DOCTORAL THESIS

Decentralized Real-Time Control Platform for Urban Drainage Systems in Climate Proof Smart Cities

Nils Kändler

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NILS KÄNDLER

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TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Civil Engineering and Architecture
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Supervisor:
Professor **Ivar Annus**
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Co-supervisor:
Professor **Raido Puust**
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Opponents:
Associate professor **Franz Tscheikner-Gratl**
Faculty of Engineering
Norwegian University of Science and Technology
Trondheim, Norway

Professor **Tiit Tammaru**
Faculty of Science and Technology
Institute of Ecology and Earth Sciences
University of Tartu
Tartu, Estonia

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Nils Kändler

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Contents

List of Publications

The list of author’s Publications, on the basis of which the thesis has been prepared:

Journal papers

I Kändler, N.; Annus, I.; Vassiljev. (2021). **Controlling peak runoff from plots by coupling street storage with distributed real time control**. Urban Water Journal. In press.

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III Kändler, N.; Annus, I.; Vassiljev, A.; Puust, R. (2019). **Peak flow reduction from small catchments using smart inlets**. Urban Water Journal. DOI: 10.1080/1573062X.2019.1611888.

Conference papers

IV Malik, H.; Kändler, N.; Alam, M. M.; Annus, I.; Le Moullec, Y.; Kuusik, A. (2018). **Evaluation of Low Power Wide Area Network Technologies for Smart Urban Drainage Systems**. Proceedings of 2018 IEEE International Conference on Environmental Engineering (EE).: 2018 IEEE International Conference on Environmental Engineering (EE), Milan, 2018, pp. 1-5. Milan, Italy: IEEE, 1−5. DOI: 10.1109/EE1.2018.8385262

V Kändler, N.; Annus, I.; Kaur, K.; Vassiljev, A. (2019). **Operative module to reduce peak flow in urban drainage system**. In: The Sixteenth International Conference on Civil, Structural & Environmental Engineering Computing, 16-19 September 2019. Elsevier.

VI Kändler, N.; Annus, I.; Vassiljev, A.; Puust, R.; Kaur, K. (2019). **Controlling Stormwater Runoff from Impermeable Areas by Using Smart Inlets**. Green Energy and Technology: New Trends in Urban Drainage Modelling. UDM 2018. Ed. Mannina, G. Springer, Cham, 263−268. DOI: 10.1007/978-3-319-99867-1_44.

VII Kändler, N.; Annus, I.; Vassiljev, A.; Puust, R.; Kaur, K. (2018). **Smart In-Line Storage Facilities in Urban Drainage Network**. Proceedings, 2 EWaS3 2018: The 3rd EWaS International Conference on “Insights on the Water-Energy-Food Nexus”, Lefkada Island, Greece, 27–30 June 2018. Ed. V. Kanakoudis and E. Keramaris. MDPI, 631. DOI: 10.3390/proceedings2110631.

Author's Contribution to the Publications

Contribution to the papers in this thesis is:

I Organizer and main writer for the Publication.

II Organizer and main writer for the Publication.

III Organizer and main writer for the Publication.

IV Co-author of the Publication. Contribution in the definition of the objectives, creation of the system's model with the typical urban drainage manhole and the conclusions of the work.

V Organizer and main writer for the Publication.

VI Organizer and main writer for the Publication. Presenter of the paper.

VII Organizer and main writer for the Publication. Presenter of the paper.

Introduction

In front of you lies the summary of the work across several years focused on smart urban stormwater systems, their decentralized control algorithms, components and efficiency analysis for improving pluvial flood resilience of urban space. The thesis is written as a dissertation based on four Publications (I, II, III and IV) and a summary article bridging and summarizing the methodology and findings presented in the articles.

Challenges of urban water services

Urban water and wastewater systems starting from raw water source, water purification plant, water conveyance and distribution network, sewer and stormwater drainage system, wastewater treatment plant, and receiving water are vital engineering domains present in every modern city and blood vessels that make cities liveable (see Figure 1). All these systems are part of a built environment, which means that they have to be persistently supervised and managed by civil engineers to ensure an adequate response to outer disturbances.

