessed by the DMM. For this purpose, different scenarios and interventions have been defined as possible action requirements for improving the current system. Each of these scenarios involves a broad range of changes in economic and technological factors, and the environmental, functional and economic aspects of sustainability have been analysed and evaluated. The historical data of 2000–2013 have been used as the database of this study and predictions have been made for the period 2014–2040.

DMM

DMM is a mass-balance model, which was developed by Venkatesh et al. (2014) for UWS, within the European research project TRUST (TRansitions to the Urban Water Services of Tomorrow). The keyword 'metabolism' refers to inflow of materials and outflow of them in the concept of emissions and by-products from a system (Venkatesh, Sægrov and Brattebø, 2014). The aim of the development was to implement a complete systematic approach to the study of metabolism and environmental effects of resource flows in UWS, i.e. water flows, material and energy consumption, resource recovery, waste and emission flow (Appendix 8).

This model offers an instrument for the investigation of possible future services, strategies and interventions in UWS (Venkatesh, Sægrov and Brattebø, 2014). Moreover, by using the DMM the UWS can be quantitatively analysed with regard to energy consumption, emissions, environmental impacts, economic and physical properties by annually-based performance indicators for the whole of the system and its subsystems (such as water distribution and wastewater transport) under different interventions toward future improvements (Venkatesh *et al.*, 2017).

The detailed concept of DMM has been presented by Venkatesh *et al.* (2014) for UWS. However, some important characteristics of this model are flexibility, simplicity and modifiability; nevertheless, it has its own shortcomings. The model has some simplicities that make it notable, such as a user-friendly interface in an MS-Excel-based model. Simplicity of this model can be both an advantage and a limitation. However, the main limitation of the DMM model is that it is a concentrated and lumped model in this version, which is based on general data of the system. The focus of this model is on investigating the impacts of long-term intervention strategies on the comprehensive view of the UWS for supporting decision-making (Venkatesh *et al.*, 2017). Therefore, DMM is a suitable tool for the initial analysis phase of strategic planning with requiring fewer data, while distributed models like WM2 can be used for more in-depth analysis requiring more detailed data (Venkatesh *et al.*, 2017). Moreover, this method has some limitations regarding uncertainty. There is always uncertainty when making assumptions for material flow rate and introducing new products and materials in the system, and it is very common that inflow, outflow and variations in materials and resources do not match (Brunner and Helmut, 2004).

In Trondheim, it is planned to add specified kilometer pipelines to the system every year and rehabilitate existing pipelines by a cured-in-place-pipe (CIPP) approach at a specific rate per year (Appendix 3 & 4). In this study, the flow of material and resources for the wastewater transport network has been considered and applied as inputs to the DMM model (Appendix 1 & 2). For calculation of pipeline material flow, some of the assumptions for transforming the pipeline length data to weights of the material are borrowed from the study that Venkatesh *et al.* (2009) has been carried out on MFA-LCA analysis of wastewater pipeline networks in Oslo, Norway. Furthermore, installation, rehabilitation, and maintenance and operation of wastewater pipelines are energy demanding and this aspect has been considered in this study.

Case system description

The city of Trondheim is the third largest in Norway with a population of 179,385 inhabitants in 2013 (Appendix 5). Prognosis from the Statistics Center Norway shows that Trondheim city will grow by around 30,000 new residents until 2025, and by 2040 there will be around a 30% increase in population compared with the year 2013 (Statistics Norway, 2015). In Trondheim, 50% of wastewater production is from households, which correlates to water consumption, and the remainder is from industry (Slagstad and Brattebø, 2014).

The wastewater transport system of Trondheim with average age of 30 years consists of about 1200 km in public and municipal sections. However, the oldest pipelines, which are still in use, are more than 100 years old. The wastewater network consists of pumping stations, combined and separate sewer pipelines for transporting foul sewage and stormwater for treatment to one of the WWTPs of Høvringen (HØRA) and Ladehammeren (LARA) before being released in Trondheim fjord (Figure 1(a)); 51.7% of the total length of the foul sewer network in Trondheim is separate, and the rest is combined. The length of the separate stormwater network in Trondheim at the end of year 2013 is 40% of the whole wastewater transport network. Moreover, there are 54 pumping stations in the wastewater transport system of Trondheim, of which three are for stormwater, 24 for foul sewer, and 27 for the combined system (Trondheim Municipality 2013). The water balance of wastewater and stormwater systems in Trondheim is shown in Figure 1(b), which illustrates the years 2009–2011.

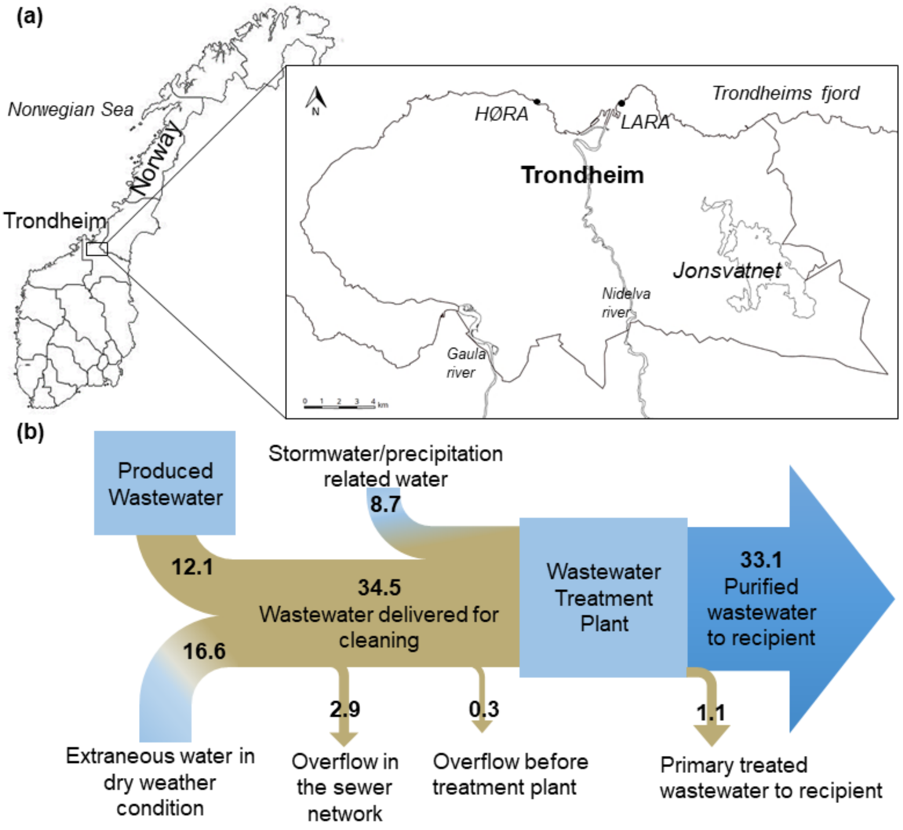

Figure 1. (a) The case study area. (b) Trondheim water balance 2009–2011 (million m^3/year) (Trondheim Municipality 2013).

This figure shows that the amount of infiltration and inflow (I/I) of extraneous water into the sewer system in dry weather conditions is about 46% of the water, which is delivered to the WWTP. It is a priority in the municipality to reduce this extraneous water, and the possible actions to handle this problem are:

- Increasing treatment capacity.
- Increasing the capacity of the wastewater transport system by separation of sewage and stormwater, installing detention basins and applying local stormwater solutions.
- Decreasing the amount of inflow and infiltration to wastewater transport system by spot repair and complete rehabilitation of sewer network.

In this study, some possible actions inside the wastewater transport system are considered by defining different scenarios and interventions in order to decrease the flaws and deficiencies and improving the current system.

Scenarios and interventions

One scenario is the combination of the actions of risk factors which influence the system in a specific way (Venkatesh, Sægrov and Brattebø, 2014). A risk factor is a specification, feature or aspect, which raises the likelihood of something undesirable happening. By identifying and understanding various risk factors, the related interventions and actions can be undertaken for preventing the unwanted consequences in the system.

According to the policies of the wastewater section of Trondheim municipality, the current plan is to improve the performance of the wastewater transport system and improve the stormwater management, in addition to having an energy management process. By analysing various risk factors, the need for new interventions arises. The risk factors that are considered in this study are population growth, asset deterioration, energy consumption (fossil fuels), and climate change. A scenario can be a combination of two or more risk factors, which affect the sewer system functionality.

The 'status quo' presents the current condition of the network without considering any risk factors and the same population growth as in the prognosis (Appendix 5). Furthermore, a constant development of the wastewater network, as average network development and pipeline installation of 2005–2013, is assumed for period 2014–2040. In addition, the rehabilitation rate is the same as the master plan for Trondheim. Besides, a 10% reduction in water demand per capita until 2040 is assumed due to increasing inhabitants' awareness of water usage and use of more water-saving facilities. Consequently, less water consumption will lead to less wastewater generation.

Table 1 demonstrates a general overview of risk factors and corresponding interventions, which are considered in this study for the wastewater transport system, according to discussions with experts in water and the wastewater section of Trondheim municipality. The black cells present the risk factors which are involved in each intervention.

Table 1. Risk factors and interventions of wastewater transport system.

Interventions	Risk factors			
	Population growth	Sewer asset deterioration	Energy consumption (Fossil fuels)	Climate change
a: Reduction of Infiltration and inflow		▨	▨	▨
b: Increase of rehabilitation rate		▨		
c: Extension of WW transportation network	▨			
d: Energy management			▨	
a+b		▨	▨	▨
a+c	▨	▨	▨	▨
a+d		▨	▨	▨
b+c	▨	▨		
b+d		▨	▨	
c+d	▨		▨	
a+b+c	▨	▨	▨	▨
a+b+d		▨	▨	▨
a+c+d	▨		▨	▨
b+c+d	▨	▨	▨	
a+b+c+d	▨	▨	▨	▨

Interventions

Various interventions can be implemented for the wastewater transport system. Some possible interventions which can be considered in this study arising from discussions with the Trondheim municipality, are listed below:

i. Intervention ‘a’: Reduction of infiltration and inflow (I/I)

Reduction in I/I of the non-sewer water to the system gradually, at a rate of 20% by the year 2040. Removing this water may add economic, environmental, and social benefits to the entire UWS. Spot repair is a solution for reduction of I/I to the wastewater network. The realistic number of repairs in this study is assumed to be 100 repairs per year. Spot repair can be supported by some high-tech tools such as fiber-optic Distributed Temperature Sensing (DTS) cables for localizing the exact I/I location in the sewer pipelines. The cost assumption for this purpose is about 1660 Euros per repair. This value adds to the operational expenses for each year.

ii. Intervention ‘b’: Increase of wastewater transport system rehabilitation rate

According to the master plan of Trondheim municipality, the rehabilitation rate, which is a combination of renovation and separation, for wastewater transport system in ‘status quo’ is around 5 km, which is 0.41% of the total wastewater network. It will increase gradually to 8 km

(0.67%) by the year 2040 (Appendix 3). In this intervention, the rate of 1.6%, which is the reference rehabilitation rate in the Oslo municipality, is assumed for the sewer system for the whole study period. This rate is quite ambitious and is selected to visualize clearly the impact of extensive rehabilitation on the environment. It is assumed that this increase in rehabilitation rate will decrease the I/I to the wastewater network by a rough estimation of 15% until the year 2040. Having detailed information regarding the size and length of pipelines, the corresponding ratio for the year 2013 is used for the whole of the study period. The cost assumption for rehabilitation of each kilometer of pipeline is about 440 Euros/m for renovation and 880 Euros/m for separation and replacement. This value has been considered in this study, for the additional rate of rehabilitation, which has not been considered in the current rehabilitation plan of Trondheim.

iii. Intervention ‘c’: Extension of wastewater transport network

In this study, it is assumed that a constant development average of 2005–2013 for the entire study period is the ‘status quo’. However, population growth may require a different extension of the sewer and stormwater networks. In this intervention, extension of the wastewater network has been considered proportional to the population growth rate. The expansion of the system as ‘status quo’ is higher than when considered based on population growth (Figure 2).

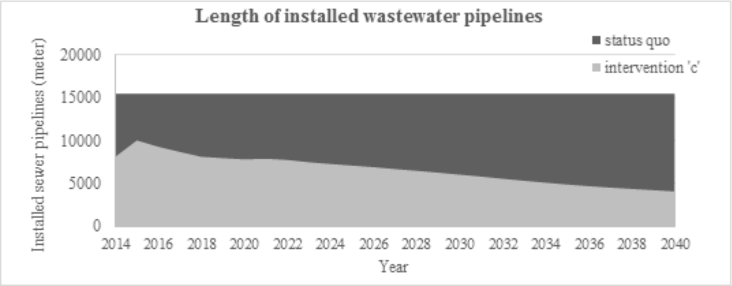

Figure 2. Extension of the sewer network based on population growth in intervention ‘c’ versus constant development as average 2005–2013 in ‘status quo’.

The existing system is generally overdesigned and possesses extra capacity for wastewater transport, especially in the combined sewers, which cope well in extreme events. This capacity can be utilized in city expansion, since the focus is on reduction of I/I into the sewer system and separation of combined networks. Also, this can be supported by blue-green solutions for stormwater management.

iv. Intervention ‘d’: Energy management

From an energy point of view, it is considered desirable to reduce energy consumption by a reasonable estimate of 20% by 2040 due to using more electricity instead of diesel and fossil fuels, automation/optimization of pumping stations, using more no-dig technology in rehabilitation of the network, and using more electric vehicles and instruments. To fulfil this purpose, an investment of 0.11 million Euros per year is assumed.

The combination of a+b, a+c, a+d, b+c, b+d, c+d, a+b+c, a+b+d, a+c+d, b+c+d, and a+b+c+d are also considered in this study and the most powerful combinations are presented in the results.

Results and Discussion

The per capita indicators, which are investigated in this study, are listed as below:

- GHG emissions per capita
- Total energy consumption per capita
- Length of pipeline per capita
- Wastewater treated per capita
- Operation and maintenance expenses per capita
- Capital expenditure per capita

Table 2 demonstrates the percentages of changes of selected indicators in 2040 for the wastewater transport system of Trondheim, which are modelled in DMM, compared with 'status quo' in the same year. In all the changes, a negative value is desirable.

Table 2. Changes of selected indicators in 2040 (in percent) for Trondheim wastewater transport system in comparison with 'status quo'.

Indicators		**Environmental**		**Physical & Functional**		**Economic**	
		GHG emissions per capita (kg CO2-eq per cap/y)	Total energy consumption per capita (kWh per cap/y)	Length of pipelines per capita (km per cap)	Wastewater treated per cap per year (m^3 per cap)	O&M expenses per capita (Euros per cap/y)	Capital expenditure per capita (Euros per cap/y)
Increase desirable? (Y/N)		N	N	Y-N	N	N	Y-N
|Interventions in 2040	a	-0.3	-0.55	0.0	-9.4	1.01	0.0
	b	29.9	24.9	12.1	-6.7	3.11	254.3
	c	-40.1	-37.6	-13.8	0.0	-4.6	-44.2
	d	-4.3	-5.0	0.0	0.0	0.08	0.0
	a+b	29.5	24.4	12.1	-16.1	4.11	254.3
	a+c	-40.4	-38.2	-13.8	-9.4	-3.6	-44.2
	a+d	-4.6	-5.6	0.00	-9.4	1.09	0.00
	b+c	-10.2	-12.6	-1.6	-6.7	-1.5	238.6
	b+d	25.6	19.9	12.1	-6.7	3.2	254.3
	c+d	-44.4	-42.6	-13.8	0.00	-4.56	-44.2
	a+b+c	-10.5	-13.2	-1.63	-16.1	-0.52	238.6
	a+c+d	-44.7	-43.2	-13.8	-9.35	-3.55	-44.2
	a+b+d	25.3	19.4	12.1	-16.1	4.19	254.3
	b+c+d	-14.5	-17.6	-1.6	-6.7	-1.45	238.6
	a+b+c+d	-14.8	-18.2	-1.6	-16.1	-0.44	238.6

It is clear from Table 2 that interventions ‘c’, ‘a+c’, ‘c+d’, ‘a+c+d’ present better results in all indicators especially in decreasing GHG emission and energy consumption per capita. Interventions ‘b+c’, ‘a+b+c’, ‘b+c+d’ and ‘a+b+c+d’ present rather good results compared with ‘status quo’ in 2040. The overweighting intervention here is intervention ‘c’, which is an extension of the system by population growth rate. This intervention represents a lower degree of network extension and construction work than ‘status quo’, which causes less resource usage and therefore more environmental and economic benefits.

Interventions ‘b’, ‘a+b’, ‘b+d’ and ‘a+b+d’ do not demonstrate good results in the wastewater transport system, regardless of decreasing the amount of wastewater, which is delivered to the treatment plant. The overweighting intervention here is ‘b’. In intervention ‘b’, increasing the rehabilitation rate and separation of the system adds more construction work to the network and therefore, the environmental and economic results are not desirable in the analysis of only a wastewater transport system. While it adds significant benefits to the environment by reduction of CSO and decreasing pollution in recipient. Moreover, decreasing the amount of I/I, which is delivered to WWTP, increases environmental advantages by less chemical- and energy-usage. However, these results are not considered here.

Interventions ‘a’, ‘d’ and ‘a+d’ demonstrate low falls in results compared with ‘status quo’. However, intervention ‘a’ adds outstanding advantages to CSO and WWTP by a reduction of I/I.

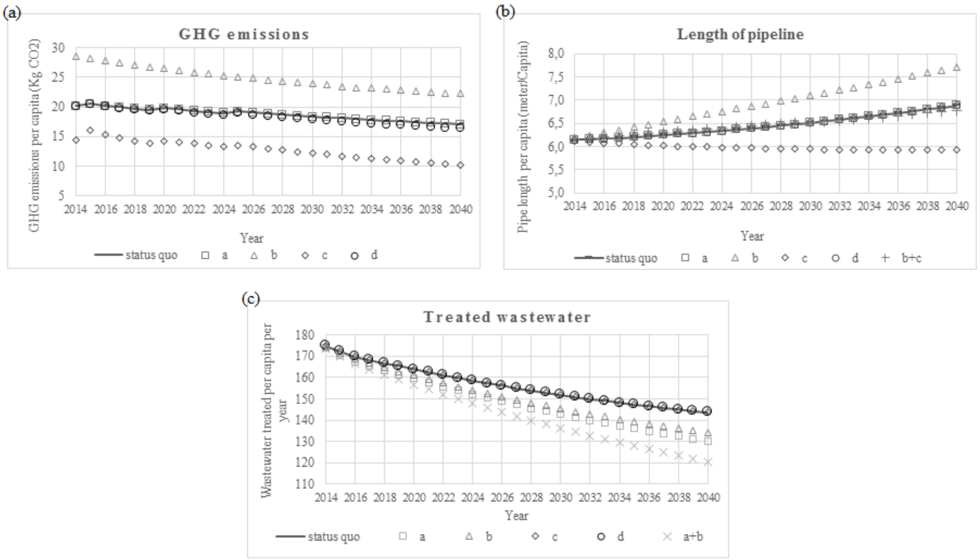

Figure 3. (a) Changes in GHG emissions per capita (‘status quo’, ‘a’, ‘b’, ‘c’, ‘d’). (b) Changes in length of pipeline per capita (‘status quo’, ‘a’, ‘b’, ‘c’, ‘d’, ‘b+c’). (c) Changes in wastewater treatment volumes per capita (‘status quo’, ‘a’, ‘b’, ‘c’, ‘d’, ‘a+b’).

Figure 3(a) demonstrates the changes in GHG emissions for different single interventions during the modelling period until 2040. In addition, total energy consumption per capita follows the same pattern as changes in GHG emission in different interventions.

From a physical point of view, as illustrated in Figure 3(b), the lengths of network per capita in interventions ‘a’ and ‘d’ are not changed compared with the ‘status quo’. In interventions ‘a’ and ‘d’ a constant rate as ‘status quo’ is assumed for the network growth until 2040. The network in intervention ‘b’ and its combinations with interventions ‘a’ and ‘d’, which are ‘a+b’, ‘b+d’ and ‘a+b+d’, has greater length because of increasing the rehabilitation length and increasing the length of the separate wastewater network. However, the length of the network in intervention ‘c’ and its combinations with interventions ‘a’ and ‘d’ is the shortest between all interventions. In intervention ‘c’ the focus is on developing the system by population growth rate. The combination of ‘b’ and ‘c’ and their combinations with interventions ‘a’ and ‘d’ illustrate an increase until year 2032 and then gradually decreases compared with the ‘status quo’.

Treated wastewater volume per capita decreases in the interventions, which are combinations of ‘a’, ‘b’ or both of them due to decreasing the I/I to wastewater pipelines. Intervention ‘a+b’, and its combination with other interventions illustrate the largest decrease in the treated wastewater per capita. The interventions ‘a’ and ‘b’ have the next most significant falls, respectively. The treated wastewater in interventions ‘c’, ‘d’, and ‘c+d’ remain the same as ‘status quo’, as well as decreasing significantly compared with year 2013 in all interventions because of the basic assumption of reduction of I/I to the sewer system by 2040 in ‘status quo’ (Figure 3(c)).

With regard to economic analysis, it is important to clarify the capital expenditure and operational and maintenance (O&M) expenses per capita. Capital expenditure refers to depreciation and interest payments, while the inputs of O&M expenses are energy, chemicals, maintenance and salaries. In this study, in interventions ‘b’ and ‘c’ the focus is on capital expenditure, due to depreciation cost of new pipelines in the system. However, in ‘a’ and ‘d’ the O&M expenses are considered with regard to extra maintenance and energy expenses. Furthermore, O&M expenses are also affected in ‘b’ and ‘c’ because of energy demand for installing and removing pipelines in the system. Capital expenditure per capita is not affected in ‘a’, ‘d’ and ‘a+d’. However, it decreases in intervention ‘c’, and intervention ‘b’ illustrates the largest increase; then, as presented in Figure 4(a), intervention ‘b+c’ shows an increase, which is less than the increase in intervention ‘b’. It is worth mentioning here that Figure 4(a) is not a smooth graph due to data on the economy from Trondheim municipality, which is used as the database of this study and is presented in ‘status quo’ (Appendix 7). O&M expenses per capita fall the most in intervention ‘c’ because of installing fewer pipelines than ‘status quo’. Other single interventions show increase in O&M expenses in comparison with ‘status quo’, while intervention ‘b’, ‘a’ and ‘d’ show the highest to lowest increases respectively. The highest O&M expenses in intervention ‘b’ is because of increasing rehabilitation rate which imposes high energy, salary and maintenance expenses (Figure 4(b)).

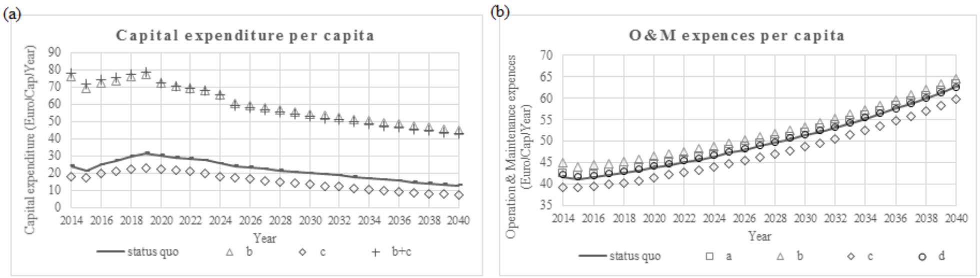

Figure 4. Changes in (a) capital expenditure, and (b) operation and maintenance expenses per capita.

The results of this study are based on the analysis of different interventions in the wastewater transport system of Trondheim, and the CSO and WWTP are not considered in this study. Furthermore, future interventions and assumptions of influx of material, energy and resources into the system are always followed by uncertainty, which is not considered in this study.