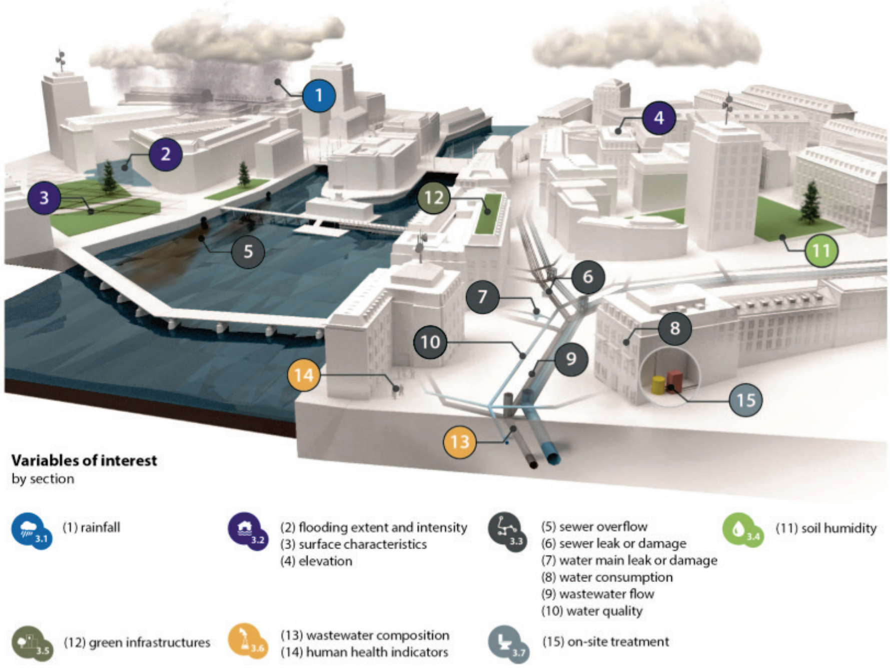

Figure 1. The main scope of urban water systems according to Eggimann et al. (2017)*.*

Cities are social hubs standing on the crossroads of a global economy and are therefore in constant process of change and development. The urban population of the world has grown rapidly from less than a million in 1950 to 4.2 billion in 2018. According to The United Nations, this trend is irreversible and 68% of the world population is expected to live in urban areas by 2050 (UN Department of Public Information, 2018). This has a severe impact on the rise of water demand, which is expected to increase by 55% by the year 2050, as predicted by OECD (OECD, 2012). This means that civil engineering infrastructure is facing a major challenge, ensuring constant enlargement and undisrupted service to keep expanding and densifying cities flourishing. The growth of the urban population has required an increase in the construction of buildings and roads, which has resulted in sealing off natural surfaces and breaking the water cycle. The soil has lost rainwater absorption capacity, making cities more vulnerable to flooding in the presence of rain events (García et al., 2014).

Finding resources and solutions for infrastructure expansion is not the only task utilities have to tackle while also the existing facilities need constant attention. Substantial parts of the water systems, especially the pipeline networks in Europe and United States are reaching the end of their life span (Berglund et al., 2020), resulting in high risk of potential pipe bursts, environmental hazards and compromised water quality.

A third megatrend shaping the water industry in the coming decades is climate change. This makes weather more turbulent and unpredicted, affecting the cities in different ways (S. Guerreiro et al., 2018). In some locations like in southern hemisphere, it accelerates droughts and heatwaves, while in other areas, it causes cloudbursts, snowstorms and floods. Rise of the sea level affects globally all metropolises situated at the shore. In the northern hemisphere, this is expected to affect rainfall intensities and frequency of extreme precipitation events (H. Madsen et al., 2014). The study of climate vulnerability of 571 European cities showed that the risks of floods (pluvial, fluvial and costal), heatwaves and droughts are consistently high in a large number of cities across Europe (Tapia et al., 2017). According to the climate models, forecasted peak intensities exceed the design values used to construct most of the stormwater infrastructure in Europe (S. B. Guerreiro et al., 2017).