Conclusion

In the present study, the wastewater transport system of the city of Trondheim is analysed from a sustainability point of view by the dynamic metabolism model (DMM). The focus of this research is on environmental, energy, physical, and economic aspects of sustainable wastewater infrastructure management in the strategic planning period 2014–2040, based on the historical database 2000–2013. The main approach of this study is to analyse the impacts of different risk factors on the wastewater transport system and compare them with 'status quo' with a constant development of the wastewater network. With this aim, four interventions: 'a' (infiltration and inflow reduction), 'b' (increasing rehabilitation rate), 'c' (extension of system regarding population growth) and 'd' (energy management) along with different combinations of these interventions have been analysed. Based on the obtained results, the overall conclusions are as follows:

Interventions of reduction of I/I (a), and energy management (d), and combinations of them (a+d) demonstrate low falls in results compared with 'status quo'. These interventions also do not affect other interventions significantly in their combinations. However, by reduction of I/I in intervention 'a', outstanding advantages will accrue to CSO and WWTP by reducing wastewater volume. Nevertheless, the results of this study do not demonstrate the comprehensive effects on the whole wastewater system.

Intervention 'b' presents the need for increasing the performance of the system by increasing the rehabilitation rate and separation of the network. This intervention does not demonstrate good results in the wastewater transport system for the selected level of rehabilitation (1.6%), regardless of reducing the amount of wastewater delivered to the treatment plant. It has also significant benefits on CSO and WWTP, which is outside the scope of this study.

Intervention 'c' is extension of the network by population growth rate, which is actually lower than the extensions of recent years ('status quo'). In the existing system extra space is supplied for wastewater and stormwater transport. Additionally, for stormwater systems, blue-green solutions can reduce the need of extra flow capacity, and this is recognized in intervention ‘c’. This intervention and its combinations with ‘a’, ‘b’ and ‘d’ present good results in all indicators especially in decreasing GHG emissions and energy consumption.

The energy management intervention (d) does not show any remarkable changes in results compared with ‘status quo’. This intervention represents automation/optimization of pumping stations, using more trenchless and no-dig technology in rehabilitation of the network and using more electric vehicles and instruments. By such measures, cities can achieve better energy management and significant reduction in diesel energy consumption. This will have major impact on the sustainable management of the wastewater system.

The results of this study provide some evidence to decision-makers in the wastewater departments of Trondheim and other cities. For future developments, which are based on various climatic, socioeconomic and anthropogenic scenarios, the fulfilment of assumptions is strongly associated with future conditions and, therefore, uncertainty plays a relevant role, and reliability of the outcomes can be affected significantly (Freni, Mannina and Viviani, 2012). Therefore, it is worth taking into account uncertainty analysis in decision-making. Moreover, it is important to consider the whole system for final analysis and decision-making. This can lead to long-term sustainable plans and management in a wastewater transport system by having more focus on the environmental feature of sustainable sewer asset management besides the economic, physical, functional and social aspects.

Supplementary data

The supplemental material for this paper is available online at https://doi.org/10.1080/1573062X.2017.1363253.

Acknowledgements

We are grateful to the wastewater department of Trondheim Municipality and the personnel of that department specially Kristin Greiff Johnsen and Birgitte Johanson for their total support with data and information. Moreover, thanks to G. Venkatesh, for his very valuable help with discussions and methodology. We would also like to express our gratitude to Ali Tabeshian, for his invaluable help and support during the writing of this paper.

SUPPLEMENTARY DATA

Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway

Maryam Beheshti & Sveinung Sægrov

DMM was applied to investigate and assess sustainability from environmental, physical, functional and economic aspects on the wastewater transport system of Trondheim in the period 2014-2040, based on historical database 2000-2013. The flow of material and resources to wastewater transport network was exploited as DMM model inputs (Appendix 1 & 2). Rehabilitation of the sewer pipelines in Trondheim consists of renovation of the existing pipelines by a cured-in-place-pipe (CIPP) technique and separation of them by adding new pipeline to the network. The inflow of material into the sewer network according to rehabilitation plan of Trondheim was considered in this study (Appendix 3 & 4). Moreover, the historic energy consumption data in wastewater transport system was used as model input. Population prognosis of Trondheim until 2040 was considered according to statistic center of Norway. Population of Trondheim is rising and according to prognosis from statistic center of Norway, Trondheim municipality will grow by around 60 000 new residents until 2040, which is 33% increase in population in comparison with year 2013 (Appendix 5). Furthermore, the energy consumption of pipeline rehabilitation, maintenance and operation was considered (Appendix 6). The economy input data of this study has been extracted from the annual investment plan of wastewater transport system of Trondheim municipality for the period 2013-2040 (Appendix 7).

Appendix 1: Pipeline data

It is necessary to acquire detailed information on characteristics of the pipeline network in Trondheim for modelling sustainability in DMM. In classifying the pipelines, diameters less than 249 mm are considered as small, between 250 mm and 499 mm are considered as medium-size and bigger than 500 mm are large pipelines. Based on available pipeline data the average percentage of pipelines with different sizes have been calculated for each year. Afterwards, according to the total length of installed pipelines in the system in each year, detailed average length of each size was calculated. In this study the average wastewater pipeline installation values from 2005-2013 were assumed as input values for the whole of prediction period 2014-2040 in status quo.

Table S1. Average length and percentage of installed and registered pipelines (2005-2013).

size	small	medium	large
Average percentage (%) (2005-2013)	52,0 %	33,3 %	14,7 %
Average length (m) (2005-2013)	7886,4	5048,9	2236,2

Appendix 2: Pipe material

The materials of Trondheim wastewater network by the end of the year 2013 is presented in figure below. As it is illustrated in this figure, the main part of the system is concrete pipeline with 81% of the total pipelines. PVC and PP pipelines are in the second score by 10% ratio. In addition, Table below presents average material distribution of installed pipelines in Trondheim based on their functionality in 2005-2013.

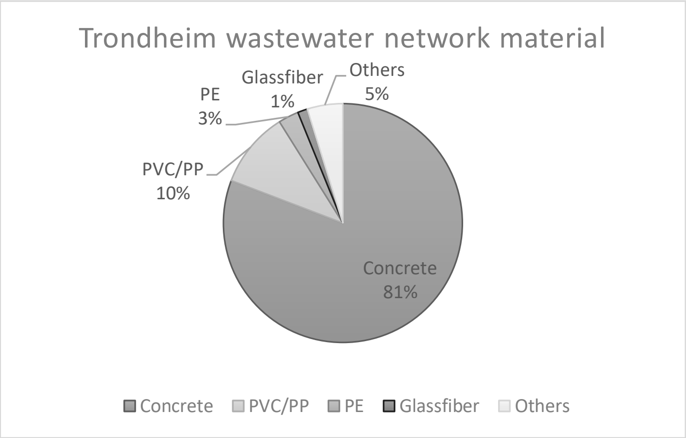

Figure S1. Wastewater pipeline material of Trondheim municipality at the end of 2013.

Table S2. Average distribution material of installed pipelines (2005-2013).

	wastewater				stormwater				Combined sewer			
Average	Concrete	PVC	PE	PP	Concrete	PVC	PE	PP	Concrete	PVC	PE	PP
2005-2013	36.8 %	52.5 %	9.4 %	1.3 %	59.4 %	36.0 %	3.7 %	0.9 %	62.4 %	16.6 %	17.4 %	3.6 %

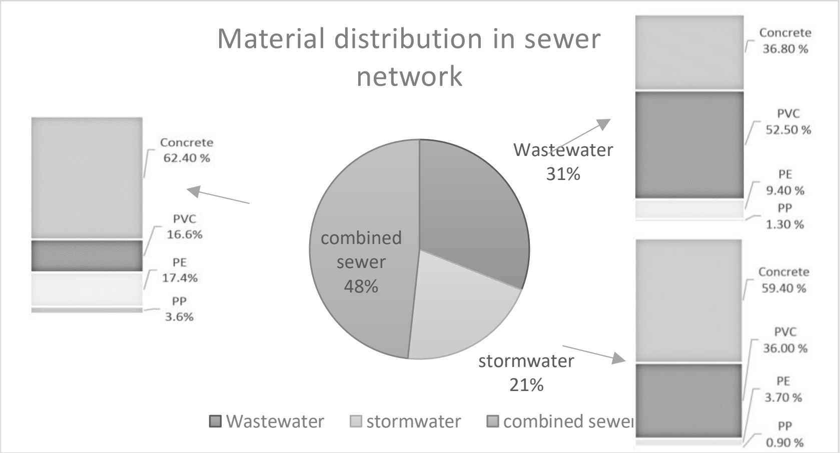

Figure S2. Average distribution material of installed pipelines (2005-2013).

Appendix 3: Renovation and replacement

Rehabilitation is a combination of renovation and replacement. The general rehabilitation objectives for Trondheim municipality are:

- minimum 5 km sewer pipelines per year in period 2013-2014
- minimum 6 km sewer pipelines per year in period 2015-2019
- minimum 7 km sewer pipelines per year in period 2020-2024
- Around 8 km sewer pipelines per year in 20-30 years

The percentage of rehabilitation length in 2013-2014, according to this plan is about 0.41% of total wastewater transport network. For rehabilitation purposes, a polyester liner is utilized as CIPP. This rehabilitation technique focuses on tightening and strengthening the existing pipelines on site with trenchless and no dig solutions. In Trondheim, renovation proportion by CIPP is currently about 1/3 of all sewer network rehabilitation and the other 2/3 is replacement of combined pipelines with separated ones.

According to Trondheim municipality in 2013, renovation is applied when:

- Combined system should be retained.
- Combined system assumed to lie minimum 20-30 years ahead.
- The renovated combined pipeline can serve as wastewater pipe in a future separate system.

However, in the case of replacement of combined pipelines by digging methods, it is important to change it to separate pipelines. In separation, the current pipeline remains as wastewater pipeline and a new stormwater pipeline is introduced to the system.

Based on the average ratios of pipeline size and length between 2005-2013 and objectives for pipeline rehabilitation lengths in future, detailed estimations for rehabilitation length for different sizes of pipelines in the study period has been made. Moreover, in order to find the influx of polyester to sewer pipelines by renovation methods, it is assumed a nominal diameter for each group of small, medium and large pipelines (small: 150, medium; 300, and large: 550 mm).

Appendix 4: Polyester for CIPP rehabilitation

Chosen Thickness of Polyester coating in a CIPP – 7.6 millimetres with a specific density of 1380 kilograms per cubic meter.

Appendix 5: Population change

Net migration to Trondheim is rising and is expected to continue. Prognosis from Statistics Center Norway shows that Trondheim municipality will grow with around 30000 new residents until 2025 compared with population of 2013. By 2040, there will be around 30% increase in population in comparison with year 2013 (Statistics Norway 2013).

Table S3. Annual percentage increases in population growth prognosis of Trondheim considered for the modelling (Statistics Norway 2013).

Year	Rate of increase compare to previous year	Year	Rate of increase compare to previous year	Year	Rate of increase compare to previous year	Year	Rate of increase compare to previous year
2014	1.39%	2021	1.19%	2028	0.91%	2035	0.74%
2015	1.56%	2022	1.14%	2029	0.91%	2036	0.65%
2016	1.48%	2023	1.13%	2030	0.90%	2037	0.64%
2017	1.46%	2024	1.11%	2031	0.77%	2038	0.64%
2018	1.44%	2025	1.26%	2032	0.76%	2039	0.64%
2019	1.42%	2026	0.93%	2033	0.76%	2040	0.63%
2020	1.4%	2027	0.92%	2034	0.75%		

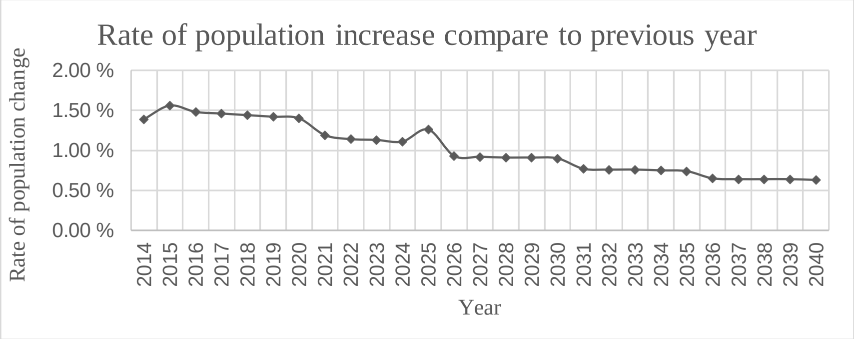

Figure S3. Annual percentage increases in population growth prognosis of Trondheim considered for the modelling (Statistics Norway 2013).

Appendix 6: Energy consumption

Diesel is consumed in installation, operation and maintenance (O&M), rehabilitation and retirement process of pipelines in water and wastewater networks. The DMM model has some assumptions for specific energy consumption for all of these activities on pipelines in the network based on different size categories. Furthermore, the historic energy consumption data in wastewater transport system was extracted from Trondheim municipality database.

Table S4. Diesel Consumption (sourced from the Appendix in Venkatesh (2011)).

Small-size pipelines	1 litre per metre
Medium-size pipelines	1.5 litre per metre
Large-size pipelines	2 litres per metre

Appendix 7: Economy

The economy input data of this study has been extracted from the annual investment plan of wastewater transport system of Trondheim municipality for the period 2013-2040. The exchange rate of Norwegian Kroners (Nok) to Euro has been considered 0.11 in this study (Source: www.xe.com, March 2015).

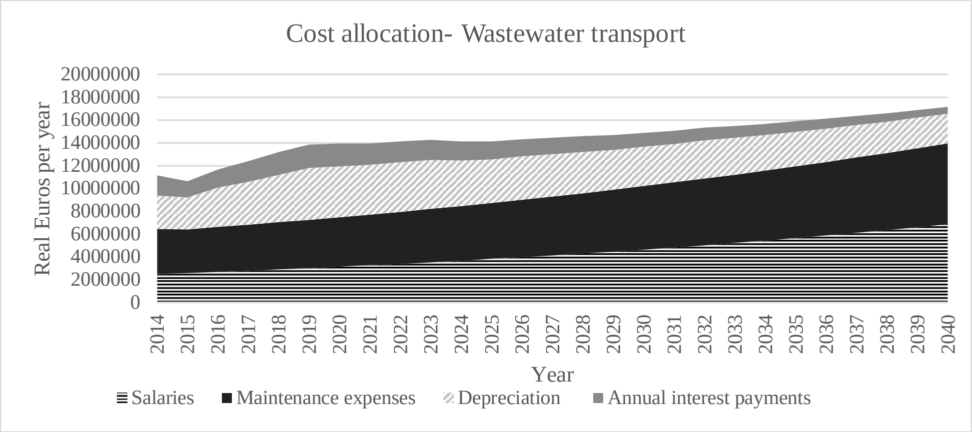

Figure S4. Cost allocation of wastewater transport system Trondheim for 2013-2040 (Trondheim Municipality; 2013).

Appendix 8: Dynamic methabolism model (DMM)

DMM is a metabolism-based model, derived from methods of material flow analysis (MFA) and life cycle assessment (LCA). This model is based on analysis of material inflow to the UWS and outflow of them in the concept of energy , GHG emissions and byproducts from the system in the life cycle of the material (Venkatesh, Sægrov and Brattebø, 2014; Venkatesh, 2011). This model implements a complete systematic approach to the study of metabolism and environmental effects of resource flows in UWS, i.e. water flows, material and energy consumption, resource recovery, waste and emission flow (Figure S5). Figure S5 demonstrates the schematic outline of the stocks and flows in different subsystems of UWS (water supply, water demand, wastewater, cyclic water recovery and resource recovery in addition to the source and recipient) as a base of DMM model (Venkatesh *et al.*, 2017). In addition, DMM offers an instrument for the investigation of possible future services, strategies and interventions in UWS (Venkatesh, Sægrov and Brattebø, 2014; Beheshti and Sægrov, 2018c). Moreover, by this model the UWS can be quantitatively analysed from different aspects, such as energy consumption, emissions, environmental impacts, economic and physical properties by annually-based performance indicators for whole of the system and its subsystems (such as water distribution and wastewater transport) under different interventions toward future improvements (Venkatesh *et al.*, 2017; Beheshti and Sægrov, 2018c). Figure S6 illustrates a holistic view of the structure of this model.

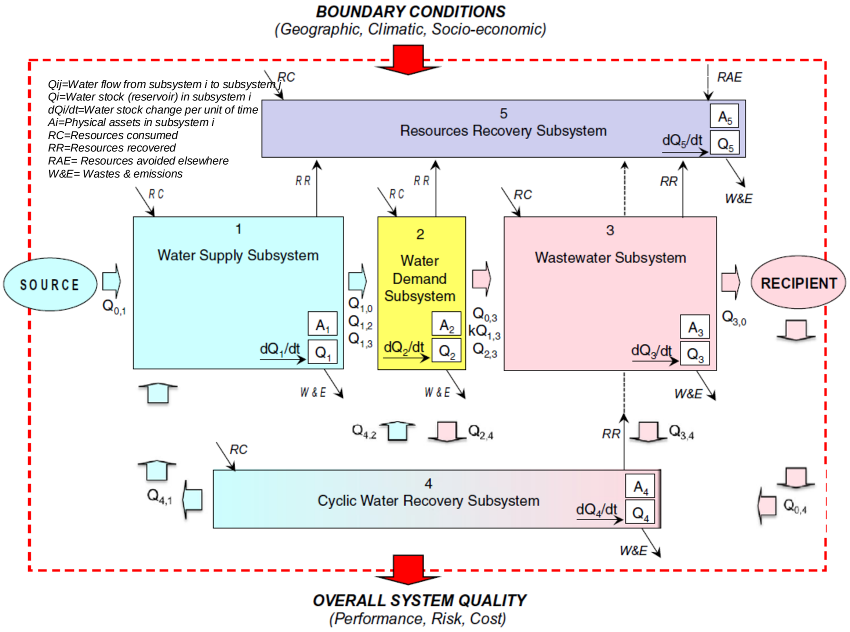

Figure S5. Metabolic flow of urban water system (Venkatesh *et al.*, 2017).

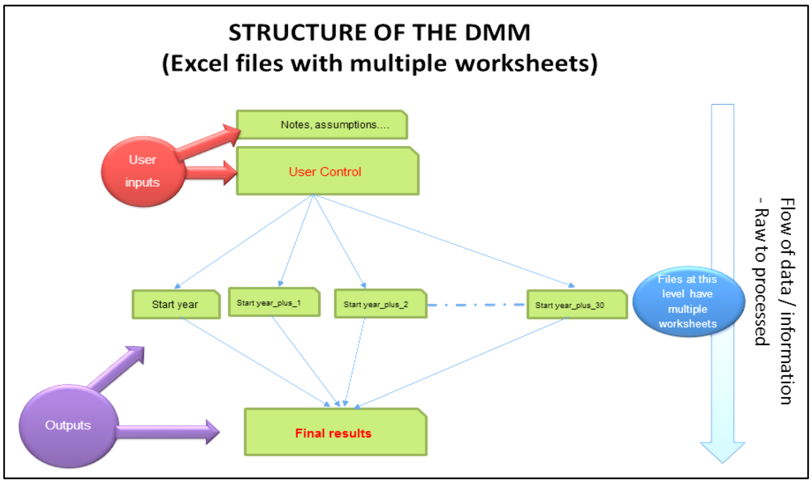

Figure S6. Dynamic metabolic model flow (Venkatesh, Sægrov and Brattebø, 2014).

6. TACTICAL PLANNING (PUBLICATION II)

The following publication *Infiltration/Inflow Assessment and Detection in Urban Sewer System*, written by Maryam Beheshti*, Sveinung Sægrov and Rita Ugarelli was published in 2015 in Vann Journal, Issue 1, pages 24-34.

Infiltration / Inflow Assessment and Detection in Urban Sewer System

Maryam Beheshti[*], Sveinung Sægrov, Rita Ugarelli

Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[*]Email: maryam.beheshti@ntnu.no

Sammendrag: Infiltrasjon og innlekking (I/I) av fremmedvann til avløpsnettet er ofte betydelig. Dette medfører økte kostnader for transport og rensing av avløpsvann. Fremmedvannet tar opp transportkapasitet og øker sannsynligheten for forurensningstap via overløp og oversvømmelser på terreng og i kjellere. Lokalisering og fjerning av fremmedvann er derfor prioritert i kommuners planer for oppgradering av avløpsnett.
Denne studien presenterer metoder for å lokalisere og kvantifisere I/I i avløpsanlegg, og diskuterer muligheter og begrensninger ved hver metode. Den konkluderer med at en kombinasjon av teknikkene er nødvendig for å oppnå tilstrekkelig kunnskap om årsaker og omfang av innlekking.

Abstract: Infiltration and inflow (I/I) of non-sewer water into the urban sewer system is a critical problem in the long term for sustainable urban water management and water infrastructural asset management, with serious environmental, social and economic impacts on cities and sewer systems. I/I of unwanted stormwater, groundwater and other extraneous sources in sewer systems decrease availability and increase the risk of hydraulic overloading of the wastewater network, which may lead to local flooding or sanitary sewer overflows. Furthermore, it has negative impacts on performance and efficiency of wastewater treatment plants and increases pumping costs, energy consumption and maintenance requirement.
There is no standard and specific operational procedure for investigating and detecting illicit connections and I/I in sewer systems. This study discusses commonly used and advanced methods of localizing and quantifying I/I level in sewer systems, and identifies advantages and limitations of each method. A combination of these techniques can provide sewer operators possibilities to compare different technologies and reducing assumptions and uncertainties in assessing and localizing I/I in the sewer system in a standardized way and support the decision-making in maintenance and rehabilitation plans with more accurate and reliable data about location and magnitude of I/I in the sewer system.

Key words: Infiltration and inflow (I/I), urban water management, Sewer system, maintenance, rehabilitation

Introduction

Urban sewer systems are one of the most significant and important water infrastructures in European cities and even all over the world. Water and wastewater networks are assumed as the lifelines of urban areas as they transport drinking water with high quality and safety to households and industries and collect polluted water for recycling and safe releasing into the environment (Rehan *et al.*, 2014). Functional efficiency and structural quality of sewer systems are the principal factors that ensure urban and industrial wastewater transportation to treatment plants without infiltration and exfiltration (Ellis & Bertrand-Krajewski 2010). Urban water and wastewater infrastructure assets are in the state of deterioration based on lack of sufficient municipal investments on their maintenance and rehabilitation (Rehan *et al.*, 2014).

There are different types of sewer systems for transporting foul wastewater and stormwater. Most European cities rely on combined sewer systems (CSS), the most common way of draining wastewater and stormwater. Combined sewer overflows (CSO) may lead to environmental problems due to the discharge of untreated and polluted wastewater to receiving waters or other final recipients and trigger urban areas flooding in extreme rain events. On the other hand, stormwater separate systems have been introduced as one of the cost-effective solutions in many regions to disconnect impervious areas from CSS for reducing CSO emissions and hydraulic overloading of sewer systems (Langeveld *et al.*, 2012). A major defect of separate sewer systems is the occurrence of faulty connections: unplanned sewer cross-connections that connect foul water outlets from residential or industrial sites to the stormwater system and/or stormwater outlets to the foul sewer system (Schilperoort *et al.*, 2013). The volume of unwanted stormwater in foul sewer systems can be significant, resulting in a number of undesirable consequences on the performance of the wastewater system. Therefore, rehabilitation is required in the case of infiltration and illicit connection detection in the sewer systems.

Unwanted water in separate foul sewer systems is a well-known problem. Approximately 50% of the stormwater is discharged into the separate foul sewers and transported to the wastewater treatment plant (Peters *et al.*, 2002; Langeveld *et al.*, 2012). Moreover, under unfavorable conditions, the amount of groundwater infiltration into the deteriorated pipes can even exceed 50% of the total wastewater volume (Kracht and Gujer, 2006). Infiltration and inflow (I/I) of unwanted stormwater, groundwater and other extraneous sources in the sewer system, are significantly unfavorable for the efficiency of the wastewater treatment plants and may overload the hydraulic load of the treatment plants up to 100 % by infiltrated water (Ellis and Bertrand-Krajewski, 2010). In addition, there is increasing evidence that in many cities, groundwater levels are controlled by the significant drainage effect of permeable sewer systems (Kracht and Gujer, 2006). Generally, infiltration decreases the availability and increases the risk of pressurization of the wastewater network (Sægrov, 2014). Practitioners often address this issue by calculating the “parasitic discharge” based on the assumption of minimum nighttime flow in the diurnal wastewater hydrograph is equal to the extraneous flows (Kracht and Gujer, 2006).

I/I of non-sewer water into the urban sewer system is a critical issue in the long term for sustainable urban water management and water infrastructural asset management, which has serious environmental, social and economic impacts on cities and sewer systems. From the environmental point of view, the efficient curbing and removal of I/I of unwanted water into the sewer systems can reduce the hydraulic overload of sewer pipelines, which decreases the probability of local flooding and deterioration of urban infrastructures (Karpf and Krebs, 2011), and its impacts on inhabitants’ life. It also reduces the probability of dissemination of sanitary sewer overflows in streets, urban areas and environment. Furthermore, from the economic point of view, it leads to lower maintenance requirements due to decreasing entry of sediments and decreases the cost and energy consumption in pumping stations and treatment plants because of removing unwanted feeding of foreign water (Langeveld, 2004; Schilperoort *et al.*, 2013). Therefore, for having the sustainable management of urban sewer systems, I/I of unwanted water into the urban sewer systems should be considered carefully and maintenance and rehabilitation plans should be implemented on these water infrastructural assets.

Efficient assessment and detection of I/I in urban sewer systems are important issues on the long-term water infrastructure asset management, which have not been considered adequately and seriously in urban areas so far. The purpose of this study is to introduce and discuss commonly used and advanced methods of detection, localization, and quantification of I/I into the sewer systems, and identify advantages and limitations of each method. Some of these methods are going to be used in the Trondheim city in Norway for assessing the level of I/I into the foul sewer systems. This gives sewer operators the possibility to compare different technologies in assessing and localizing I/I in the sewer system in a standardized way and can support the decision-making on when and where to rehabilitate, depending on the selection criteria (hydraulic, social, environmental, economic, etc.).

Infiltration Detection and Measurement Methods

Infiltration is the entry of groundwater into the sewer system and service connections through defective pipes, pipe joints, connections, manhole walls, and so forth. In separate sewer systems, it is also very important to detect illicit and faulty connections, which result in infiltration and inflow of unwanted water into the pipeline network from different sources. Efficient removal of I/I into the sewer systems requires knowledge about the locations of I/I sources and illicit connections. There are several methods available for assessing and localizing the infiltration and inflow of unwanted stormwater, groundwater, and other extraneous sources into the sewer system. Typically, the assessment of I/I in sewer systems is based on the conventional and rather inaccurate method of flow rate measurement, analysis of diurnal flow and load variation and balancing of water inputs and outputs (De Bénédittis and Bertrand-Krajewski, 2004; Rutsch, Rieckermann and Krebs, 2005; Ellis and Bertrand-Krajewski, 2010). Moreover, new measurement methods have been developed to assess I/I into sewer systems based on limited analytical effort and with little environmental risk.
These methods can be divided into two groups: quantitative methods for assessing the magnitude, volume and discharge of I/I, and qualitative methods for detecting the location of I/I sources. Each of these methods is based on some assumptions and has its own limitations and advantages. There is no unique and standard way of evaluation and localization of I/I in the sewer systems and a combination of these methods can be valuable for reducing assumptions and uncertainties and obtaining more independent, accurate and reliable data about location and magnitude of I/I in the sewer system. Finally, maintenance and rehabilitation can contribute to the improvement of the performance of sewer systems in the long term for sustainable urban water management. The systematic process for detection of unwanted water in specified catchments with different properties in Trondheim city is proposed in Figure 1.

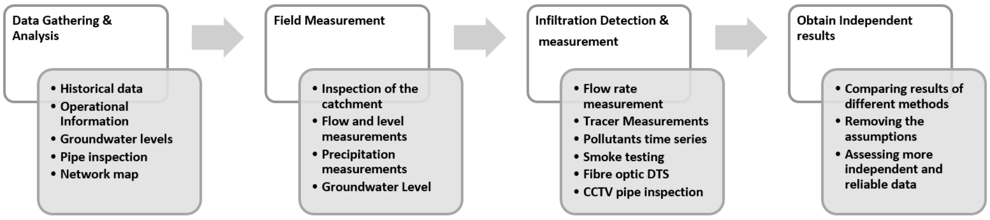

Figure 1. Systematic method for detecting unwanted water in sewer system.

Quantitative methods

Flow rate method

The flow rate measurement method is one of the conventional methods of infiltration assessment in sewer systems. This method is based on the simple assumption of constant infiltration of groundwater in daily Dry Weather Flows (DWF). DWF is the mean daily sewage flow in a foul sewer system during a day and the day before of dry weather or less than 0.3 mm/day rainfall intensity because of avoiding contribution of stormwater inflow to flow measurement (excluding public or local holidays) (Karpf and Krebs, 2011). Moreover, for excluding the contribution of snow-melt flow in DWF measurement, the day of DWF and three days before the air temperature should not be in the range of -2 to +2 ºC (Karpf and Krebs, 2011). Equation 1 is the basic method for calculating the I/I in the sewer system (SEPA, 2014).

$$DWF=P*G+I+E \qquad \text{(Eq. 1)}$$

Where:
P= Population served
G = daily average water consumption per capita ($\frac{Liters}{Person*day}$) (typically 150-160 liters in Norway)
I = daily average I/I ($\frac{Liters}{day}$)
E = daily average industrial effluent flow ($\frac{Liters}{day}$)

Krapf and Krebs (2011) made some refinements in this basic method and developed a new approach for quantifying the components of I/I – infiltration from groundwater and Inflow from surface water– separately. The quantification of infiltration in this approach needs groundwater level and the level of wastewater in the pipes, whereas the inflow quantification refers to the permanent and temporary surface water flow, e.g. surface watercourses and flood events (Karpf and Krebs, 2011).

Figure 2 illustrates the constant or base infiltration (BI) at the minimum nighttime flow, theoretical dry weather flow (DWF) and wastewater flow of a DWF week in the separate sewer network of Risvollan catchment in Trondheim. Risvollan is one of the study catchments in Trondheim, Norway with a good database and a measuring station to investigate hydrological parameters through the year. The amount of base infiltration in week 7, 2007 with 0 mm rainfall is 35.5% of total wastewater flow in the separate foul sewer of Risvollan catchment, which is a high volume in the dry weather conditions and is increased significantly in the wet weather conditions.

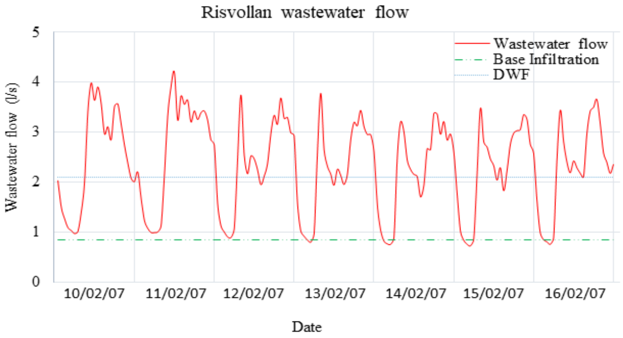

Figure 2. Wastewater flow, theoretical dry weather flow and base infiltration in the separate sewer of Risvollan catchment, Trondheim.

Tracer methods

Tracer techniques have proven to be one of the most powerful tools to characterize water residence time, flow and pollutant transport in hydrological systems (Koeniger *et al.*, 2009). The ideal tracer should have the following features (Pitt *et al.*, 1993):

- A significant difference in concentration between possible pollutant sources
- Small variations in concentrations within each likely pollutant source category
- A conservative behavior (no significant concentration changes due to physical, chemical or biological processes)
- Ease of measurement with adequate detection limits, good sensitivity, and repeatability.

Stable isotopes method

The stable isotopes method is a tracer method and relies on different isotopic signatures of main water from a distant hydrological source and infiltrating water from groundwater and local precipitation, as a direct natural tracer (Ellis and Bertrand-Krajewski, 2010). Stable isotopes (δ^{18}O and δ^{2}H of water) provide a reliable tool to quantify the infiltration of foreign water in sewer system (Kracht, Gresch and Gujer, 2007). Figure 3 illustrates daily wastewater isotopic characterization graph and hydrograph of wastewater flow contributors: ‘foul sewage’ and ‘infiltration’.

In this method, the infiltration fraction is calculated by equation 2, which is based on the concentration of different isotopes as tracers (Ellis and Bertrand-Krajewski, 2010).

$$X_{\text{infiltration}}(t) = \frac{C_{\text{foul sewage}}(t) - C_{\text{Spillwater}}(t)}{C_{\text{foul sewage}}(t) - C_{\text{infiltration}}(t)} \qquad \text{(Eq. 2)}$$

The stable isotopes composition of the foul sewage and local groundwater are assumed as tracers for foul sewage and infiltration respectively. Then infiltration flow can be calculated by equation 3 (Ellis and Bertrand-Krajewski, 2010).

$$Q_{infiltration}(t) = X_{infiltration}(t) * Q_{wastewater}(t) \qquad \text{(Eq. 3)}$$

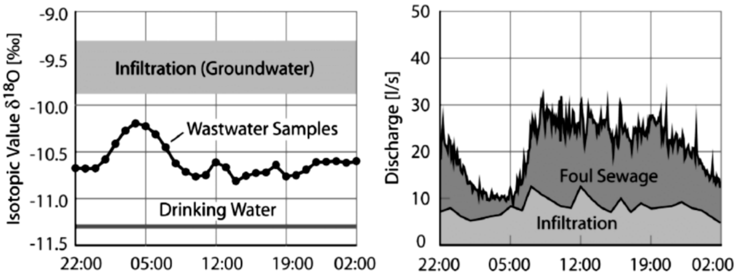

Figure 3. Isotopic characterization and disintegration of a daily wastewater hydrograph into "foul sewage" and "infiltration" (Kracht and Gujer, 2006; Ellis and Bertrand-Krajewski, 2010).

Pollutant time series method

The pollutants time series method quantifies infiltration fraction by analyzing time-series of pollutant concentrations and wastewater flows. Automatically operating in-line devices are applied in this method to obtain time-series of pollutant concentrations with a high temporal resolution. Based on the time-series of the wastewater flows, a modelled time-series of pollutant concentration is calculated, and by fitting this model series to the measured data, a set of parameters, which define $Q_{infiltration}$, can be estimated (Ellis and Bertrand-Krajewski, 2010).

The method may be applied at the outlet of any sub-catchment where a continuous discharge of wastewater can be assured. However, a minimum amount of wastewater flow is required for the operation of the measuring devices, which may be critical during minimum nighttime flow. It is assumed that infiltrated water contains negligible concentrations of contaminants. Furthermore, the main types of industrial effluents should be excluded, as this may hinder a regular data analysis.

Qualitative methods

Smoke Testing

Smoke testing is an engineering surveying method to locate, identify and classify the potential sources of infiltration and inflow from stormwater outlets into separate foul sewers. This method involves pumping large volumes of a vegetable-based, non-toxic, odorless smoke into sewer network through a manhole (Figure 4). The smoke is generated by a smoke generator engine and travels through the sewer network. Smoke tends to escape through places like openings and vents of the sewer system in the testing area and they may point out to the infiltration/inflow sources in the system (Hoes *et al.*, 2009; City of Toledo, 2011). This method has the ability to find some of the infiltration/inflow places, and for having more accurate results the network should be monitored with a CCTV television camera (Schwindamann, 2008).

Dye Testing

Dye testing is a tracing method for detecting the path of the flow with tracking dye and determining illicit connections existing in sewer systems. In this method, a fluorescent non-toxic dye is added to a water source, which is suspected as a source of infiltration and inflow into the sewer system. In another way, a period of heavy rainfall is simulated by flooding the stormwater system with pumped water from a large tank. Dyes of different colors are applied to different places. The sewer system is monitored simultaneously by a television camera (CCTV) and infiltration of stormwater is confirmed by finding dye in the sewer system.

The alternative way is to have field staff detecting plumbing fixtures and placing the dye into them. The dye is flushed through the system with running water. When the first dye is observed at the downstream of the tested facility, alternative dye colors are added in the upstream to test multiple fixtures simultaneously. The dye test is repeated until it is confirmed in the sewer or in a storm sewer, or surface water. An illicit connection will be detected in the case of finding the dye in a location other than a sewer system.

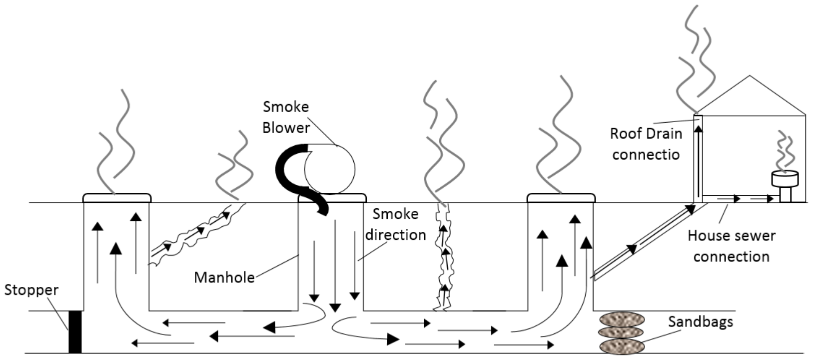

Figure 4. Smoke Testing process for finding potential sources of infiltration and inflow into a foul sewer system.

DTS method

Fibre-optic Distributed Temperature Sensing (DTS) is a widely-used technique measuring temperature with a high resolution and high frequency along cables with lengths up to many kilometers (Vosse *et al.*, 2013). The method is based on proven technology, which for decades has been used in the industries of oil drilling, fracture control in pipeline systems, industrial process control and leakage detection in dams and hydrology (Johansson, 1997; Schilperoort *et al.*, 2013). This technique has also proven to be a powerful tool to detect and locate infiltration and illicit connections in stormwater sewers (Haan de *et al.*, 2011; Langeveld *et al.*, 2012). The application of fibre-optic DTS in sewer systems has been developed since 2010 (Vosse *et al.*, 2013). DTS enables the monitoring of the performance of house connections and detection of foul sewage inflows to storm sewers and vice versa (Schilperoort *et al.*, 2013). Stormwater inflow can only be detected as long as the temperature of this inflow differs from the in-sewer temperatures. In addition, the in-sewer propagation of storm and wastewater can be monitored, enabling a detailed view on advection (Schilperoort *et al.*, 2013). The installation of a fibre-optic cable in a combined sewer system has also proven feasible (Langeveld *et al.*, 2012).

Figure 5 gives an overview of the DTS monitoring results in a foul sewer on 28 April 2011 in the Netherlands. The horizontal axis indicates the length along the fibre optic cable in the sewer system and the vertical axis indicates the time of monitoring. The figure illustrates the measured temperature values of each point along the cable per minute in a time-span of 2 hours. The temperature variation after 04:30 is due to a storm event. The flow direction in this figure is from right to left and the exact places of stormwater inflows into the sewer system are demonstrated in this figure (Schilperoort *et al.*, 2013).

DTS method can also be in the classification of quantified methods. This method can quantify I/I in the sewer system by assuming that I/I has a different temperature and volume (T_2, V_2) from the in-sewer water in the sewer system (T_1, V_1) (Figure 6). The mixture has a new temperature and volume (T_3, V_3). By the help of the laws of conservation of energy ($V_1T_1 + V_2T_2 = V_3T_3$), conservation of mass ($V_1 + V_2 = V_3$), and in-sewer temperature changes ($\Delta T = T_3 - T_1$), the volumetric ratio of I/I (V_2) and in-sewer water before infiltration (V_1) will be derived (Schilperoort, 2011).

$$\frac{V_2}{V_1} = \frac{\Delta T}{(T_2 - T_1) - \Delta T}$$

(Eq. 4)

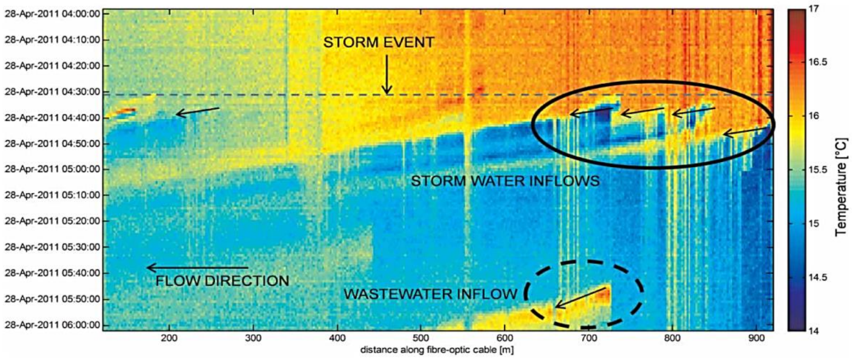

Figure 5. DTS monitoring results in a foul sewer (Schilperoort, 2011).

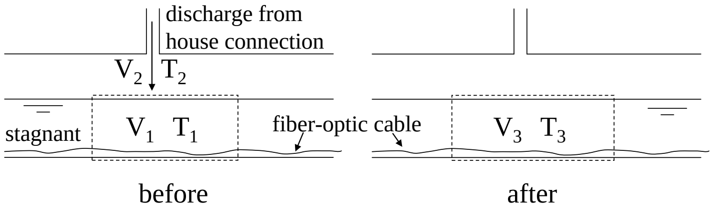

Figure 6. Different temperature and volume of in-sewer water before and after (T_1, V_1; T_3, V_3) mixing with I/I (T_2, V_2) (Schilperoort, 2011).

CCTV for Inspection of sewer network

Pipe inspection is crucial for the choice of the rehabilitation method, for instance, full replacement or a no-dig solution (Sægrov, 2014). Pipe inspection by Closed Circuit Television (CCTV) is a traditional and useful tool to detect and localize pipe defects and their types, misconnections and illicit connections, and I/I sources in the sewer systems (Tuomari and Thompson, 2003). However, the probability of finding the faulty connections from households to storm sewers by this method is low because of not having continues discharges from these misconnections (Hoes *et al.*, 2009). Nevertheless, this method can give important information about the severity and position of I/I sources and together with other tools provide a good basis for rehabilitation.

Comparison & Discussion

Various methods can be used currently for localization and quantification of I/I into the sewer system. The advantages and limitations of the presented infiltration/inflow assessment methods are summarized in Table 1. A combination of using these techniques can provide the possibility to compare different technologies and reduce assumptions and uncertainties in assessing and localizing I/I in the sewer system in a standardized way and support the decision-makers in maintenance and rehabilitation plans with more independent, accurate and reliable data.

In Trondheim city, a combination of these methods is planned to apply for quantification and qualification of I/I in separate sewer systems. Analyzing the gained results from different methods will help in reducing the uncertainties and assumptions and obtaining more accurate and reliable data and knowledge about the sewer system. This approach can be outlined in different steps for I/I control in Trondheim:

1. Flow measurement in sub-catchment (overview of situation)
2. Tracer methods in several locations for determining local sites of infiltration
3. DTS method to detect I/I sources
4. CCTV inspection and smoke testing to identify problems in detail.

Table 1. Advantages and limitations of different methods in assessing infiltration and inflow in sewer systems.

Classification	Method	Advantages	Limitation
Quantitative methods	Flow rate measurement	Simple method	Based on simplified assumptions
		Widely-used method	Inaccurate results
	Stable isotopes method	Do not introduce radioactive or chemical contaminants into the environment (Koeniger *et al.*, 2009)	Drinking water and groundwater should have homogenous but distinct isotopic signatures (Ellis and Bertrand-Krajewski, 2010)
		Cause less disturbance and environmental impact than tritium, salts or dye tracers (Koeniger *et al.*, 2009)	Components of drinking water and groundwater sources should interact (Ellis and Bertrand-Krajewski, 2010)
			Inhomogeneity of the local groundwater or other origins of parasitic waters is crucial (Ellis and Bertrand-Krajewski, 2010)
			Comprehensive hydrologic and hydrogeological investigation (Ellis and Bertrand-Krajewski, 2010)
			Definable, accessible for sampling, and precise statistically describable 'infiltration main source' (Ellis and Bertrand-Krajewski, 2010)
	Pollutant time series method	Flexible infiltration measurements (Ellis and Bertrand-Krajewski, 2010)	Preparation of the experimental team (Ellis and Bertrand-Krajewski, 2010)
		Automatically-operating in-line devices for obtaining pollutant concentration (Ellis and Bertrand-Krajewski, 2010)	Local boundary conditions at the investigation site (flow condition, accessibility) (Ellis and Bertrand-Krajewski, 2010)
		Wide practical applicability with considering natural storage and interflow phenomena (Ellis and Bertrand-Krajewski, 2010)	In the case of using submersible UV-VIS spectrometer, bias-, and drift-free operation is required (Ellis and Bertrand-Krajewski, 2010)
		Simplifying measurements in rainy seasons, when infiltration increases due to elevated groundwater (Ellis and Bertrand-Krajewski, 2010)	Time-consuming and expert-oriented measurement
Qualitative methods	Smoke Testing	Inexpensive method	Not a very accurate method (Schwindamann, 2008).
		relatively easy method	Don't find all the infiltration points (Schwindamann, 2008)
		Environment-friendly method	A television camera is needed for monitoring the network (Schwindamann, 2008).
		No need to restricted space entry	
	Dye Testing	Inexpensive method	Difficult to see dye in high-flow or turbid conditions
		Relatively easy method	Time-consuming in low flows
		Points to a specific source	Entering a facility is necessary
		No need to restricted space entry	Rather labour-intensive
			Require entrance onto private premises
	DTS Method	Source of unwanted water localized exactly (Schilperoort and Clemens, 2009; Langeveld *et al.*, 2012)	High initial cost of the DTS device
		Takes place in the public part of the system and without the residents of the area involved (Schilperoort and Clemens, 2009)	Expert-oriented method in non-automated process (Vosse *et al.*, 2013)
		Safer results compared to more traditional research (Schilperoort and Clemens, 2009; Langeveld *et al.*, 2012)	Almost new technique with low experience in sewer systems
		Large areas –up to several hundred- can be examined and monitored simultaneously	Results are by nature not-easily-reproducible (Vosse *et al.*, 2013)
		Use of single instrument in an easy and safe location	Performance of stormwater separating manifolds varies over time & making them unreliable (Langeveld *et al.*, 2012)
		set-up is easy in use and nearly free of maintenance	Time-consuming method
	CCTV method	Effective technique	Expensive
		Inspection of active taps	Ineffective if inactive taps convey illicit discharges (Tuomari and Thompson, 2003)
		Provide observations record	time-consuming to interpret results (Tuomari and Thompson, 2003)
		Only way for pipe inspection between manholes	Conducted in water-filled or obstructed sewers

Conclusions

I/I of stormwater and groundwater into the sewer system is a serious concern in the long term. The purpose of this paper is to present and discuss different qualitative and quantitative methods in assessing and detecting I/I into the sewer system in the long term by rehabilitation plans. Each of these methods is based on some assumptions and has its own limitations and advantages. There is no unique and standard way of evaluation and localization of I/I in the sewer systems and a combination of these methods can be valuable for reducing assumptions and uncertainties and obtaining more independent, accurate and reliable data about location and magnitude of I/I in the sewer system. A combination of quantitative and qualitative methods will be utilized in localizing and assessing of I/I in the foul sewer systems of Trondheim, Norway. This gives sewer operators the possibility to compare different technologies in assessing infiltration/inflow in the sewer system in a standardized, qualified and quantified way. Use of these I/I assessment methods can support the decision-makers on when and where to rehabilitate, depending on the selection criteria. The application of different methods for evaluating infiltration in sewer systems depends on available data and resources. It should also be considered that an uncertainty assessment should be carried out when various methods are used. Comprehensive and detailed understanding of the locations of any excess water inflow or the illicit connections is necessary for the efficient restriction and removal of infiltration/inflow in the sewer systems. Some infiltration/inflow assessment methods, e.g. tracer method, can be quite labor-intensive and may require entrance onto private premises, while inflows are often only detected by chance. DTS method, smoke testing, and CCTV inspection are the qualitative methods, which are planned to apply in separate foul sewer network of Trondheim. Detecting infiltration/inflow into sewer system by fibre-optic DTS method is a rather new technique in sewer systems. DTS technique is a strong technique for detecting illicit connections to storm sewers, and detecting stormwater entering foul sewers based on previous experiments and researches. Furthermore, the continuous monitoring in time and space makes the DTS a powerful method for investigating flows with different temperatures. Pipe inspection by CCTV is also a useful tool in the case of detecting defects, their features and locations by video camera inspection.

7. OPERATIONAL PLANNING (PUBLICATION III)

The following publication *Detection of extraneous water ingress into the sewer system using tandem methods- A case study in Trondheim City*, written by Maryam Beheshti and Sveinung Sægrov, was published in 15 January 2019 in the Jornal of water science and technology, Volume 79, Issue 2. DOI: https://doi.org/10.2166/wst.2019.057**.**

Detection of extraneous water ingress into the sewer system using tandem methods- A case study in Trondheim City

Maryam Beheshti* and Sveinung Sægrov

Department of Civil and Environmental Engineering, Norwegian University of Science and
Technology (NTNU), Trondheim, Norway
* Email: maryam.beheshti@ntnu.no

Abstract: Infiltration and inflow (I/I) of extraneous water in separate sewer systems are serious concerns in urban water management for their environmental, social and economic consequences. Effective reduction of I/I requires knowing where excess water ingress and illicit connections are located. The present study focuses on I/I detection in the foul sewer network of a catchment in Trondheim, Norway, during a period without snowmelt or groundwater infiltration. Fiber-optic distributed temperature sensing (DTS) was used for the first time in Norway to detect I/I sources in tandem with closed-circuit television inspection (CCTV) and smoke testing. DTS was an accurate and feasible method for I/I detection, though it cannot identify exact types of failure and sources of I/I. Therefore, other complementary methods must be used, *e.g.*, CCTV or smoke testing. CCTV was not completely useful, however, in confirming the DTS results. This study provides practical insights for the rehabilitation and repair of sewer networks that suffer from the undesirable I/I of extraneous water.

Keywords: Distributed temperature sensing (DTS); CCTV; infiltration and inflow (I/I); separate sewer system; smoke testing, sewer infrastructure asset management

Introduction

Separate sewer networks efficiently and reliably convey foul sewage to wastewater treatment plants. However, large volumes of unwanted water infiltration and inflow (I/I) can pose serious management challenges. I/I from extraneous water and illicit connections can overload the sewer system, cause sanitary sewers to overflow, threaten public health, and increase energy and chemical consumption during treatment while decreasing overall treatment efficiency (Beheshti & Sægrov 2018a). This specific concern threatens sustainable asset management of sewer infrastructure in the long term and reduces environmental, social and economic sustainability (Beheshti *et al.* 2015; Beheshti & Sægrov 2018a).

The efficient reduction and removal of unwanted water from sewer systems require comprehensive and detailed understanding of I/I from illicit connections and extraneous water sources (Beheshti *et al.* 2015). Illicit connections, including unintended sewer cross-connections, are a major problem in separate sewers because sewage contaminates the storm sewers and stormwater can overload the foul sewers (Hoes *et al.* 2009; Beheshti & Sægrov 2018a). Extraneous water also contributes to I/I and includes stormwater, groundwater, and drainage water (Hoes *et al.* 2009).

In Trondheim, Norway (~200,000 residents), the sewer network includes both combined and separate sewers; about 52% of the total network is currently a separate system (Beheshti & Sægrov 2018b). A water balance of Trondheim's wastewater system from 2009 to 2011 indicated that extraneous water via I/I was about 46% of total water delivered to the wastewater treatment plant during dry weather conditions (Beheshti & Sægrov 2018b). This significant amount of unwanted water can increase even more during wet weather, so Trondheim municipality has made solving this problem a high priority.

There are no defined standards for detecting or locating I/I sources in sewer systems, though both conventional and high-tech techniques are being used, such as smoke testing, dye testing, closed-circuit television camera (CCTV), electro-scan and distributed temperature sensing (DTS) (Tuomari & Thompson 2003; Schilperoort *et al.* 2013; Beheshti *et al.* 2015). There are limitations to the common methods of I/I detection (*e.g.,* dye testing), such as being labour intensive, requiring entrance into private premises and introducing environmental risks, in addition to high uncertainty to identify I/I sources (Hoes *et al.* 2009; Schilperoort *et al.* 2013; Beheshti *et al.* 2015). Smoke testing is another practical and reliable method for finding misconnections from stormwater outlets in separate foul sewers. Smoke is injected into the foul sewer system, and in the case of any defect or misconnection in the sewer network, the smoke leaks out, signaling the location of I/I sources (Hoes *et al.* 2009; Beheshti *et al.* 2015). CCTV is also commonly used for finding illicit connections, cracks, and problematic part of the network. In this method, the sewer network is inspected by a sewer operator, who receives live footage inside the pipeline via a moving robot with attached CCTV camera. However, because of intermittent discharges from households, the chance of finding illicit connections with CCTV in storm sewers is low, making the results imprecise and inaccurate (Hoes *et al.* 2009).

Modern and high-tech I/I detection methods, such as DTS and electro-scan, have high accuracy and low environmental risks, in addition to requiring less analytical effort (Beheshti & Sægrov 2018a). Electro-scan is a new technique in sewer monitoring based on measuring the electrical resistance of the pipe wall. The principle behind this method is that the electricity flows through pipe defects and the electrical resistance indicates where there is water leakage (Harris & Dobson 2006; Tuccillo *et al.* 2011). Fiber-optic DTS was developed in the 1980s for telecommunication (Dakin *et al.* 1985; Tyler *et al.* 2009; Vosse *et al.* 2013). The method became widely applicable in different fields, such as for leakage control in the oil, gas and dam industries (Johansson 1997; Vosse *et al.* 2013) as well as for hydrologic applications (Selker *et al.* 2006; Westhoff *et al.* 2011), soil moisture studies (Jansen *et al.* 2011; Ciocca *et al.* 2012), power transmission (Yilmaz & Karlik 2006; Shen *et al.* 2016), air temperature measurement (Petrides *et al.* 2011; de Jong *et al.* 2015) and vegetation coverage in forests (Krause *et al.* 2013). DTS has been applied in urban sewer systems for pipeline monitoring and I/I detection since 2009 (Pazhepurackel 2009; Schilperoort & Clemens 2009). The principle of I/I detection in DTS is based on analysis of thermal behavior of sewage along a fiber-optic cable installed in the sewer network (Beheshti & Sægrov 2018a).

This study aimed to locate I/I sources from illicit connections and extraneous water into a foul sewer network by various techniques in tandem. Combining different detection methods reduces uncertainties and inaccuracies. DTS was used for the first time in Norway and was complemented by CCTV and smoke testing to detect I/I in the separate foul sewer network of the Lykkjbekken catchment (Trondheim). This study demonstrated that DTS in combination with supplemental methods is effective at locating individual I/I sources in sewer pipelines. By precisely identifying these sources, the municipality can prioritize rehabilitation and spot repairs, efficiently decreasing unwanted water ingress into the sewer system.

Material and Methods

DTS technology

Distributed temperature sensing (DTS) is a high-tech monitoring technique for detecting I/I sources from illicit connections and extraneous water in sewer networks (Pazhepurackel 2009; Schilperoort & Clemens 2009). This method is based on continuous temperature measurement along the fiber-optic cable in the wastewater network, up to several kilometers (Beheshti & Sægrov 2018a). Potential I/I sources can be located precisely by monitoring and analyzing the thermal behavior of sewage, so long as I/I water differs in temperature (Schilperoort, 2011; de Jong *et al.* 2015; Beheshti & Sægrov 2018a). However, this technology has some limitations, such as high initial costs of the instrumentation and installation, and requiring a high-skilled operation.

The temporal resolution of DTS measurement is normally in the range of 18–60 s and the spatial resolution is 0.5 to 2 m, with thermal accuracy of ±0.1 to 0.2°C (Hoes *et al.* 2009). DTS can be used in public parts of the sewer network without requiring entry to private premises. DTS uses mounted fiber-optic cables in the sewer pipeline and a control unit that consists of a laser instrument, an optoelectronic sensor and a computer (Beheshti & Sægrov 2018a). Figure 1 demonstrates the standard layout of the method.

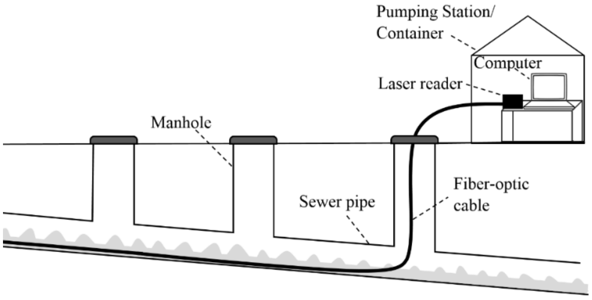

Figure 1. Schematic outline of the DTS method in a sewer pipe and the control unit stored outside the sewer system in pumping station (Beheshti & Sægrov 2018a).

Smoke testing

Smoke testing is a practical method to detect, identify and classify potential sources of I/I in a wastewater collection system, especially in detecting misconnected stormwater drains and outlets in separate foul sewers (Hoes *et al.* 2009; Beheshti *et al.* 2015). In this method, vegetable-based smoke, produced by a smoke generator, is injected into isolated parts of the sewer network, where I/I is suspected. The smoke, which tends to escape through openings and vents, pinpoints I/I sources in the separate sewer network (Figure 2).

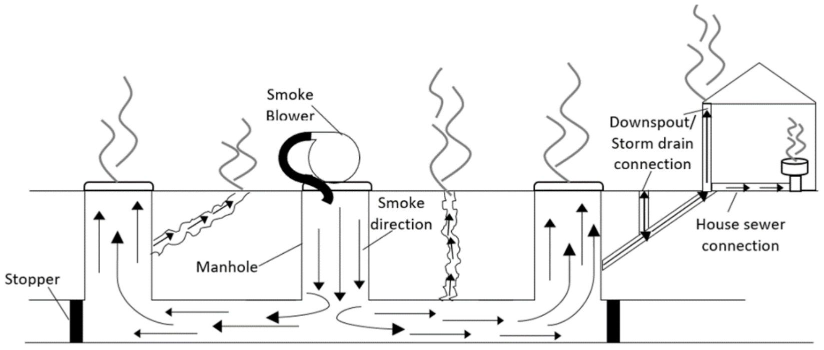

Figure 2. Schematic outline of the smoke testing process to find potential sources of I/I in a foul sewer system (Beheshti *et al.* 2015).

Smoke testing is a practical method for finding the misconnected storm drains connected to separate sanitary sewers. This method is not feasible in finding all types of I/I sources in sewer networks, however, it can be effective in combination with other I/I detection techniques.

CCTV method

CCTV is a common method in sewer maintenance to inspect and assess the status of the wastewater network. In this method, a remote-control, closed-circuit video camera is inserted into the sewer network through a manhole and moves inside the sewer network by a small robot, allowing the operator to inspect the network and detect problematic parts via real-time visual inspection. However, it is difficult to detect all illicit connections from foul sewage outlets into the storm sewers when there is no continuous flow from households. (Hoes *et al.* 2009). Additionally, the method is based on visual inspection, and there is the possibility of over- or under-estimating the status of the network due to operator errors and invisible defects in the pipeline. Another drawback of CCTV in detecting I/I sources is its dependence on the presence of rainfall or a high groundwater table.

Case study

The study area for the present study was Lykkjbekken catchment in Trondheim, which is located near the main water source of the city, Lake Jonsvatnet (63°22'46"N 10°32'35"E - 63°21'47"N 10°29'16"E; see Figure 3a). Lykkjbekken catchment is a rural area, and the studied sewer section covers an area of around 10 km^2 with ~ 200 inhabitants. The catchment has a separate foul sewer system consisting of a pumping station and small PVC pipelines (160 mm internal diameter). The wastewater network was prone to high volumes of extraneous water I/I from unknown sources particularly during rainfalls, due to the increased water level in the pumping station that was likely to be from infiltration. However, the sewer network inspection by CCTV during the spring 2015 with high groundwater table did not detect any pipe defect or groundwater infiltration in the under study sewer network. The I/I of unwanted water increased the probability of overloading the system, especially in wet seasons, and magnified the risk of contaminating the drinking water source due to sewer overflow from the pumping station. Therefore, DTS was applied to monitor the sewer network and detect I/I sources, especially the rainfall-derived infiltration and inflow sources.

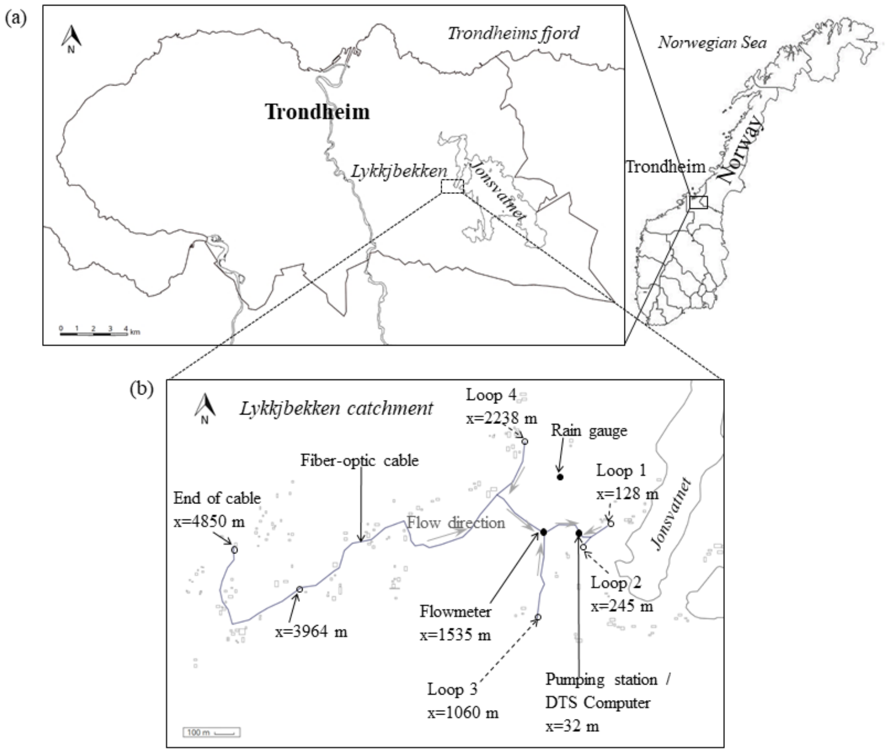

Figure 3. a) The location of Lykkjbekken catchment in Trondheim, Norway, b) DTS cable installation in Lykkjbekken catchment.

The fiber-optic DTS cables were installed in the separate foul sewer of Lykkjbekken catchment over a length of 4.8 km (see Figure 3b). The monitoring campaign was from August 23 to November 20, 2015, while an in-sewer temperature measurement with a resolution of 0.01℃ was recorded every 18 s for each 50 cm interval of the cable. The DTS computer and laser reader was a Yokogawa DTSX3000 unit, stored outside the sewer network in the pumping station, and was connected to one end of the cable downstream of the sewer network. For monitoring several sewer sections simultaneously with a continuous monitoring system, the cable was looped into and then out of pipeline branches at four locations (Figure 3b). As a consequence of these loops, the temperature was recorded twice, effectively providing replicate temperature measurements at the four pipeline branches.

Precipitation and temperature measurement

Precipitation measurement is a key parameter for assessing rainfall-derived I/I in separate sewer networks (Beheshti & Sægrov 2018a). To assess the impacts of rain and stormwater into the sewer network, a tipping bucket rain gauge with the standard resolution of 0.2 mm was installed in the catchment to record precipitation during the monitoring campaign.

Air temperature and the presence of snow in the catchment affects the thermal behavior of the sewer network. Several hydrological studies in runoff and stream water temperature have found that the air-water temperature relationship can be modeled with an S-shaped, non-linear regression, which is linear for air temperatures of 0 to 20℃ (Stefan & Preud'homme 1993; Mohseni & Stefan 1999; Webb *et al.* 2008; Ficklin *et al.* 2012). Rainfall-derived I/I has a similar temperature to ambient air temperature and can therefore be modeled using the linear regression (Beheshti & Sægrov 2018a). However, in the presence of snow, the temperature of the extraneous water from the snowmelt runoff can be set to 0.1℃ (*i.e.*, just above the freezing point of water), regardless of the ambient air temperature (Ficklin *et al.* 2012; Beheshti & Sægrov 2018a).

Results and Discussion

The performance of the foul sewer system of Lykkjbekken catchment in Trondheim was assessed for detection of rainfall-derived I/I sources and illicit connections by various methods. An initial CCTV inspection was conducted in the network, and no defects in the pipeline were detected. Afterward, the sewer network was monitored by DTS while there was no snowmelt or groundwater inflow. DTS technique was used during both wet and dry weather conditions to investigate the effects of extraneous water and illicit connections on the thermal behavior in the sewer system and locate I/I sources. The case study was located in a catchment with low wastewater flow and high probability of sedimentation of debris and toilet papers on the fiber-optic cables. Therefore, maintenance of the installed cables was important to avoid any blockage by carrying out regular sewer flushing during the monitoring campaign (Beheshti & Sægrov 2018a).

Figures 4 and 5 display the DTS monitoring data during storm events on August 27–28 and November 11, 2015, respectively. In these heat-maps, the vertical axis presents the time and the horizontal axis demonstrates the length of 'x' along the fiber-optic cable from x=32 m, where the cable enters the sewer system, to the end of the cable at x= 4850 m. The fiber-optic cable acts as a linear temperature sensor and measures the temperature during the monitoring campaign with spatial and temporal resolutions of 0.5 m and 18 s, respectively. Each pixel in these graphs represents a recorded temperature for a single spot and time along the cable. The recorded temperatures (℃) are colored according to the color gradient on the right side of the DTS monitoring graph. Precipitation and air temperature were measured simultaneously to control for their effects on I/I. The flow direction is generally from right to left, except in the replicated sides of loops at the four pipeline branches.

By analyzing the sewage thermal behavior during wet conditions after the start of rainfall in Figures 4 and 5, the I/I locations experienced unexpected temperature changes. The abrupt thermal changes at locations x=3964 m, 128 m and 245 m on the cable can be associated with stormwater inflow. However, x=128 m and 245 m were located at loops 1 and 2, where the cable did not continue upstream; the I/I could therefore be caused by stormwater inflow where there was no cable present.

The inflows into the sewer network with different temperatures than the in-sewer wastewater can be detected in DTS monitoring graphs as sudden thermal changes. The heat spread is quite visible along the wastewater flow and illustrated by some arrows in Figures 4 and 5. The gradient of the arrows changes due to the velocity, volume, and temperature of the in-sewer wastewater and external inflows. Additionally, the larger the time horizon is, the steeper is the arrow (Figure 4a), and in the higher time resolutions, the thermal diffusion of the inflows are indicated by lower gradients (Figure 4b).

The DTS results in Figure 4 demonstrated an increase in the downstream temperatures of potential I/I locations (x=3964 m, 245 m and 128 m), relative to their upstream temperature after a heavy rainfall began on August 27, 2015. However, in the rainfall on November 11 (Figure 5), the potential I/I locations experienced a decrease in sewage temperature. This can be justified by comparing the temperatures of air and wastewater. Figure 6 presents the time transect of x=3964 m during the rainfall on November 11, 2015. Temperature variations in upstream and downstream of that point illustrate the impacts of rainfall-derived I/I and air temperature on thermal behaviors of the sewer network in a linear graph.

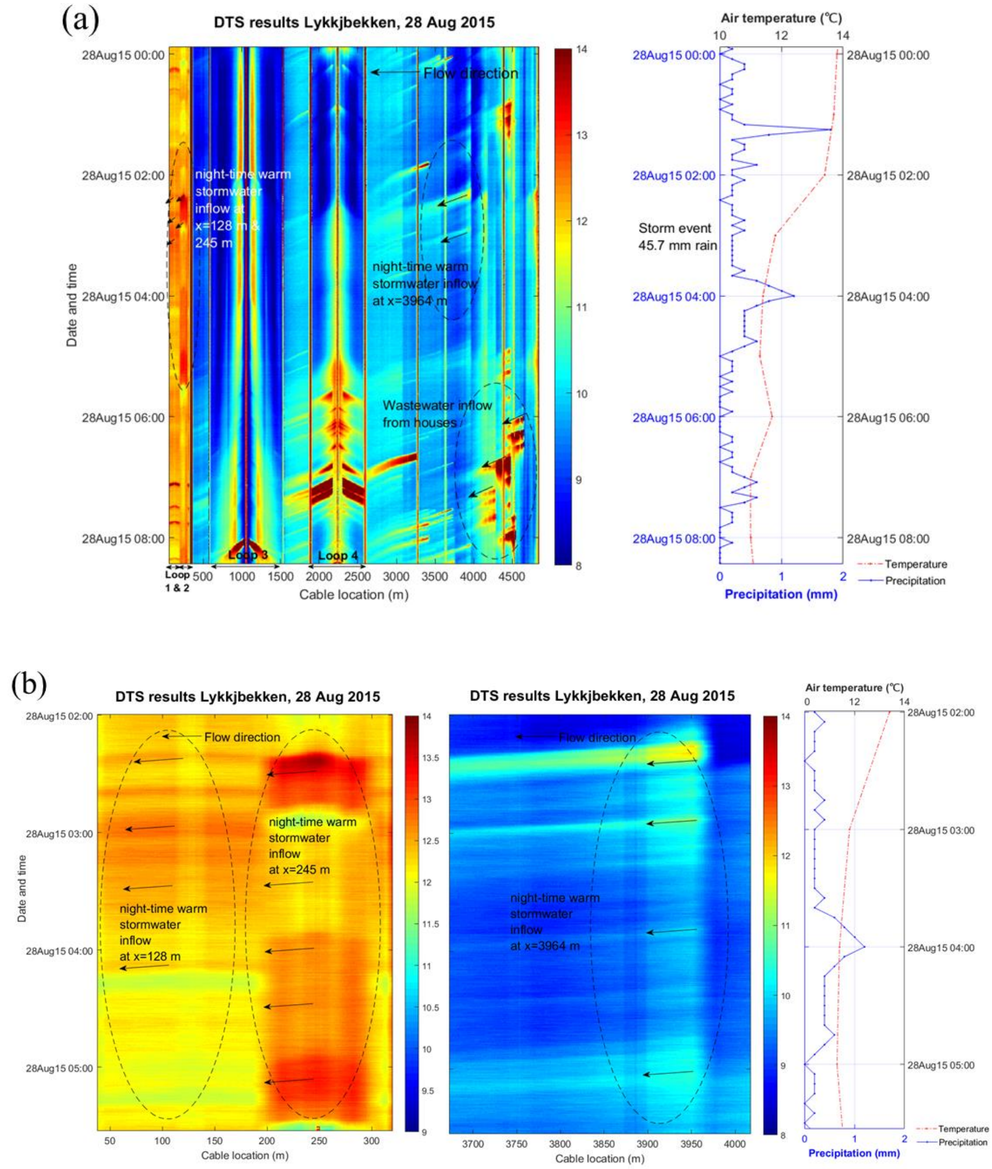

Figure 4. a) DTS monitoring results in foul sewer network of Lykkjbekken catchment (left), with 5 min precipitation and hourly temperature data (right) 27–28 August, 2015, and b) a closer view of rainfall-derived I/I at x=128 m and 245 m (left) and x=3964 m (middle), with 5 min precipitation and hourly temperature data (right). Color-gradient scales indicate temperature (°C).

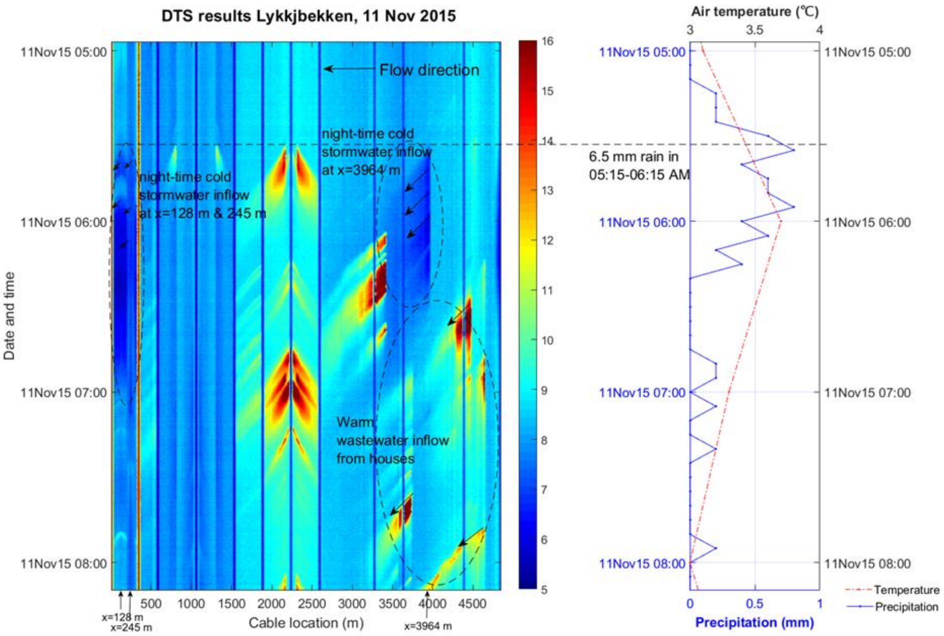

Figure 5. DTS monitoring data in foul sewer network of Lykkjbekken catchment (left), with 5 min rainfall depth and hourly temperature data (right) for November 11, 2015. Color-gradient scales indicate temperature (°C).

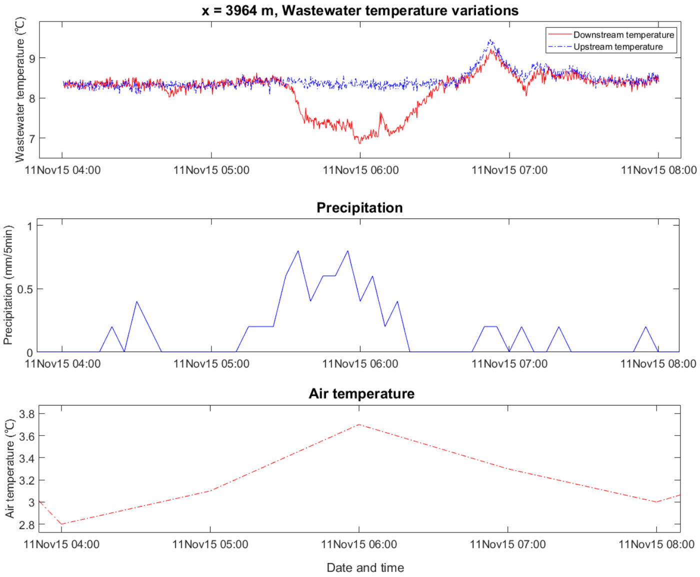

Figure 6. Time transect of wastewater temperature variations in upstream and downstream of a rainfall-derived I/I source in x=3964 m in addition to rainfall intensity, and air temperature on November 11, 2015.

The corresponding rainfall-derived I/I on August 27, 2015 (Figure 4) occurred during a night with the air temperature of 12–19°C, which was warmer than the sewage temperature (~8°C). Because rainfall-derived I/I has a similar temperature to air temperature when there is no snow in the catchment, the I/I increased water temperatures in the sewer. In contrast, rainfall-derived I/I on November 11, 2015 (Figure 5) coincided with a cold night (~3°C), and the corresponding I/I was colder than the wastewater (8°C). Thus, temperature of rainfall-derived I/I water can be either lower or higher than the wastewater, depending on ambient air temperature.

DTS locates the problematic parts of the network but is not practical to identify potential I/I sources. Therefore, supplemental methods are needed to inspect locations with I/I. In this study, a CCTV inspection was conducted to inspect and verify the results from DTS. However, this inspection was not helpful in verifying the sources of I/I. Therefore, smoke testing was used to inspect potential problems detected by DTS. In this case, the smoke identified misconnected downspouts (yard and roof drain) at x=3965 m and 128 m as sources of I/I. Location x=245 m was placed on loop 2, and the inflow could be caused by stormwater upstream of that point, where no fiber-optic cable was installed. CCTV was not effective in detecting the misconnected storm drain outlets, as they were connected to foul sewers as house connections and could not be identified via camera inspection.

After finding and identifying the I/I sources, it is important to prioritize them for rehabilitation by assessing their severity. In misconnected storm drains to sanitary sewers, this can be estimated roughly by comparing the size of the impervious areas connecting to storm drains. However, this method is not so precise and is not applicable in all types of I/I sources, and therefore a more accurate method is needed. To accurately quantify the unwanted water I/I from individual sources, the thermal behavior of wastewater and unwanted water I/I should be analyzed by the help of conservation of mass and energy, which was described in detail in an article by Beheshti & Sægrov 2018a.

In general, DTS technology is an accurate and applicable method for sewer monitoring and I/I detection. Continuous sewage temperature measurement over long periods gives the possibility to monitor thermal behavior in the sewer network under different conditions and locate potential I/I sources from groundwater, rainfall, snowmelt, and illicit connections. Furthermore, the frequency of sporadic I/I failures in pipelines can be detected with long-term temperature monitoring, which is an important factor in evaluating pipeline needs and determining I/I rehabilitation measures (*e.g.*, spot repair, renovation or replacement). Though DTS is feasible and has advantages over alternative methods for detecting I/I, there is a high initial cost for instrumentation and installation. Furthermore, expert technicians are required for installation, operation and data analysis. Therefore, further development is necessary to make DTS a practical and widely available method for sewer monitoring.

Conclusions

In this study, the DTS technique was applied for the first time in Norway in tandem with CCTV and smoke testing to detect I/I sources in a separate sewer network. The application of DTS in the Lykkjbekken catchment in Trondheim was demonstrated to be a strong and feasible method for I/I detection. DTS detected three more I/I sources than CCTV. Smoke testing confirmed the DTS results by identifying illicit stormwater connections from downspouts in two of the I/I sources.

Rainfall-derived I/I affects the thermal behavior of sewage to a great extent. Rainfall inflows coinciding with warm days (relative to in-sewer water) can be detected as warm spills into the sewer networks, while cold I/I correspond to rain events on cold days. Therefore, assessing the surrounding air temperature is essential in similar studies.

After detecting the I/I sources, their status and severity can be assessed to prioritize them in sewer rehabilitation plans. In misconnected storm drains, this can be roughly evaluated by comparing the size of the impervious areas connecting to misconnected storm drains. However, analyzing the thermal variations of the wastewater in I/I locations is an accurate way to quantify all types of I/I in the sewer network and assess the status of individual I/I sources (Beheshti & Sægrov 2018a).

This case study provides sewer operators a framework for identifying problematic parts of a pipeline and make smart decisions (*i.e.,* spot repairing, renovation or full replacement of the sewer pipeline). Identifying and remedying I/I sources decreases extraneous water in the sewer system, which is essential for sustainable sewer asset management. However, DTS is a semi-commercial technique with the high initial cost and requirements to expert installation and operation, so improvements are necessary before the method becomes more practical and widely accessible for I/I assessment.

Acknowledgment

The authors acknowledge the wastewater department of Trondheim Municipality, as well as its personnel, especially Kristin Greiff Johnsen and Vidar Figenschou for their support. Thanks also to Remy Schilperoort, Cornelis de Haan and Erik Liefting at PARTNERS4URBANWATER for their invaluable advice and cooperation. The authors are also grateful to Michael Waak at NTNU for his valuable help and comments.

8. OPERATIONAL PLANNING (PUBLICATION IV)

The following publication *Quantification Assessment of Extraneous Water Infiltration and Inflow by Analysis of the Thermal Behavior of the Sewer Network*, written by Maryam Beheshti and Sveinung Sægrov, was published in 10 August 2018 in Water Journal, Volume 10, Issue 8, DOI: https://doi.org/10.3390/w10081070.

This article belongs to the Special Issue Technologies and Interventions to Support Sustainable Urban Water Management.

Quantification assessment of extraneous water infiltration and inflow by analysis of the thermal behavior of the sewer network

Maryam Beheshti* and Sveinung Sægrov

Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), N-7491, Trondheim, Norway
*Correspondence: maryam.beheshti@ntnu.no; Tel.: +47- 405-41-549

Abstract: Infiltration and inflow (I/I) of unwanted water in separate urban sewer networks are critical issues for sustainable urban water management. Accurate quantification of unwanted water I/I from individual sources into a sewer system is an essential task for assessing the status of the sewer network and conducting rehabilitation measures. The study aim was to quantify extraneous water I/I into a sanitary sewer network by a temperature-based method, i.e., fiber-optic distributed temperature sensing (DTS), which was applied for the first time in a separate sewer network of a catchment in Trondheim, Norway. The DTS technology is a relatively new technology for sewer monitoring, developed over the past decade. It is based on continual temperature measurement along a fiber-optic cable installed in the sewer network. The feasibility of this method has been tested in both experimental discharges and for the rainfall-derived I/I. The results achieved from the monitoring campaign established the promising applicability of the DTS technique in the quantification analysis. Furthermore, the application of this method in quantifying real-life, rainfall-derived I/I into the sewer system was demonstrated and verified during wet weather conditions.

Keywords: distributed temperature sensing (DTS); extraneous water Infiltration and Inflow (I/I); rainfall-derived Infiltration and Inflow; sewer system; stormwater management; sustainable urban water management

Introduction

Urban sewer systems are one of the most important city lifelines, conveying wastewater and stormwater to treatment plants. Representing a high asset value (Beheshti and Sægrov, 2018c), urban sewer systems in most cities all over the world are undergoing deterioration due to aging (Rehan *et al.*, 2014). Thus, accurate monitoring, maintenance and rehabilitation are necessary for their preservation. However, their underground location makes it difficult to monitor and understand their status. Infiltration and inflow (I/I) of unwanted water into separate sewer networks are significant challenges in urban sewer systems. Answering questions about location and magnitude of unwanted water intrusion is essential for understanding the sewer network performance for sustainable urban water management.

I/I of unwanted water into separate sewer networks have negative outcomes on social, environmental and economic aspects of sustainable urban wastewater management, as well as on chemical and energy resources. These undesirable phenomena trigger overloading of sewer networks and wastewater treatment plants. Moreover, I/I increase the risk of local flooding and sanitary sewer overflow in urban areas, while escalating pumping operation time. All of these consequences are followed by diminished performance of sewer systems and amplified costs, energy consumption, maintenance and operation, and negative urban and environmental issues (Ellis and Bertrand-Krajewski, 2010; Schilperoort *et al.*, 2013; Beheshti, Sægrov and Ugarelli, 2015; Zhang *et al.*, 2018)

In general, I/I from extraneous and illicit water are equal to ~50% of the wastewater volume (Langeveld *et al.*, 2012; Beheshti, Sægrov and Ugarelli, 2015). Extraneous water refers to I/I from rain-induced infiltration, direct stormwater inflow, groundwater infiltration, drain water, leakages from the drinking water network and other extraneous sources in separate sewer systems(Hoes *et al.*, 2009; Staufer, Scheidegger and Rieckermann, 2012; Zhang *et al.*, 2018) , which may include illicit and faulty cross-connections between stormwater outlets and the wastewater system (Hoes *et al.*, 2009; Schilperoort *et al.*, 2013) . In some cities, extraneous water can even exceed the wastewater volume (Ellis and Bertrand-Krajewski, 2010). Therefore, it is important to perform rehabilitation measures to manage and control this issue.

There are various conventional and innovative techniques available for I/I measurement in sewer systems, such as the flow-rate measurement and tracer methods (Ellis and Bertrand-Krajewski, 2010; Beheshti, Sægrov and Ugarelli, 2015) . The flow-rate measurement is a method based on analyzing the water balance and diurnal flow rate in dry weather conditions and assigning the minimum nighttime flow as the I/I-related flow (Kracht, Gresch and Gujer, 2007; Beheshti, Sægrov and Ugarelli, 2015; Zhang *et al.*, 2018) However, this method can be inaccurate due to sewer overflow in overloaded systems (Zhang *et al.*, 2018). Furthermore, the assumption of having no flow during nighttime, the omission of sewer network exfiltration, and instrumental errors during flow measurement—especially in shallow wastewater flows—makes the flow-rate measurement method unreliable. Tracer methods, e.g., pollutant indices, the stable isotopes method, and chemical tracers, are other I/I measurement methods in sewer systems. The pollutant indices methods are based on analyzing the in-sewer pollutant time series, such as chemical oxygen demand, total nitrogen and total phosphorus, for evaluating the I/I volume (Kracht and Gujer, 2005; Zhang *et al.*, 2018)Alternatively, stable isotopes of water molecules ($\delta^{18}O$ and $\delta^{2}H$) can be used as natural tracers for assessing the I/I into the sewer networks (Kracht, Gresch and Gujer, 2007; Beheshti, Sægrov and Ugarelli, 2015)These tracer-based methods can provide accurate I/I assessments but require intensive field measurement and laboratory analysis, especially in large catchments (Zhang *et al.*, 2018) .

In contrast to the conventional methods, adaptive and innovative I/I detection and measurement techniques like distributed temperature sensing (DTS) may have higher accuracy with fewer environmental risks. The DTS technology is a monitoring technique developed in the 1980s in the UK for testing telecommunication cables (Dakin *et al.*, 1985; Tyler *et al.*, 2009). The technique is based on analyzing system behavior by measuring the temperature along spans of fiber-optic cables over time (de Jong, Slingerland and van de Giesen, 2015). The DTS method has become a broadly applicable technique in different fields, i.e., leakage control in dams and the oil industry, fire control, and pipeline monitoring (Johansson, 1997; Vosse *et al.*, 2013) .

Furthermore, DTS has various applications in the field of water, such as stream hydrology (Selker *et al.*, 2006; Westhoff, M. C.; Savenije, H. H. G.; Luxemburg, W. M. J .; S., Stelling G.; van de Giesen, N. C.; Selker, J. S.; Pfister, L.; Uhlenbrook, 2007; Westhoff, M. C.; Gooseff, M. N.; Bogaard, T. A.; Savenije, 2011), limnology (Vercauteren, N.; Huwald, H.; Bou-Zeid, E.; Selker, J. S.; Lemmin, U.; Parlange, M. B.; Lunati, 2011), groundwater science (Lowry *et al.*, 2007; Henderson, Day-Lewis and Harvey, 2009; Mamer and Lowry, 2013), and urban sewer systems research (Hoes *et al.*, 2009; Schilperoort and Clemens, 2009; Langeveld *et al.*, 2012) . The application of DTS in full-scale sewer systems has been developed since 2009, when Pazhepurackel (2009) and Schilperoort and Clemens (2009) tested this technology in combined sewers (Pazhepurackel, 2009; Schilperoort and Clemens, 2009) . Moreover, this method was applied successfully in separate storm sewers for detecting illicit connections from sanitary sewers (Hoes *et al.*, 2009; Haan de *et al.*, 2011; Langeveld *et al.*, 2012). Schilperoort (2011) has reported the successful application of fiber-optic DTS cables in separate sanitary sewer systems for localizing the extraneous water I/I from stormwater inflow, groundwater infiltration and illicit connections (Schilperoort, 2011). Among different I/I detection methods that has been previously studied by Beheshti et al. (2015) (Beheshti, Sægrov and Ugarelli, 2015), the DTS technology was chosen to be the main focus in the present study.

Over the last decade, the detection of I/I in sewer systems has attracted a lot of attention, while there are few studies on the I/I quantification issue. I/I quantification is a valuable tool for assessing the condition of the sewer network. The aim of this study was to scrutinize and quantify the extraneous water I/I entering the separate sewer systems from individual I/I sources by analyzing the thermal behavior of the wastewater. Therefore, the feasibility of the DTS for I/I quantification was investigated for the first time in a full-scale separate sewer system in Trondheim, Norway. For this reason, experimental artificial inflows with different temperatures and discharges were applied to the measurement campaign. Moreover, to demonstrate the feasibility of this method in the full-scale system, rainfall-derived I/I quantification was applied during wet weather conditions. The results can be used for evaluating the severity of individual I/I sources in each pipe section and decreasing I/I into the sewer system with rehabilitation.

Methodology

Distributed Temperature Sensing (DTS) Technology

Fiber-optic distributed temperature sensing (DTS) is a technology for sewer monitoring, i.e., detecting illicit connections and extraneous water I/I in sewer systems, that has been used over the past decade. The principle of this method is monitoring the thermal changes in the sewer system by temperature measurement up to several kilometers in continuous time along a fiber-optic cable. This method is a combination of installed fiber-optic cables in the sewer network and a control unit that consists of a laser instrument, an optoelectronic sensor and a computer. Figure 1 illustrates the standard layout of the DTS monitoring technique in a sewer network. The laser instrument emits laser pulses continuously into the fiber-optic cable, the optoelectronic sensor reads the backscattered light, and the computer is responsible for interpreting the receiving values to readable data (Hoes *et al.*, 2009; Schilperoort and Clemens, 2009; Tyler *et al.*, 2009). Imperfections along the glass fibers reflect the laser light. The reflection spot of the laser light can be localized as (Hoes *et al.*, 2009; Zhou *et al.*, 2016):

$$L=c\Delta T/2n \tag{1}$$

where

L: the laser light reflection location;
ΔT: laser light reflection duration from the initial time that laser pulses into the cable;
c: the laser light speed in the fiber (~2/3 of the light speed in vacuum);
n: the reflective index of optical fiber.

It should be noted that the laser light reflects back from the location L to the detector and, therefore, the total length of its travel would be $2L$. Furthermore, the spatial accuracy of the reflection spot is $c\Delta T$.

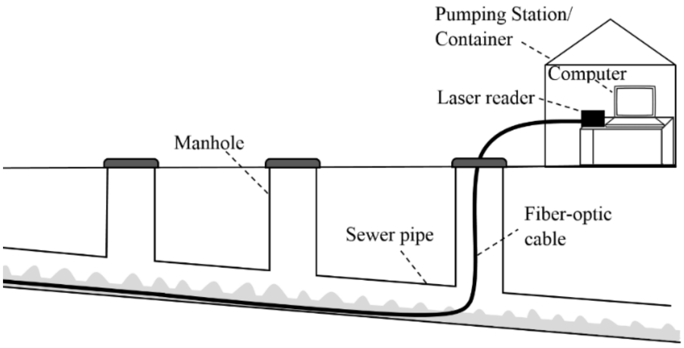

Figure 1. Standard layout of the distributed temperature sensing (DTS) technique in a sewer network and the control unit stored outside the sewer system in a pumping station.

By passing the laser light through the fiber, several mechanisms, such as physical features of the surrounding cable, affect the specifications of the light transmission, and different scatterings with various wavelength and intensity form. This can be interpreted by computer software into physical parameters like temperature for each location along the cable. The most important scatterings are “Raman” and “Rayleigh”, which can be used to plot temperature against distance. Raman light consists of two broadband components, Stokes and anti-Stokes, respectively, at longer and shorter wavelengths than the main source laser light (Hoes *et al.*, 2009). The temperature of each single reflection location is derived from the ratio of thermal-dependent anti-Stokes and thermal-independent Stokes intensities(Lopez-Higuera, 2002; Hoes *et al.*, 2009). The Rayleigh backscatters have the same wavelength as the laser source and provide information about the reflection location by known light speed and measured travel time(Lopez-Higuera, 2002; Schilperoort and Clemens, 2009). The corresponding location of L on the measurement campaign can be defined by using hot water or freeze spray on different locations.

Typically, the DTS system can measure the temperature with time and spatial resolution of 18–60 sec and 0.5–2 m, respectively, along the fiber-optic cable functioning as a linear sensor. It is applicable to have cables anywhere in the network to gain information about the thermal behavior of the sewer system and detect the problematic parts of it. Any changes in the temperature of in-sewer water are recorded, and the exact place of the I/I source can be determined. This method can be used in I/I detection in sewer systems, as long as the infiltrated water has a different temperature than in-sewer water(Hoes *et al.*, 2009; Schilperoort *et al.*, 2013).

The DTS system can be calibrated by putting the fiber-optic cable in a medium with known temperature, e.g., an ice-bath, before installation. For calibration of the cable after installation, the same procedure can be done by reference measurement of more than two calibration sections with a length of at least 10 times the length of the spatial sampling interval coiled cable, which are far from each other (Selker *et al.*, 2006; Tyler *et al.*, 2009). In this method, the accuracy of calibration of a DTS system by standard thermometer measurement can yield up to ± 0.1 °C(Hoes *et al.*, 2009; Schilperoort, 2011). Since the signal attenuation process in the fiber-optic cables is in theory completely log-linear, two temperature-offset measurement may be adequate for the calibration process in normal conditions (Schilperoort, 2011). It is also necessary to do temperature-offset measurements by standard individual thermometers in more than two separated locations along the cable when there are splices and connectors in the cable for calibrating raw DTS data with slope and offset parameters (Schilperoort, 2011). The long-term installation of fiber-optic cables in the sewer network, however, can trigger a drift in measured temperature, which is typically below 1 °C and can increase up to several degrees centigrade(Tyler *et al.*, 2009). In this case, dynamic calibration during the entire installation period with the aforementioned methods is needed to correct the offset and control the drift (Tyler *et al.*, 2009). All these calibration methods were considered in the present study to secure the precision and accuracy of the results.

Infiltration and Inflow Quantification

DTS technology can be used to characterize I/I entering the sewer system; i.e., quantifying the extraneous water volume entering the sewer system. Schilperoort (2011) proposed a theoretical approach for quantifying discharges(Schilperoort, 2011). This approach is based on the assumption of temperature and volume differences between extraneous water I/I (T_2, V_2) and the in-sewer water (T_1, V_1), which results in a new temperature and volume (T_3, V_3) in the mixed flow, assuming instantaneous mixing (Figure 2). The inflow share, which is the ratio of the volume of I/I (V_2) and the upstream in-sewer water (V_1), is calculated by Equation (2) (Schilperoort, 2011). This equation is derived from the conservation laws for energy ($V_1T_1 + V_2T_2 = V_3T_3$) and mass ($V_1 + V_2 = V_3$), as well as the in-sewer wastewater temperature change ($\Delta T = T_3 - T_1$).

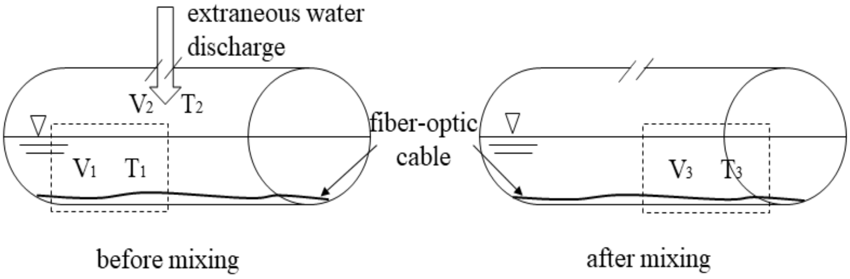

Figure 2. Extraneous water I/I with volume V_2 and temperature T_2 into the separate sewer network with volume V_1 and temperature T_1 resulting in a mixed flow with a new volume V_3 and temperature T_3

$$\frac{V_2}{V_1} = \frac{\Delta T}{(T_2 - T_1) - \Delta T} \tag{2}$$

The volume (V) in Equation (2) can be replaced with discharge ( ), when ‘t’ is the duration of the I/I mixing process, which is equal for both in-sewer and extraneous flows ($t = t_1 = t_2$). Therefore and Equation (2) can be rewritten as:

$$\frac{Q_2}{Q_1} = \frac{\Delta T}{(T_2 - T_1) - \Delta T} \tag{3}$$

The inflow share, or relative contribution of I/I to the sewer network (), can be estimated based on the temperatures of I/I (T_2) and in-sewer water (T_1 and T_3). Moreover, for estimating the absolute contribution, it is necessary to measure the upstream or downstream flow. The accuracy of ΔT is dependent on the thermal precision of the DTS instrument, the defined measurement resolution, and the distance between the measurement site and the instrument(Tyler *et al.*, 2009; Schilperoort, 2011).

Characterizing unwanted water I/I is a challenging task when I/I flow is low relative to the wastewater flow. This may result in the fiber optic cable being submerged completely under water. In this situation, instantaneous mixing cannot happen between the extraneous discharges and the in-sewer water layer above the cable, making it difficult to accurately measure the temperature changes and the location of I/I sources(Schilperoort, 2011). To avoid this problem in the present study, the analysis was carried out in a separate sanitary sewer, which was not submerged.

Case System Description

The DTS measurement campaign was conducted in the separate sanitary sewer system of Lykkjbekken catchment in Trondheim, Norway. The catchment was a rural area and located near Jonsvatnet Lake, the main water source of the city (63°22'46" N 10°32'35" E–63°21'47" N 10°29'16" E). The sewer network of this catchment consisted of small PVC pipes with 160 mm internal diameter, which were rehabilitated and inspected by closed-circuit television (CCTV) camera. The fiber-optic DTS cable was installed in the Lykkjbekken sewer network over a length of around 4.8 km in a three-month monitoring campaign (23 August 2015–20 November 2015). The DTS instrument was a Yokogawa's DTS ×3000 unit, which was stored outside the sewer network in the pumping station and connected to one end of the cable on the downstream side of the sewer pipeline. The temperature with the resolution of 0.01 °C was recorded with time and spatial resolution of 18 seconds for each 50 cm of the cable. Figure 3a illustrates a schematic overview of the DTS monitoring campaign inside the sewer network of Lykkjbekken catchment.

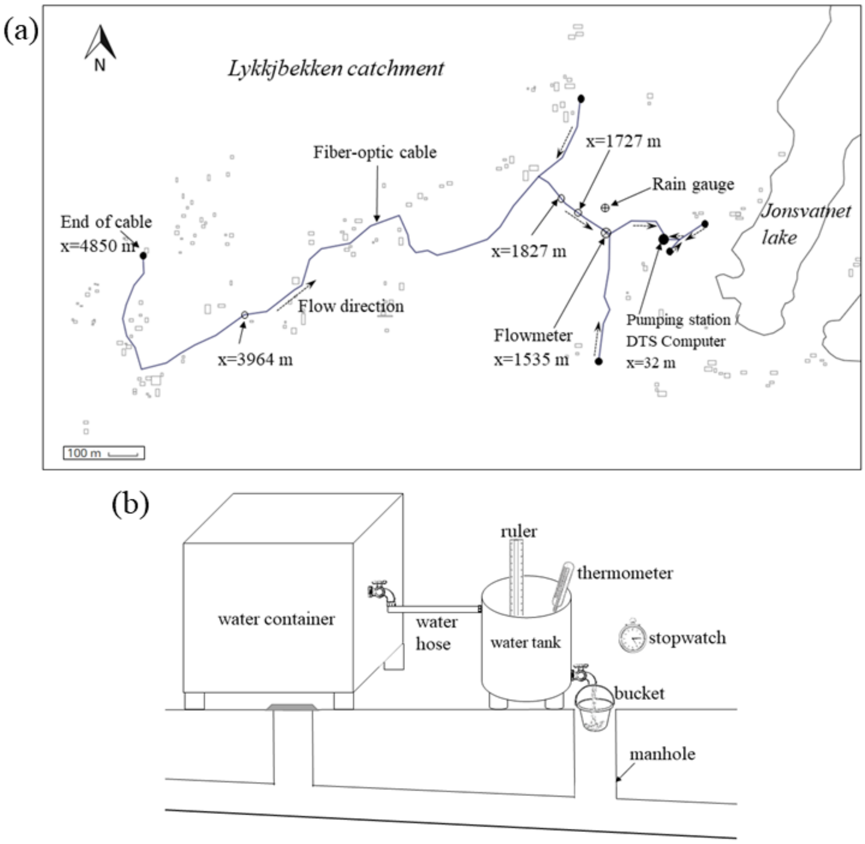

Figure 3. Schematic overview of the (**a**) DTS cable installation in the separate sewer network of Lykkjbekken catchment; and (**b**) experimental setup of the artificial inflow into the sewer network.

Experimental Setup

To test the feasibility of DTS technology in quantifying the volume of extraneous water I/I into the sewer system, a number of experimental artificial discharges with different temperatures, flows, and velocities were spilled into the sewer network of Lykkjbekken catchment (Table 1). The test locations were x = 1727 m and x = 1827 m on the fiber-optic cable (Figure 3a).

Table 1. Artificial discharge characteristics in the sewer network of Lykkjbekken, Trondheim.

Date	**Test Number**	**Test Location (m)**	**Time (hh:mm)**		**Temperature (°C)**	**Discharge (L/s)**	**Inflow Share (%)**
			Start	**End**			
28 Aug. 2015	1	1727	09:42	09:47	34	0.079	5.8%
28 Aug.2015	2	1727	09:53	09:59	33	0.13	9.8%
28 Aug.2015	3	1827	10:24	10:28	31	0.188	26%
28 Aug.2015	4	1827	10:35	10:40	32	0.356	51.8%
28 Aug.2015	5	1827	11:49	11:54	20	0.060	4.7%
28 Aug.2015	6	1827	11:58	12:02	20	0.338	61.3%
28 Aug.2015	7	1827	12:05	12:08	20	1.69	389%
28 Aug.2015	8	1827	12:13	12:17	20	0.18	12.6%
28 Aug.2015	9	1727	12:30	12:32	20	0.46	7.18%
28 Aug.2015	10	1727	12:34	12:39	20	0.208	12.13%
28 Aug.2015	11	1727	12:42	12:45	20	0.41	90.2%
28 Aug.2015	12	1727	12:47	12:53	20	0.05	4.47%
28 Aug.2015	13	1727	12:53	12:58	20	0.09	5.67%
23 Oct.2015	14	1727	08:35	11:55	13	0.07	9.27%
23 Oct.2015	15	1727	12:25	13:05	11	0.067	5.76%
23 Oct.2015	16	1727	13:05	13:25	11	0.056	18.5%
23 Oct.2015	17	1727	13:25	15:38	11	0.059	12.6%
23 Oct.2015	18	1827	13:42	13:48	11	0.0016	0.47%
6 Nov.2015	19	1727	08:47	12:10	1	0.056	8.18%
6 Nov.2015	20	1727	12:15	14:30	9.5	0.056	103%

The experimental setup for artificial discharges was quite simple and consisted of a water tank with a valve, water containers with different water temperatures, water hose, thermometer, stopwatch, ruler and a bucket (Figure 3b). The tank was connected to the water container by a water hose. A thermometer controlled the temperature of the water and the ruler controlled the water level inside the tank to be able to maintain a steady water level, while there was an inflow into the tank from the container and an outflow from the tank to the manhole. The discharge and velocity of the artificial inflow were calculated by the time needed to fill the bucket with a defined volume, and by adjusting the tank valve, different discharges were provided.

Precipitation and Flow Measurement

Precipitation and flow measurements are key parameters in I/I studies. Precipitation is an important variable in hydrological rainfall-runoff studies and has a direct impact on the surface runoff and the groundwater discharge. From the I/I point of view, this variable is a dominant element on the quality and quantity of in-sewer water parameters (Schilperoort, 2011). However, the wastewater flow measurement is a challenging task, and the current flowmeters in the market do not respond well, especially to low flows, therefore their results in shallow flows can be inaccurate. In addition, the presence of debris in wastewater and sedimentation problems on the flowmeter sensors are additional challenges in flow measurement in wastewater networks with shallow flows.

In this study, rainfall and wastewater flow were monitored by installing a rain gauge and a flowmeter in Lykkjbekken catchment, see Figure 3a. For the precipitation measurement, a tipping bucket rain gauge with a standard resolution of 0.2 mm was applied. Moreover, an ultrasonic Doppler flowmeter was installed downstream of the artificial discharge point to measure the in-sewer flow in order to check the accuracy of the DTS method in quantifying the extraneous water.

The artificial discharges were added at two and three manholes upstream of the flowmeter at x = 1535 m. There were no household connections between these points to have an accurate flow measurement and avoid the contribution of any wastewater spills. Furthermore, the results from CCTV inspection and DTS monitoring did not show any I/I contribution from groundwater or other sources in that part of the network.

Infiltration and Inflow (I/I) Temperature

To use the DTS method for quantification of rainfall-derived inflows, it is important to have the temperature of runoff. The heat balance has a great impact on the temperature of runoff and stream water and is connected to the meteorological circumstances, such as air temperature (Stefan and Preud'homme, 1993). Several studies have successfully modeled the stream temperature based on a linear and non-linear relationship with air temperature(Stefan and Preud'homme, 1993; Mohseni and Stefan, 1999; Webb *et al.*, 2008; Ficklin *et al.*, 2012). The stream-air temperature relationship uses an S-shaped logistic function, with temperature between 0–20 °C following a linear regression and temperatures outside of this range following a non-linear relationship. The non-linear behavior is due to the influence of snowmelt and groundwater at low temperatures and evaporative cooling and enhanced back radiation at high temperatures (Mohseni and Stefan, 1999). The temperature of surface runoff and lateral soil flow from rain has a linear regression with air temperature, which is close to the ambient air temperature and can be approximated to the average daily temperature (Ficklin *et al.*, 2012). However, the runoff from snowmelt has a temperature just above the freezing point and can be set to 0.1 °C (Kobayashi, 1984; Ficklin *et al.*, 2012). On the other hand, surfaces heated in excess of the ambient air due to solar radiation (de Jong, Slingerland and van de Giesen, 2015) may initially transfer some heat to the runoff at the start of rain events. Therefore, nighttime inflows can be considered to eliminate the influence of short-wave solar radiation and improve quantification accuracy.

Groundwater temperature varies seasonally. To accurately quantify groundwater infiltration, groundwater temperatures should be measured using a well in the catchment. Annually, however, groundwater temperatures are assumed to be 1–2 °C higher than the average air temperature(Todd, 1980). To quantify I/I from unwanted sources with unknown temperature, e.g., from illicit connections or groundwater, an accurate temperature can be measured using a sensor or looping the fiber-optic cable. The temperature sensor should be installed at the location of an I/I source after its detection, and I/I quantification can then be performed accurately. However, installation of these sensors in the sewer is not easy. Moreover, differentiating the temperature of wastewater from I/I in submerged sewers is difficult and may make I/I temperature measurements inaccurate. Alternatively, it is possible to measure the temperature of I/I from illicit and faulty connections, by looping the DTS cable in the I/I location before entering to the sewer, and then continuing the cable to the next part of the network (Schilperoort and Clemens, 2009).

Results and Discussion

Artificial Discharge I/I Assessment

In this study, the applicability of the DTS technology was examined for quantification of the extraneous water I/I into the sewer system. Therefore, different artificial discharges were applied to analyze the wastewater thermal behavior from the I/I aspect. The DTS cable recorded water temperature upstream and downstream of the artificial discharges with known temperature, volume, and flow. As a result, the inflow share, which is the volumetric proportion of I/I to the sewer network in comparison with the upstream flow, was estimated by the equations of conservation of mass and energy (Equations (2) and (3)). Table 1 in the experimental setup presents the characteristics and results of the artificial discharge tests conducted in the Lykkjbekken catchment.

For I/I quantification, it is important to calibrate the fiber-optic cable accurately to achieve precise results. In the present study, due to the presence of some fusion splices, the cable was calibrated with reference measurements at six calibration sections along the cable using standard thermometer sensors. Figure 4 demonstrates the calibration of the DTS measurement in the Lykkjbekken catchment. The temperature-offsets verify the log-linearity of the signal attenuation process. The sedimentation of debris and wet wipes on fiber-optic cables, however, may reduce the sensitivity and accuracy of temperature measurements during low flow and long-term installation and can also increase the risk of sewer blockage. To avoid this problem in the present study, the maintenance of the sewer network was conducted by pipeline flushing during the DTS monitoring campaign.

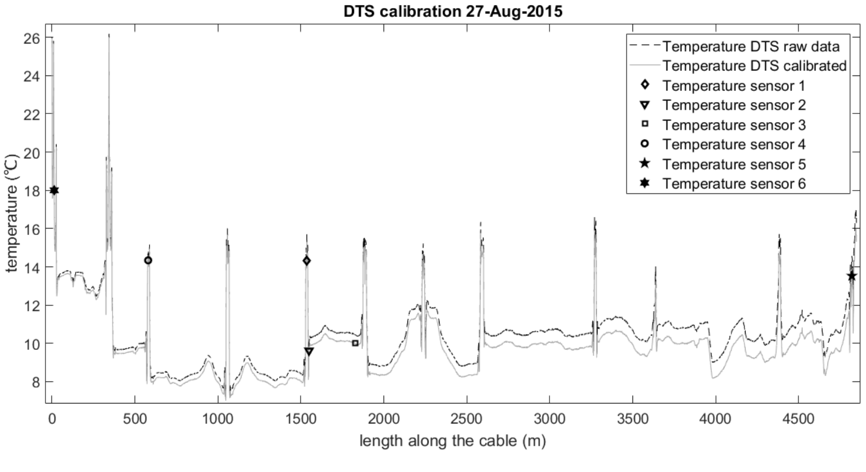

Figure 4. DTS calibration by six standard thermometers along the installed fiber-optic cable.

Figures 5–7 demonstrate the results of some artificial discharge tests with different temperatures and flows. In these figures, the upstream and downstream temperatures of infiltration point and the calculated infiltration share by Equation (3) are presented. According to the pumping data, water consumption curve, and flowmeter data, the average daily flow in the network was 0.5 L/s. Furthermore, considering the physical characteristics of the network, i.e., material, slope, and diameter by using Manning's equation, the corresponding velocity for the average daily flow in both test locations was around 0.65 m/s. The travel distance for the flow from the I/I experimental location was around 12 m per 18 sec (the time span of DTS measurement). Therefore, to analyze the DTS data in x = 1727 m and x = 1827 m, the upstream of x = 1733 m and 1833 m, and the downstream of x = 1721 m and 1821 m were considered, respectively, to compare the temperature of downstream with the upstream of the previous time-step.

As can be concluded from the graphs in Figure 5, the temperature differences between upstream and downstream have a significant role in calculations of the inflow share. The artificial flows can have the same temperature and discharge while the inflow shares and calculated in-sewer flows can vary based on wastewater temperature fluctuations caused by upstream spills from households. In Figure 5, the 2 min inflow of 0.46 L/s and 20 °C had an average share of 7.18% (test number 9), while the average share for 3 min inflow of 0.41 L/s and 20 °C was 90.2% (test number 11), which was due to the different upstream temperatures and flows.

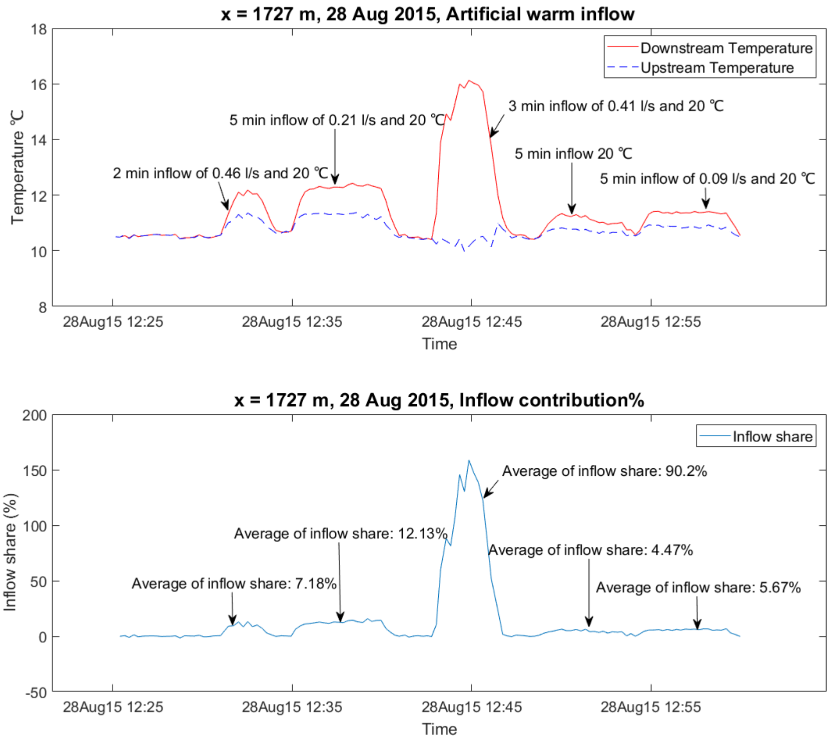

Figure 5. (**a**) Upstream and downstream temperatures on 28 August 2015 around warm artificial discharge in location x = 1727 m; (**b**) percentage of inflow share in comparison with the upstream flow.

The thermal behavior of the sewer system against cold water I/I was examined in this study as well. Figure 6 shows the thermal analysis of the system in cold I/I tests at x = 1727 m by demonstrating the detailed temperatures of upstream and downstream of the injection point and the calculated inflow shares in comparison with the upstream flows. The average inflow share during 3 hours and 23 minutes of 0.05 L/s inflow and 1 °C was around 8.18% of the flow, while it varied between 3–15% during this time span. The reason can be explained by the wastewater flow and temperature fluctuations due to the upstream domestic spills.

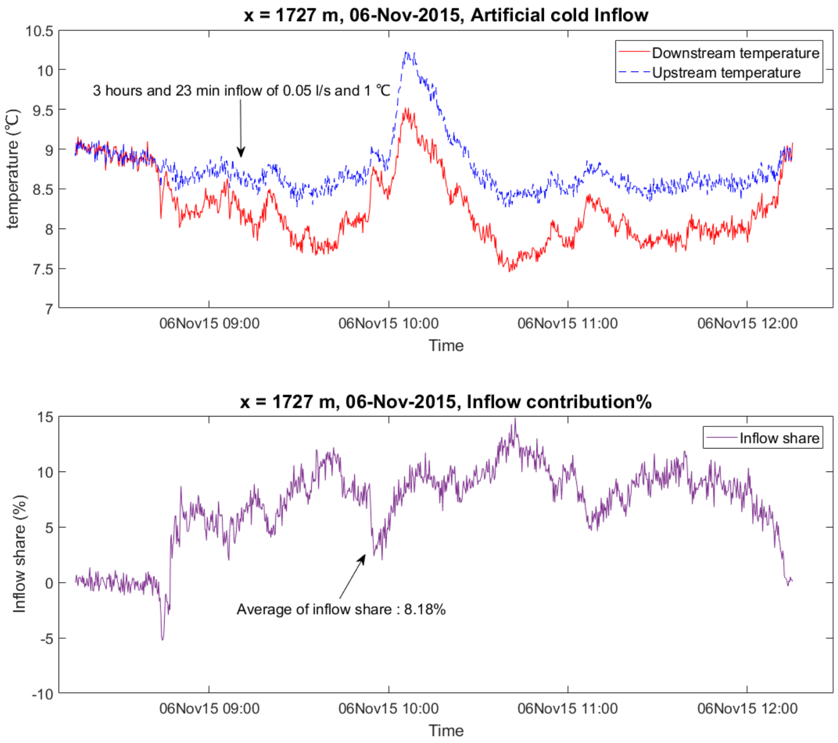

Figure 6. (**a**) Upstream and downstream temperatures on 6 November 2015 around cold artificial discharge in location x = 1727 m; (**b**) percentage of inflow share in comparison with the upstream flow**.**

In the next experiments, the thermal behavior of the wastewater was studied under the artificial inflows with the temperature close to the wastewater temperature. As demonstrated in Figure 7, it is hard to find out the correct amount of I/I when the temperature of the inflow is close to the temperature of the wastewater, due to the fact that the numerator and denominator of Equations (2) and (3) become close to zero.

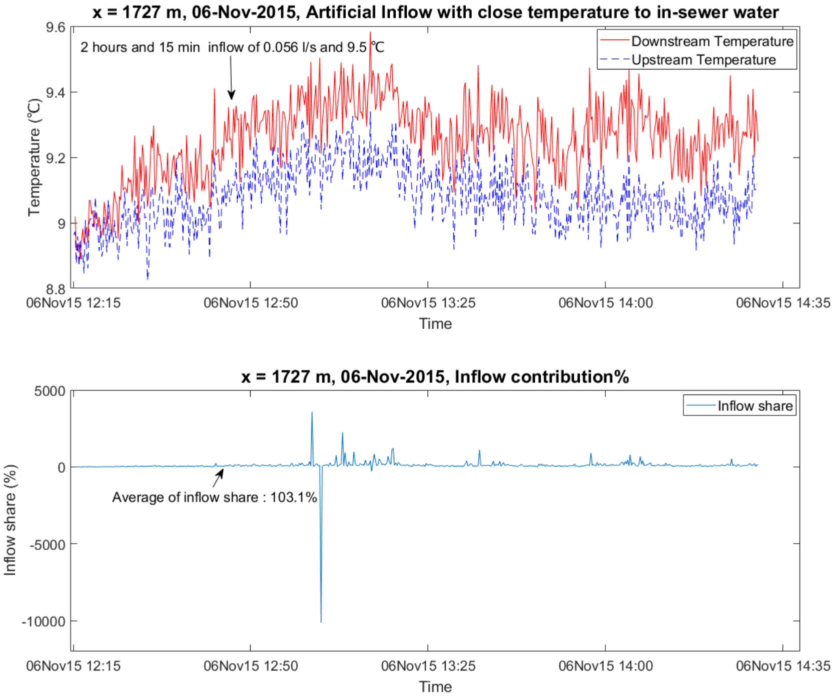

Figure 7. (**a**) Upstream and downstream temperatures on 6 November 2015 around artificial discharge with close temperature of in-sewer water in x = 1727 m; (**b**) percentage of inflow share in comparison with the upstream flow.

For verifying the application of the thermal method in I/I quantification, the flow data downstream of the artificial inflow point (measured by an ultrasonic Doppler flowmeter) was exploited. Figure 8 demonstrates the measured flow by the flowmeter and the calculated flow by the DTS method (Equation (3)) versus time.

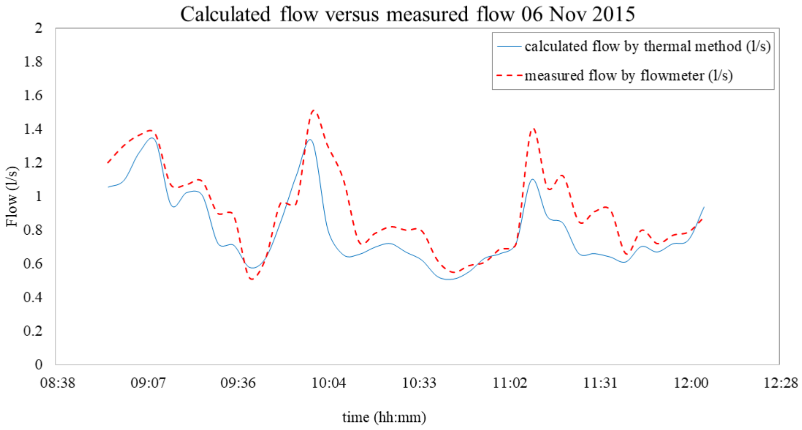

Figure 8. Measured flow by the flowmeter and calculated flow by DTS method versus time on 6 November 2015 at x = 1727 m.

By comparing the calculated wastewater flow with the measured flow by the flowmeter in Figure 8, both datasets demonstrated the same tendency and good correlation (72%) with each other. The relative error of ultrasonic flow data from the calculated flow by the thermal method was 11.96%, which can be due to the instrumental measurement errors of the flowmeter. In practice, the uncertainty and relative error in wastewater flow measurement by Doppler ultrasonic flowmeters can vary and even exceed 6–12%, which arises from different parameters, such as beam width, beam angle, and inherent instrumental errors(Larrarte *et al.*, 2008). Moreover, application of flowmeters in low and shallow flows can have high uncertainty and inaccuracy, which is also the case in the present study. Therefore, the deviation of flowmeter data from the calculated flow in Figure 8 is in the acceptable range, verifying the accuracy of the results for the thermal-based flow measurement. Nevertheless, a specific laboratory calibration is needed to assess the accuracy of these types of flowmeters, which was out of the scope of this study.

Low Infiltration Artificial Discharge

The capability of the DTS in finding out the low I/I was analyzed by an artificial injection with a low discharge of 0.0016 L/s and a temperature of 11 °C into the sewer network of Lykkjbekken (Figure 9).

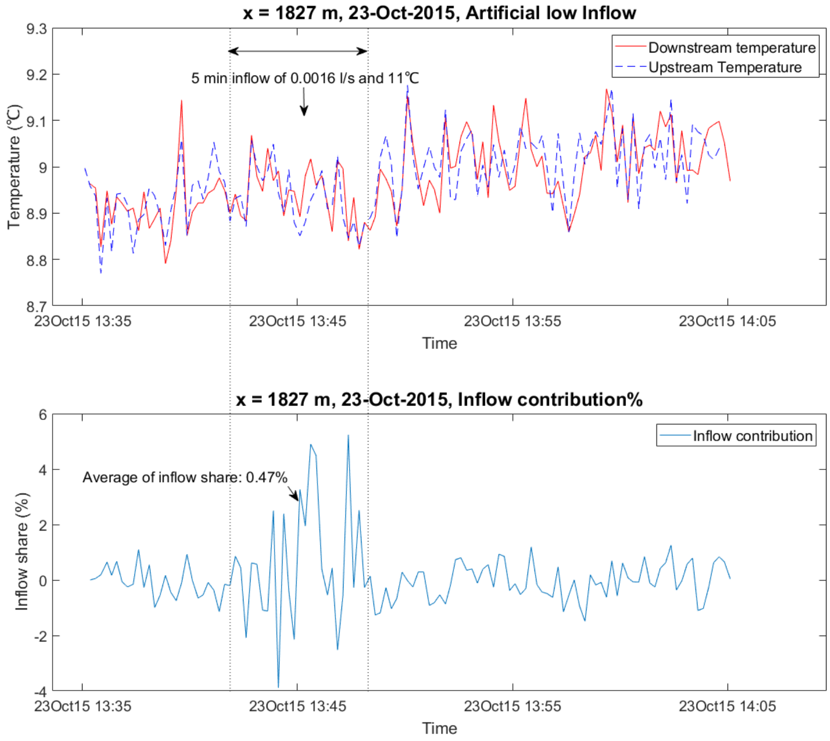

Figure 9. (**a**) Upstream and downstream temperatures on 23 October 2015 around artificial low discharge in x = 1827 m; (**b**) percentage of inflow share in comparison with the upstream flow.

In Figure 9, the quantification analysis of the low-flow injection was investigated by analyzing the temperature data upstream and downstream of the injection point. The calculations demonstrated that the average inflow share was around 0.47% of the upstream flow, and the calculated wastewater flow by Equation (3) was around 0.36 L/s. These calculated numbers were reasonable for the wastewater network of the Lykkjbekken catchment. Considering the error of flow measurement by ultrasonic flowmeters (6–12%), the calculated results were in good agreement with the downstream flow data from the water consumption curve and the flowmeter (0.41 L/s). However, in low-flow injections, the temperature changes are not significantly larger than the measurement noises, and therefore makes it difficult to identify these types of flows in DTS monitoring graphs.

Rainfall-Derived I/I Assessment

To demonstrate the application of the DTS method in the quantification of rainfall-derived I/I, the location x = 3964 m was considered, which confronted notable I/I of extraneous water in rain events. The real-life I/I calculation in the present study was based on the assumption of having the same temperature for nighttime surface runoff as the surrounding temperature, and there was not any snow in the catchment. Moreover, the household spills reduced drastically during nighttime, resulting in more accurate rainfall-derived I/I assessment during wet weather conditions. Therefore, to assess the real-life I/I, the upstream and downstream temperatures of the location x = 3964 m were analyzed during the storm events at midnight of 11 November 2015 (Figure 10) and 28 August 2015 (Figure 11).

Figures 10a and 11a demonstrate the DTS monitoring results in the heat-map format and illustrate the continuous thermal behavior of the sewer system along the fiber-optic cable installed in the sewer pipeline section. In the DTS monitoring heat-map, the horizontal axis shows the location of the cable along the sewer network and the vertical axis presents the time, while each pixel on the figure represents an in-sewer temperature for a specific time and location. The exact location of extraneous water I/I can be detected by analyzing temperature changes caused by different spills from various sources into the sewer network.

As can be seen in Figure 10a, the DTS results indicate a decrease in downstream temperatures of x = 3964 m in comparison with the upstream location, after starting the rain event at 05:15 on 11 November 2015 with an intensity of 6 mm/hour. The I/I was related to inflow of relatively cold stormwater at that location in a cold night (3 °C) from the misconnected roof and yard drains. With using upstream and downstream temperatures recorded by the DTS (Figure 10b), and assuming the stormwater temperature to be equal to the air temperature, the relative contribution of inflow with respect to upstream volume was derived according to Equation (2) (Figure 10c). The dominated temperature of wastewater before inflow was around 8.2 °C and stormwater inflow with a temperature equal to the surrounding temperature (around 3.1–3.7 °C) decreased the temperature of the wastewater significantly. In this case, the calculated inflow share was between 14–42% with a mean value of 20.7% during this rainfall.

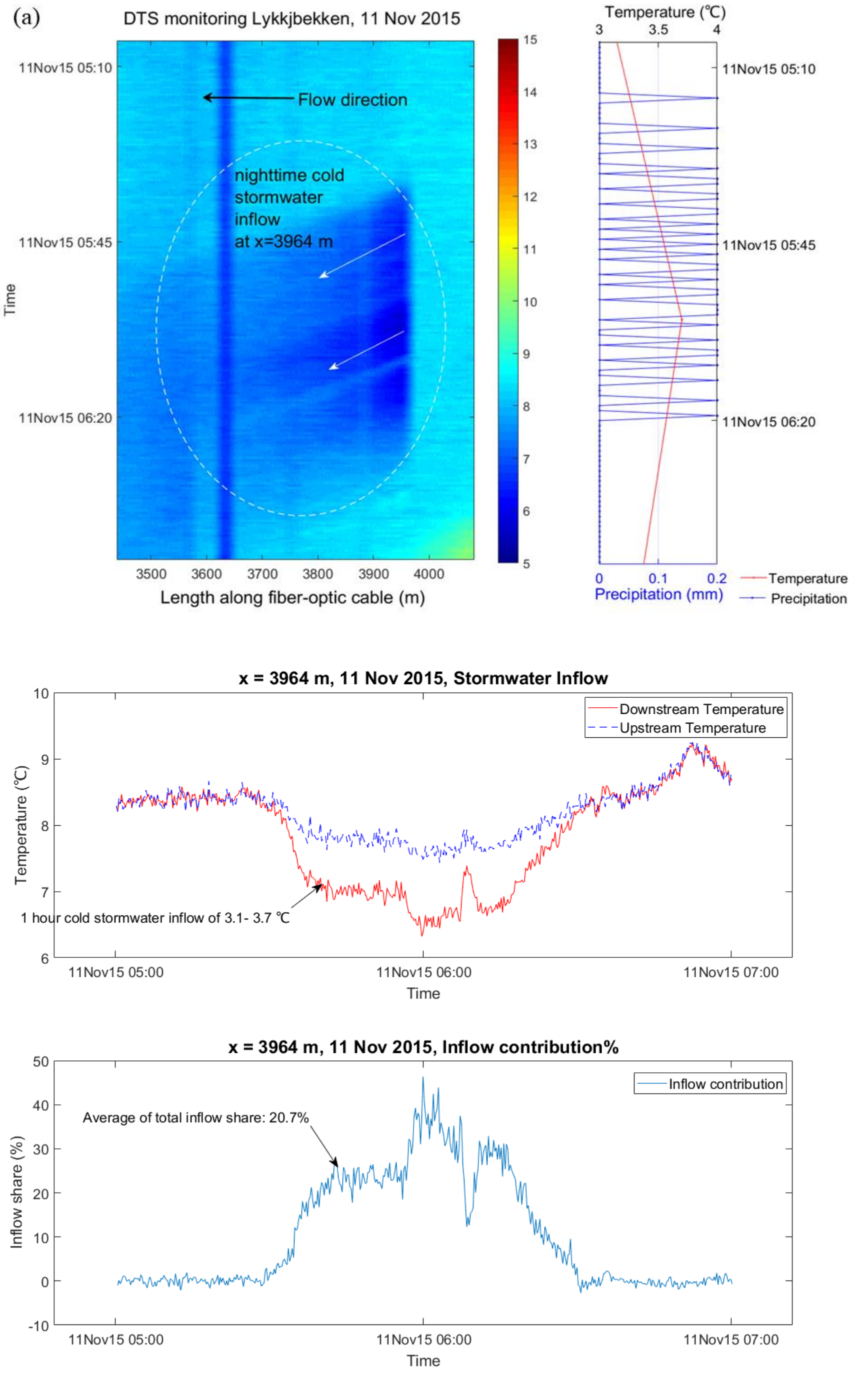

Figure 10. (a) DTS monitoring results around the rainfall-derived I/I point of x = 3964 m in storm event of 11 November 2015; (**b**) the upstream and downstream temperatures around real stormwater infiltration at x = 3694 m; (**c**) percentage of I/I share in comparison with the upstream flow.

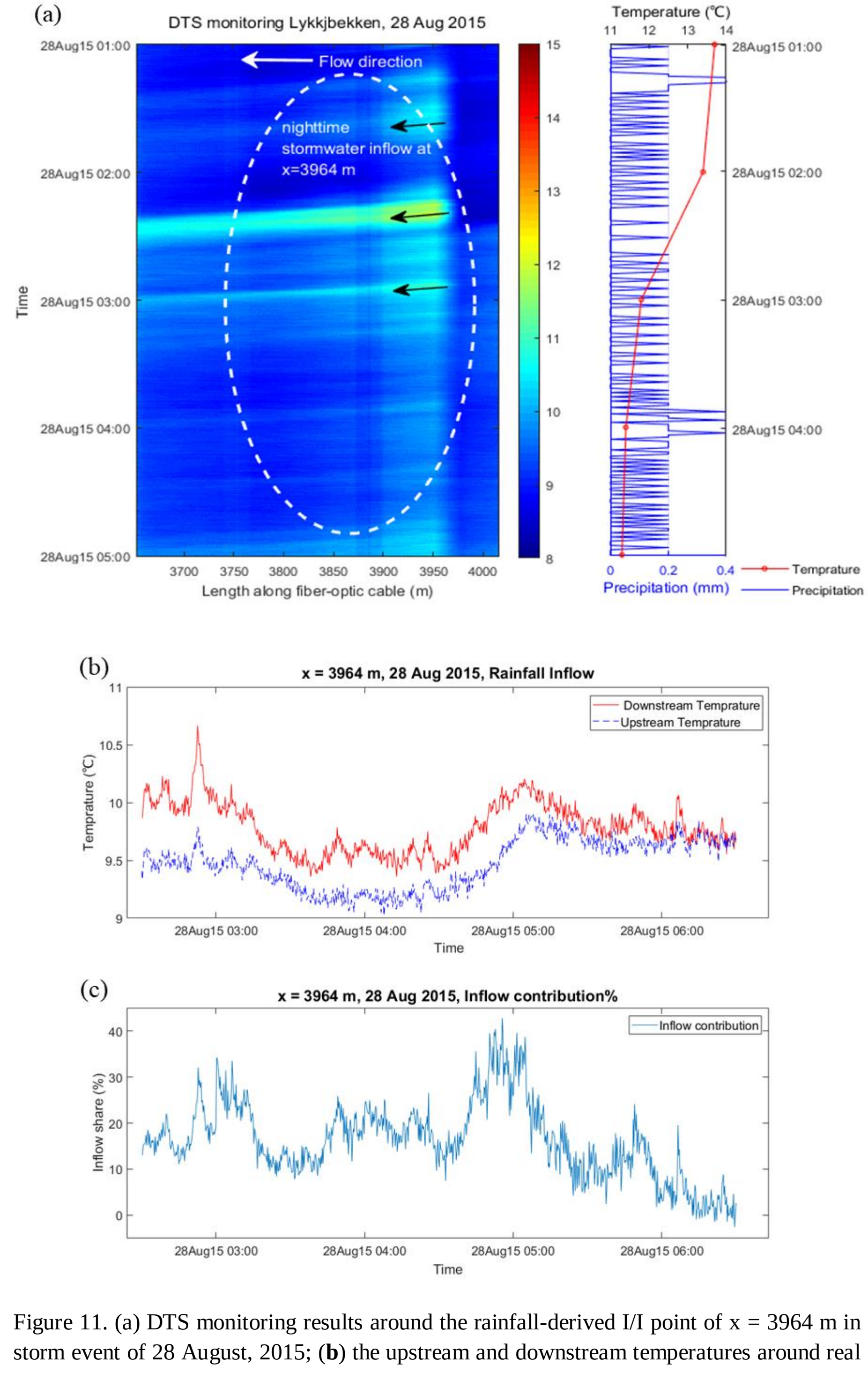

Figure 11. (a) DTS monitoring results around the rainfall-derived I/I point of x = 3964 m in storm event of 28 August, 2015; (**b**) the upstream and downstream temperatures around real stormwater infiltration at x = 3694 m; (**c**) percentage of I/I share in comparison with the upstream flow.

Figure 11 shows a warm stormwater inflow into the sewer network in the midnight of 28 August 2015 with air temperature of 11–13 °C, which was warmer than the wastewater temperature (8–9 °C). Using the same assumptions, which were described above for the rainfall of 11 October 2015, the inflow share in this case was between 4–42% with an average of 18.3% (Figure 11c). The rainfall-derived I/I calculations in different rainfalls in location x = 3694 m showed the severity of the I/I source and pointed to the immediate need for rehabilitation or spot-repair of that location. Moreover, the temperature differences between rainfall-derived I/I in both warm and cold nights highlighted the direct influence of the surrounding temperature on the temperature of the rainfall-derived I/I and the importance of the air temperature measurement in rainfall-derived I/I assessments.

Conclusions

In the present study, the application of the DTS technique for accurate quantification of extraneous water ingress and infiltration from individual I/I sources in the separate sewer networks was considered and analyzed in a catchment in Trondheim, Norway. I/I measurements were carried out by analyzing the thermal behavior of in-sewer water and utilizing an equation based on the conservation of energy and mass (Equation (2)). For this purpose, both experimental artificial discharges and real-life rainfall-derived I/I during wet conditions were assessed.

In experimental flows, artificial discharges with different temperatures and flows were applied to check the feasibility of the DTS method in quantifying I/I contributions in the sewer network. These results verified the applicability of the method in quantification goals, except when I/I water temperature was the same as in-sewer water. Moreover, in low-flow I/I, the difference between the temperature changes and measurement noises were not significant, making I/I detection difficult with DTS monitoring. In addition, this method demonstrated robustness and practicability in I/I measurement during wet conditions. Analyzing the thermal behavior of the in-sewer water during storm events revealed that the temperature of the rainfall-derived I/I in sewer networks was dependent on ambient air temperature. Therefore, monitoring the air temperature in this type of study was very important and should always be considered.

The results of this study identified the condition of the sewer network by determining the severity of individual I/I sources in the sewer network. I/I assessment is a demanding task in sewer rehabilitation and can support the urban water decision-makers and sewer operators in prioritizing and spot-repairing problematic parts of the network. These types of measures are valuable for sewer-infrastructure asset management as well as sustainable urban water management.

Acknowledgments

The authors wish to acknowledge the wastewater department of Trondheim Municipality and the personnel of that department, especially Kristin Greiff Johnsen and Vidar Figenschou, for their total support in this project. Thanks also to Remy Schilperoort, Cornelis de Haan and Erik Liefting at PARTNERS4URBANWATER for their invaluable advice and cooperation. The authors are also grateful to Ali Tabeshian, Michael Waak and Knut Alfredsen at NTNU and Paul Uwe Thamsen at TU Berlin for their valuable comments.

9. CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

In the current Ph.D. research, the application of IAM in improving the sewer system efficiency and performance was demonstrated in the context of restriction of unwanted water I/I. The study path was defined through the IAM planning levels. The strategic level planning starts with “increasing resilience and performance of the sewer system” (publication I). The tactical level focused on defining a systematic method to assess unwanted water in the sewer systems in addition to the selection of practical methods and projects at the medium-term period (publication II). Moreover, to demonstrate the performance of the sewer network from I/I point of view in a cost-effective way, mathematical modeling was applied in tactical level (chapter 4 and publication V). At the operational level, corresponding operations, measures, and projects to detect and assess unwanted water I/I in the sewer network were carried out at the short-term period (publication III and IV).

At the strategic planning level, the wastewater transport system of the city of Trondheim was analyzed for period 2014–2040 from the sustainability point of view by the dynamic metabolism model (DMM) and compared with ‘status quo’ (**publication I**). The ‘status quo’ presents the current condition of the network without managing any risk factors and considering the same population growth as in the prognosis for period 2014–2040. In addition, constant development of the wastewater network as the average value for the years 2005 to 2013 with the same rehabilitation rate in the Trondheim master plan, as well as 10% reduction in water demand per capita until 2040 were assumed. It can be concluded from the results of this study, which were based on some realistic assumptions for wastewater transport system of Trondheim, that interventions of reduction of I/I (a), and energy management (d), and the combination of them demonstrated less GHG emission and energy consumption in comparison with ‘status quo’, which is important from the environmental aspect of the sustainability analysis. However, low changes and improvements in other variables, e.g. economy and assets, in comparison with ‘status quo’ can be seen. It should be mentioned that by reduction of I/I, outstanding benefits will be added to WWTP and CSO due to wastewater volume reduction. Intervention ‘d’ resulting in better energy management and a significant reduction in diesel energy consumption, which will have a major impact on the sustainable management of the wastewater system. The intervention of extension of wastewater network regarding population growth (c) presented good and desirable results from environmental, functional and economic aspects, especially in decreasing GHG emissions and energy consumption. The reason is that the extension of the network by population growth rate is lower than the extension rate of the recent years (status quo). Moreover, in the existing system, extra space is supplied for wastewater and stormwater transport, and intervention ‘c’ displayed the benefits of using the available capacity of existing infrastructure. Therefore, densification of existing areas or establishment of new areas should be considered in city development plans. It clearly shows that the benefits of densification overrun other interventions. Additionally, for stormwater systems, blue-green solutions can reduce the need for extra flow capacity, which was considered in intervention ‘c’. On the other hand, the environmental and economic results related to the intervention of increasing the rehabilitation rate and separation of the network (b) were not desirable in comparison with ‘status quo’ in the analysis of the wastewater transport system, due to adding more construction work to the network. This has significant benefits for WWTP by reduction of CSO and I/I volume, which results in consumption of less energy and chemicals. However these results were out of the scope of this study and were not considered here because of lack of data.

In the tactical level, a systematic method to assess unwanted water in the sewer systems by rehabilitation plans was defined as well as evaluating the available I/I assessment and detection methods in the sewer system (**publication II**). There is no unique and standard way of evaluation and localization of I/I in the sewer systems, while each I/I assessment method is based on some assumptions and has its limitations and advantages. Therefore, a combination of these methods can be valuable for reducing assumptions and uncertainties and obtaining more independent, accurate and reliable data about the location and magnitude of I/I in the sewer system. Some infiltration/inflow assessment methods, *e.g.*, tracer method, can be quite labor-intensive and may require entrance onto private premises, while inflows are often only detected by chance. The results of this study give the sewer operators the possibility to compare different technologies in assessing infiltration/inflow in the sewer system in a standardized, qualified and quantified way depending on the selection criteria.

Moreover, gathering and analyzing the historical data for assessing the I/I status in sewer systems should be done in tactical planning level to detect the presence of unwanted water in the sewer system and convince the municipalities to invest on I/I detection, assessment, and restriction projects. To investigate the status of the sewer network from I/I aspect in a cost-effective way mathematical modeling and simulation can be applied, which are valuable in demonstrating the presence of unwanted water I/I in the sewer system, and convincing utilities to consider I/I management projects in their plans. A combination of hydrological and hydraulic modeling of the sewer system, together with hydrogeological modeling of the groundwater should be carried out. Analyzing the historical data, i.e., hydrological, hydrogeological and sewer flow data, and sewer infiltration modelling in Lykkjbekken catchment demonstrated and proofed the presense of unwanted water in that sewer network specially in wet weather conditions due to rainfall-induced I/I. The validation of these simulations can be done by analyzing historical data and direct monitoring of the sewer network by I/I techniques.

In the operational level, I/I detection and measurement projects were implemented in a case study in Trondheim. The DTS was applied for the first time in Norway in tandem with CCTV and smoke testing to detect I/I sources in a separate sewer network (**publication III**). The application of DTS was demonstrated to be a strong and feasible method for I/I detection. DTS detected more I/I sources than CCTV. Smoke testing confirmed the DTS results and identified illicit stormwater connections from downspouts in the I/I sources. Rainfall-derived I/I affects the thermal behavior of sewage to a great extent. Rainfall inflows coinciding with warm days (relative to in-sewer water) can be detected as warm spills into the sewer networks, while cold I/I discharges correspond to rain events on cold days. Therefore, monitoring the surrounding air temperature in this type of studies is essential. It is important to assess individual I/I sources by I/I quantification methods to evaluate the severity of detected I/I sources. It is hard to know if all I/I sources were detected by DTS. However, after repairing detected sources less illicit water is entering the system. There can still be some I/I sources in parts of the sewer network, which were not covered in this study. This study emphasized that DTS was an important tool to solve the infiltration problems in Lykkjbekken catchment.

I/I quantification was carried out by analyzing the thermal behavior of wastewater by DTS technique and utilizing an equation based on the conservation of energy and mass (**publication IV**). For this purpose, both experimental artificial discharges and real-life rainfall-derived I/I during wet conditions were assessed. In experimental flows, artificial discharges with different temperatures and flows were applied to check the feasibility of the DTS method in quantifying I/I contributions in the sewer network. The results verified the applicability of the thermal method in quantification goals, except when I/I water temperature was the same as in-sewer water. Moreover, in low-flow I/I and I/I with close temperature to in-sewer water, the difference between the temperature changes and measurement instrumental noises were not significant, making I/I detection difficult with DTS monitoring. Furthermore, this method demonstrated robustness and practicability in I/I measurement during wet conditions. I/I quantification has some limitations as well. The accuracy of the flowmeter is the major one. Wastewater flow measurement is a challenging issue, especially in shallow flows, which was discussed in the chapter 8. The temperature measurements of I/I is another challenge. It is important to use the same sensor for all measurements otherwise; the measurements from different sensors can result in high uncertainty in quantification issue. For example if we measure the air temperature with another sensor, it should be calibrated together with the DTS cables. Moreover, the measurement of I/I temperature is needed with adjustment of the cable in I/I location, which needs extensive resources.

The results of these studies identified the condition of the sewer network by I/I detection and determining the severity of individual I/I sources in the sewer network. I/I assessment is a demanding task in sewer rehabilitation and can support the urban water decision-makers and sewer operators in prioritizing the problematic parts of the network and make smart decisions (*i.e.*, spot repairing, renovation or full replacement of the sewer pipeline). Identifying and remedying I/I sources decreases extraneous water in the sewer system, which is essential for sustainable sewer asset management.

9.2 Recommendations for future studies

The following research topics were identified as the subjects for further researches since they could not be included in the scope of this study.

A. **Strategic planning of the whole wastewater system:** The results of the presented strategic planning in the publication I did not demonstrate the comprehensive effects on the whole wastewater system. To obtain a sustainable IAM of sewer network and making decisions, it is indispensable to consider different aspects of sustainability accurately and manage them in a comprehensive system with wastewater transport system, CSO, and wastewater treatment plant. This can lead to long-term sustainable planning and management in a wastewater transport system by having more focus on the environmental features of sustainable sewer asset management besides the economic, physical, functional and social aspects.

B. **Uncertainty analysis in strategic planning:** In the long-term strategic planning, for future developments, which are based on various climatic, socioeconomic and anthropogenic scenarios, the fulfillment of assumptions is strongly associated with future conditions and, therefore, uncertainty plays a relevant role, and reliability of the outcomes can be affected significantly (Freni, Mannina and Viviani, 2012). Therefore, uncertainty analysis is recommended in decision-making.

C. **Uncertainty and SWOT analysis in tactical planning:** Uncertainty assessment is useful and valuable in applying various I/I techniques and can be considered in future studies. Moreover, analyzing internal strengths, weaknesses together with external opportunities and threats (SWOT analysis) are valuable and recommended before approving I/I projects. Cost and availability of materials, transportation, carbon footprints, and construction labor as well as considering environmental impacts are important factors in the assessment of the suitability of I/I techniques.

D. **I/I assessment by other methods in operational planning:** Future studies can focus on the application of other I/I assessment methods such as, *e.g.*, tracer methods, electro scan, water level measurement, stable isotopes method and pollutant time series method. Each of these methods is based on some assumptions and can be a subject for future I/I assessment studies. Moreover, a combination of them is a valuable tool to obtain reliable I/I detection and assessment data.

E. **I/I assessment by cost-effective methods:** The DTS technique has high initial cost and is an expert oriented method in installation, operation, and data analysis, so improvements are necessary before the method becomes practical and widely accessible for I/I assessment. It is important to develop and find more cost-effective methods for I/I detection. Temperature measurement monitoring, which was described in Table 3.1 in chapter 3, is an inexpensive method in I/I detection, which can be used for detecting the problematic parts of the network. In addition, using cable temperature sensors can be used as a cost-effective alternative method instead of DTS fiber-optic cables for I/I detection and assessment in problematic parts of the network with the same principle as DTS method. However, more investigation is needed to prove their applicability and accuracy in I/I projects, which can be a subject for future studies.

F. **Smart I/I detection:** Smart technologies and solutions for water management such as digitalization and internet of things (IOT) can provide better monitoring and faster diagnosis of the problems in urban water and wastewater infrastructure systems. More research is needed on I/I detection for example through warning systems connecting to the ubiquitous sensor network in a fast and effective way.

G. **Accurate flow measurement:** The wastewater flow measurement is a challenging task, and the current flowmeters in the market do not respond well, especially to low flows. Therefore, flow measurement in shallow flows can be inaccurate. Also, the presence of debris in wastewater and sedimentation problems on the flowmeter sensors are additional challenges in flow measurement in wastewater networks with shallow flows. More research is needed on developing flowmeters without these problems.

References

Alegre, H. and Coelho, S. T. (2012) ‘Infrastructure Asset Management of Urban Water Systems’, in Ostfeld, A. (ed.) *Water Supply System Analysis - Selected Topics*. Online publication: InTech, pp. 49–73. doi: 10.5772/52377.

Ana, E. V. and Bauwens, W. (2010) ‘Modeling the structural deterioration of urban drainage pipes: the state-of-the-art in statistical methods’, *Urban Water Journal*, 7(April), pp. 47–59. doi: 10.1080/15730620903447597.

Ashley, R. *et al.* (2008) ‘Making Asset Investment Decisions for Wastewater Systems That Include Sustainability’, *Journal of Environmental Engineering*, 134(March), pp. 200–209. doi: doi:10.1061/(ASCE)0733-9372(2008)134:3(200).

Beheshti, M. and Sægrov, S. (2018a) ‘Detection of extraneous water ingress into the sewer system using tandem methods- A case study in Trondheim City’, *Water Science & Technology*.

Beheshti, M. and Sægrov, S. (2018b) ‘Quantification assessment of extraneous water infiltration and inflow by analysis of the thermal behavior of the sewer network’, *Water*, 10(8). doi: 10.3390/w10081070.

Beheshti, M. and Sægrov, S. (2018c) ‘Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim, Norway’, *Urban Water Journal*. Taylor & Francis, 15(1), pp. 1–8. doi: 10.1080/1573062X.2017.1363253.

Beheshti, M., Sægrov, S. and Ugarelli, R. (2015) ‘Infiltration / Inflow Assessment and Detection in Urban Sewer System’, *Vann*, (1), pp. 24–34. Available at: https://vannforeningen.no/wp-content/uploads/2015/01/Beheshti.pdf.

Behzadian, K. *et al.* (2014) ‘WaterMet2: a tool for integrated analysis of sustainability-based performance of urban water systems’, *Drinking Water Engineering and Science*, 7(1), pp. 63–72. doi: 10.5194/dwes-7-63-2014.

Behzadian, K. and Kapelan, Z. (2015) ‘Advantages of integrated and sustainability based assessment for metabolism based strategic planning of urban water systems’, *Science of the Total Environment*. Elsevier B.V., 527–528, pp. 220–231. doi: 10.1016/j.scitotenv.2015.04.097.

De Bénédittis, J. and Bertrand-Krajewski, J.-L. (2004) ‘Infiltration in sewer systems: comparison of measurement methods.’, in *Proceedings of the 4th International Conference on Sewer Processes and Networks*. Funchal, Madeira, Portugal, pp. 301–308.

Brunner, P. H. and Helmut, R. (2004) *Pratical Handbook of Matreial Flow Analysis, Complete Casting Handbook*. CRC Press LLC. doi: 10.1016/B978-1-85617-809-9.10003-9.

Chen, Z., Ngo, H. H. and Guo, W. S. (2012) ‘A critical review on sustainability assessment of recycled water schemes.’, *Science of the Total Environment*, 426: 13–31. doi: 10.1016/j.scitotenv.2012.03.055.

Ciocca, F. *et al.* (2012) ‘Heated optical fiber for distributed soil-moisture measurements: A lysimeter experiment’, *Vadose Zone Journal*, 11. doi: 10.2136/vzj2011.0199.

City of Toledo (2011) *Inflow and Infiltration Study*. Lincoln County, Oregon. Available at: http://www.cityoftoledo.org/documents/PW/ToledoI+IReportFinal.pdf.

Dakin, J. P. *et al.* (1985) 'Distributed optical fibre Raman temperature sensor using a semiconductor light source and detector', *Electronics Letters*, 21(13), pp. 569–570. doi: 10.1049/el:19850402.

Ellis, B. *et al.* (2005) *APUSS: assessing the significance of infiltration and exfiltration on the performance of urban sewer systems.* London: IWA Publishing. Available at: http://apuss.insa-lyon.fr/APUSS Final Report version March 2005.pdf.

Ellis, B. and Bertrand-Krajewski, J.-L. (2010) *Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems (APUSS)*. London: IWA Publishing.

Ellis, J. B. *et al.* (2005) *APUSS: assessing the significance of infiltration and exfiltration on the performance of urban sewer systems.* Available at: http://apuss.insa-lyon.fr/APUSS Final Report version March 2005.pdf.

Ficklin, D. L. *et al.* (2012) 'Development and application of a hydroclimatological stream temperature model within the Soil and Water Assessment Tool', *Water Resources Research*, 48(1), pp. 1–16. doi: 10.1029/2011WR011256.

Finnveden, G. *et al.* (2009) 'Recent developments in Life Cycle Assessment', *Journal of Environmental Management*. Elsevier Ltd, 91(1), pp. 1–21. doi: 10.1016/j.jenvman.2009.06.018.

Freni, G., Mannina, G. and Viviani, G. (2012) 'Role of Modeling Uncertainty in the Estimation of Climate and Socioeconomic Impact on River Water Quality', *Journal of water resources planning and management*, 138(October), pp. 479–491. doi: 10.1061/(ASCE)WR.1943-5452.0000208.

Garcia-Montiel, D. C. *et al.* (2014) 'Food sources and accessibility and waste disposal patterns across an urban tropical watershed: implications for the flow of materials and energy.', *Ecology and Society*, 19(1), p. 37.

Garfì, M. *et al.* (2011) 'Multi-criteria analysis for improving strategic environmental assessment of water programmes. A case study in semi-arid region of Brazil', *Journal of Environmental Management*. Elsevier Ltd, 92(3), pp. 665–675. doi: 10.1016/j.jenvman.2010.10.007.

Gupta, V., Sorooshian, S. and Yapo, P. (1999) 'STATUS OF AUTOMATIC CALIBRATION FOR HYDROLOGIC MODELS : COMPARISON WITH MULTILEVEL EXPERT CALIBRATION', 4(April), pp. 135–143.

Haan de, C. J. *et al.* (2011) 'Locating illicit connections with DTS: classification of findings.', in *12th International Conference on Urban Drainage, Porto Alegre/Brazil*.

Harris, R. J. and C. Dobson (2006) 'Sewer Pipe Infiltration Assessment : Comparison of Electro-Scan, Joint Pressure Testing and CCTV Inspection', in *Pipeline Division Specialty Conference 2006*. Chicago, Illinois, United States: American Society of Civil Engineers (ASCE). doi: https://doi.org/10.1061/40854(211)61.

Henderson, R. D., Day-Lewis, F. D. and Harvey, C. F. (2009) 'Investigation of aquifer-estuary interaction using wavelet analysis of fiber-optic temperature data', *Geophysical Research Letters*, 36(L06403). doi: 10.1029/2008GL036926.

Hoes, O. A. C. *et al.* (2009) 'Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing', *Water Research*. Elsevier Ltd, 43(20), pp. 5187–5197. doi: 10.1016/j.watres.2009.08.020.

HOFER, T. *et al.* (2014) 'Using Temperature Sensors to Detect Occurrence and Duration of Combined Sewer Overflows', in *13th International Conference on Urban Drainage*. Sarawak, Malaysia, pp. 1–8.

IPCC (2007) *INTERGOVERNMENTAL PANNEL ON CLIMATE CHANGE - IPCC. Climate change 2007: synthesis report*. Geneva, Switzerland. doi: 10.1017/CBO9780511546013.

Jansen, J. *et al.* (2011) 'Estimating soil heat flux using distributed temperature sensing', *IAHS Publ*, 343, pp. 140–144.

Johansson, S. (1997) *Seepage monitoring in embankment dams, Ph.D. thesis*. Royal Institute of Technology, Sweden.

de Jong, S. A. P., Slingerland, J. D. and van de Giesen, N. C. (2015) 'Fiber optic distributed temperature sensing for the determination of air temperature', *Atmospheric Measurement Techniques*, 8(1), pp. 335–339. doi: https://doi.org/10.5194/amt-8-335-2015.

Karpf, C. and Krebs, P. (2011) 'Quantification of groundwater infiltration and surface water inflows in urban sewer networks based on a multiple model approach', *Water Research*. Elsevier, 45(10), pp. 3129–3136. doi: 10.1016/j.watres.2011.03.022.

Kobayashi, D. (1984) 'Separation of the snowmelt hydrograph by stream temperatures', *Journal of Hydrology*, 76, pp. 155–162.

Koeniger, P. *et al.* (2009) 'Stable isotopes applied as water tracers in column and field studies', *Organic Geochem*. doi: 10.1016/j.orggeochem.2009.07.006.

Kracht, O., Gresch, M. and Gujer, W. (2007) 'A stable isotope approach for the quantification of sewer infiltration', *Environmental Science & Technology*, 41(16), pp. 5839–5845.

Kracht, O. and Gujer, W. (2005) 'Quantification of infiltration into sewers based on time series of pollutant loads.', *Water Science and Technology*, 52(3), pp. 209–218.

Kracht, O. and Gujer, W. (2006) 'Tracer based quantification of sewer infiltration: experiences using natural isotopes (δ18O, δ2H)', in *4th Swiss Geoscience Meeting, Bern*.

Kragset, B. T. (2018) *Modelling of infiltration and inflow in different hydrological situations, A case study at Lykkjbekken pumping station, Trondheim*. Norwegian university of science and technology (NTNU).

Krause, S. *et al.* (2013) 'Fibre-optic distributed temperature sensing for characterizing the impacts of vegetation coverage on thermal patterns in woodlands', *Ecohydrology*, 6, pp. 754–764.

Langeveld, J. G. (2004) *Interactions within the Wastewater System., Ph.D. thesis*. Delft University of Technology, Delft, the Netherlands.

Langeveld, J. G. *et al.* (2012) 'Monitoring the performance of a storm water separating manifold with distributed temperature sensing', *Water Science and Technology*, 66, pp. 145–150. doi: 10.2166/wst.2012.152.

Larrarte, F. *et al.* (2008) 'Acoustic Doppler flow-meters: A proposal to characterize their technical parameters', *Flow Measurement and Instrumentation*, 19(5), pp. 261–267. doi: 10.1016/j.flowmeasinst.2008.01.001.

Lee, N. and Walsh, F. (1992) 'Strategic environmental assessment: an overview', *Project Appraisal*, 7(3), pp. 126–136. doi: 10.1080/02688867.1992.9726853.

Lopez-Higuera, J. M. (2002) *Handbook of Optical Fibre Sensing Technology*. West Sussex, England: John Wiley & Sons Ltd.

Loubet, P. *et al.* (2014) ‘Life cycle assessments of urban water systems: A comparative analysis of selected peer-reviewed literature’, *Water Research*. Elsevier Ltd, 67(0), pp. 187–202. doi: 10.1016/j.watres.2014.08.048.

Lowry, C. S. *et al.* (2007) ‘Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor’, *Water Resources Research*, 43(W10408). doi: 10.1029/2007WR006145.

Ludzia, A., Larsson, R. and Aguayo, S. (2014) ‘Utvärdering av dagvattensystemets hållbarhet i Augustenborg , Malmö Evaluation of a sustainable urban drainage system in Augustenborg , Malmö’, pp. 107–112.

Mamer, E. A. and Lowry, C. S. (2013) ‘Locating and quantifying spatially distributed groundwater-surface water interactions using temperature signals with paired fiber-optic cables’, *Water Resources Research*, 49, pp. 7670–7680. doi: 10.1002/2013WR014235.

Marlow, D. R. *et al.* (2013) ‘Towards sustainable urban water management: A critical reassessment’, *Water Research*. Elsevier Ltd, 47(20), pp. 7150–7161. doi: 10.1016/j.watres.2013.07.046.

Mohseni, O. and Stefan, H. G. (1999) ‘Stream temperature/air temperature relationship: A physical interpretation’, *Journal of Hydrology*, 218(3–4), pp. 128–141. Available at: https://www.sciencedirect.com/science/article/pii/S0022169499000347.

Muleta, M. and Boulos, P. (2008) ‘Analysis and Calibration of RDII and Design of Sewer Collection Systems’, in *World Environmental and water resource Congress 2008*. doi: 10.1061/40976(316)642.

Nilsson, M. *et al.* (2005) ‘Testing a SEA methodology for the energy sector: A waste incineration tax proposal’, *Environmental Impact Assessment Review*, 25(1), pp. 1–32. doi: 10.1016/j.eiar.2004.04.003.

Oost, D., Beyer, J. and Vermeulen, N. P. E. (2003) ‘Fish bioaccumulation and biomarkers in en v ironmental risk assessment : a re v iew’, *Enviironmental Toxicology and Pharmacology*, 13(2), pp. 57–149. doi: 10.1016/S1382-6689(02)00126-6.

Pazhepurackel, V. (2009) *Fremdwasserbestimmung in Kanalisationen mittels faseroptischer Temperaturmessungen. (External water determination in sewer systems by fiber-optic temperature measurements.), MSc. thesis*. ETH Zürich, Switzerland.

Peters, W. *et al.* (2002) ‘Laboratory investigation on the sewage separation of a manifold’, *Rioleringswetenschap*, 2(7), pp. 43–53.

Petrides, A. C. *et al.* (2011) ‘Shade estimation over streams using distributed temperature sensing’, *Water Resources Research*, 47(W07601). doi: 10.1029/2010WR009482.

Pitt, R. *et al.* (1993) *Investigation of inappropriate pollutant entries into storm drainage systems: a user’s guide*. Cincinnati, Ohio.

Rehan, R. *et al.* (2014) ‘Financially sustainable management strategies for urban wastewater collection infrastructure – development of a system dynamics model’, *Tunnelling and Underground Space Technology*. Elsevier Ltd, 39, pp. 116–129. doi: 10.1016/j.tust.2012.12.003.

Rossman, L. A. (2015) ‘Storm Water Management Model User ’ S Manual’, *Environmental Protection Agency U.S (EPA)*, (July), p. 295.

Rutsch, M., Rieckermann, J. and Krebs, P. (2005) ‘Quantification of sewer exfiltration – A review.’, in *10th ICUD conference*. Copenhagen, Denmark.

Sægrov, S. (2013) *Norsk Vann report B17/2013*.

Sægrov, S. (2014) ‘Ledningsteknologi for vann og avløp (Pipeline technology for water and wastewater)’, in Ødegaard, H. (ed.) *Vann- og avløpsteknikk (Water and wastewater engineering)*. 2nd edn. Trondheim: Norsk Vann, pp. 374–409.

Salhofer, S., Wassermann, G. and Binner, E. (2007) ‘Strategic environmental assessment as an approach to assess waste management systems. Experiences from an Austrian case study’, *Environmental Modelling and Software*, 22(5), pp. 610–618. doi: 10.1016/j.envsoft.2005.12.031.

Schilperoort, R. (2011) *Monitoring as a tool for the assessment of wastewater quality dynamics, Ph.D. thesis*. Delft University of Technology, Delft, The Netherlands.

Schilperoort, R. *et al.* (2013) ‘Searching for storm water inflows in foul sewers using fibre-optic distributed temperature sensing’, *Water Science and Technology*, 68, pp. 1723–1730. doi: 10.2166/wst.2013.419.

Schilperoort, R. P. S. and Clemens, F. H. L. R. (2009) ‘Fibre-optic distributed temperature sensing in combined sewer systems’, *Water Science & Technology*, 60(5), p. 1127. doi: 10.2166/wst.2009.467.

Schneider, C. *et al.* (2013) ‘How will climate change modify river flow regimes in Europe?’, *Hydrology and earth system science*, 17, pp. 325–339.

Schwindamann, C. (2008) ‘Benefits of smoke testing collection systems realized’, *The Kansas lifeline*. Available at: http://www.krwa.net/lifeline/currentissue/0807_082.pdf.

Selker, J. S. *et al.* (2006) ‘Distributed fiber-optic temperature sensing for hydrologic systems’, *Water Resources Research*, 42(W12202). doi: 10.1029/2006WR005326.

SEPA (2014) *Regulatory Method (WAT-RM-07) Sewer Overflows*.

Shen, X. *et al.* (2016) ‘Temperature Measurement of Power Cable Based on Distributed Optical Fiber Sensor’, *Journal of Physics: Conference Series*, 679(12053), pp. 1–2. doi: https://doi.org/10.1088/1742-6596/679/1/012053.

Slagstad, H. and Brattebø, H. (2014) ‘Life cycle assessment of the water and wastewater system in Trondheim, Norway – A case study’, *Urban Water Journal*, 11(November), pp. 323–334. doi: 10.1080/1573062X.2013.795232.

Statistics Norway (2015) *ssb.no*. Available at: https://www.ssb.no/statistikkbanken/ (Accessed: 20 May 2015).

Statistics Norway (2018) *SSB*. Available at: https://www.ssb.no/befolkning/statistikker/folkemengde/aar-per-1-januar.

Staufer, P., Scheidegger, A. and Rieckermann, J. (2012) ‘Assessing the performance of sewer rehabilitation on the reduction of infiltration and inflow’, *Water Research*, 46(16), pp. 5185–5196. doi: 10.1016/j.watres.2012.07.001.

Stefan, H. G. and Preud’homme, E. B. (1993) ‘Stream temperature estimation from air temperature’, *JAWRA Journal of the American Water Resources Association*, 29(1), pp. 27–45. doi: 10.1111/j.1752-1688.1993.tb01502.x.

Strutt, J. *et al.* (2008) ‘Assessing the carbon footprint of water production’, *Journal / American Water Works Association*, 100(6).

Sundt-Hansen;, L. E. *et al.* (2017) ‘Modelling climate change effects on Atlantic salmon: Implications for mitigation in regulated rivers’, *Science of the Total Environment*, 631–632, pp. 1005–1017. Available at: https://doi.org/10.1016/j.scitotenv.2018.03.058.

Todd, D. K. (1980) *Ground-Water Hydrology*. 2nd edn. New York: John Wiley.

Trondheim Municipality (2013) *Hovedplan avløp og vannmiljø 2013-2014 (Masterplan for water and wastewater)*. Trondheim, Norway. doi: 11/27828.

Tuccillo, M. E. *et al.* (2011) ‘Field Demonstration of Electro-Scan Defect Location Technology for Condition Assessment of Wastewater Collection Systems’, *Water Environment Federation*, 17, pp. 265–281. doi: doi.org/10.2175/193864711802837309.

Tuomari, D. and Thompson, S. (2003) ‘Sherlocks of storm water’ effective investigation techniques for illicit connection and discharge detection’, in *Proceedings of the National Conference on Urban Storm Water, Chicago, IL, USA, February 17–20, 2003*. Chicago, IL, USA.

Tyler, S. W. *et al.* (2009) ‘Environmental temperature sensing using Raman spectra DTS fiber-optic methods’, *Water Resources Research*, 45(4). doi: 10.1029/2008WR007052.

Venkatesh, G. (2011) *Systems performance analysis of Oslo’s water and wastewater system*, *Doctor*. Trondheim, Norway: PhD Thesis, Norwegian University of Science and Technology (NTNU).

Venkatesh, G. *et al.* (2017) ‘Metabolism-modelling approaches to long-term sustainability assessment of urban water services’, *Urban Water Journal*. Taylor & Francis, 9006(March), pp. 11–22. doi: 10.1080/1573062X.2015.1057184.

Venkatesh, G., Hammervold, J. and Brattebø, H. (2009) ‘Combined MFA-LCA for analysis of wastewater pipeline networks: Case study of Oslo, Norway’, *Journal of Industrial Ecology*, 13(4), pp. 532–550. doi: 10.1111/j.1530-9290.2009.00143.x.

Venkatesh, G., Sægrov, S. and Brattebø, H. (2014) ‘Dynamic metabolism modelling of urban water services - Demonstrating effectiveness as a decision-support tool for Oslo, Norway’, *Water Research*. Elsevier Ltd, 61, pp. 19–33. doi: 10.1016/j.watres.2014.05.004.

Vercauteren, N.; Huwald, H.; Bou-Zeid, E.; Selker, J. S.; Lemmin, U.; Parlange, M. B.; Lunati, I. (2011) ‘Evolution of superficial lake water temperature profile under diurnal radiative forcing’, *Water Resources Research*, 47(W09522). doi: 10.1029/2011WR010529.

Villarroel Walker, R. *et al.* (2014) ‘The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism’, *Journal of Environmental Management*. Elsevier Ltd, 141, pp. 104–115. doi: 10.1016/j.jenvman.2014.01.054.

Vosse, M. *et al.* (2013) ‘Processing of DTS monitoring results: Automated detection of illicit connections’, *Water Practice and Technology*, 8(3–4), pp. 375–381. doi: 10.2166/wpt.2013.037.

Webb, B. W. *et al.* (2008) ‘Recent advances in stream and river temperature research’, *hydrological Processes*, 22(7), pp. 902–918.

Westhoff, M. C.; Gooseff, M. N.; Bogaard, T. A.; Savenije, H. G. H. (2011) ‘Quantifying hyporheic exchange at high spatial resolution using natural temperature variations along a first-order stream’, *Water Resources Research*, 47(W10508). doi: 10.1029/2010WR009767.

Westhoff, M. C.; Savenije, H. H. G.; Luxemburg, W. M. J .; S., Stelling G.; van de Giesen, N. C.; Selker, J. S.; Pfister, L.; Uhlenbrook, S. (2007) ‘A distributed stream temperature model using high resolution temperature observations', *Hydrology and earth system science*, 11(4), pp. 1469–1480. doi: 10.5194/hess-11-1469-2007.

Yilmaz, G. and Karlik, S. E. (2006) 'A distributed optical fiber sensor for temperature detection in power cables', *Sensors and Actuators A: Physical*, 125(2), p. 148/155. doi: 10.1016/j.sna.2005.06.024.

Zhang, M. *et al.* (2018) 'Quantifying rainfall-derived inflow and infiltration in sanitary sewer systems based on conductivity monitoring', *Water Research*, 558, pp. 174–183. doi: 10.1016/j.jhydrol.2018.01.002.

Zhou, Y. H. *et al.* (2016) 'Feedback Design of Temperature Control Measures for Concrete Dams Based on Real-time Temperature Monitoring and Simulation of Construction Process', in *4th APG Symposium and 9th EADC on INNOVATIVE TECHNOLOGIES FOR DAMS AND RESERVOIRS TOWARD THE FUTURE GENERATIONS in Sapporo, Japan*, pp. 97–102.