Cities and towns with combined sewer systems, i.e., stormwater and wastewater conveyed in the same pipeline, are the most affected by these factors described above. Combined sewer systems have typically dedicated spots – combined sewer overflows (CSO) where the excess water is let out from the system into the nature to avoid hydraulic overload of the wastewater treatment plant (WWTP). Both urbanization and climate change are increasing combined sewer overflows affecting negatively the quality of natural water bodies. Water quality study in Copenhagen in 2012 revealed that stormwater runoff from CSOs and independent outlets contributed 64% of the total discharge of Perfluorinated chemicals or Perfluorochemicals (PFC), while WWTPs contributed only 36% (COHIBA, 2010). Runoff from urban areas is responsible for 12% of the total nitrogen and 24% of total phosphorus loads to the Baltic Sea in 2014 (HELCOM, 2018). These numbers will probably increase because of the impact of climate change (Eckart et al., 2017).

Addressing the risk of pluvial floods

Although major challenges are ahead for the whole urban water sector, this thesis focuses mainly on urban drainage systems (UDS) with combined or separate stormwater collection (see Figure 2). If the capacity of the stormwater facilities is exceeded, the system becomes surcharged and will most likely cause pluvial flooding. Flooding with larger extent is in many cases a major disruption in the urban environment, posing risk on human health and properties (Hammond et al., 2015). It can also trigger cascading effects of failure of other critical infrastructure like electricity networks, telecommunication networks, traffic and railway transport (de Bruijn et al., 2017).

The financial loss of pluvial flooding can be also significant. For example, 3.8 million properties are thought to be at risk from pluvial flooding in UK (Environment Agency, 2009). In the Netherlands, total damage between 1986 and 2009 from pluvial flood was 674 million euros (Sušnik et al., 2015).

Flooding has also direct negative impact on the environment and the water quality of receiving waters. Firstly, the pollutants accumulated on the surface are washed off during the event; secondly, wastewater from separate sewer pipeline typically constructed in parallel with the stormwater system can cause spillage during the event; and thirdly, untreated water will be led to the receiving water through the CSOs. Pluvial flooding has also direct financial consequences. Sušnik et al. (2015) calculated that even in the case of quite moderate flood depths that are not exceeding 0.2 m, the cost of damage per affected property is over two thousand euros. The total sum of flood losses will reach millions of euros per event even for moderately small communities in Europe.

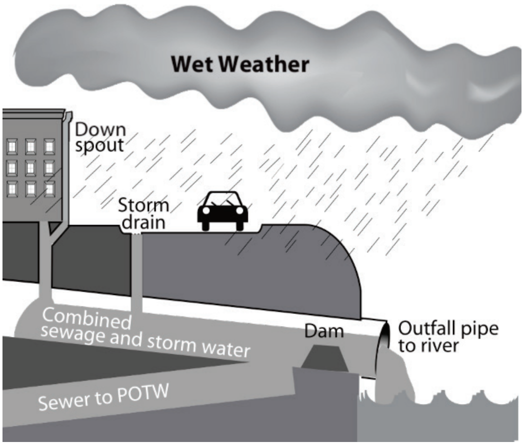

Figure 2 Typical layout of an urban drainage system (U.S. Environmental Protection Agency, 2004).

Due to the severe impact of pluvial floods there is extensive research ongoing to seek feasible solutions for flood risk reduction and alleviation of the negative impacts. Despite that effort, still research gaps exist in the field, especially those related to predictive and decentralized control systems that can be applied to existing UDS with minimum cost and the maintenance of which is executable for utilities and municipalities. The main gaps addressed in this thesis are the following:

- There are no feasible out-of-box predictive control solutions currently available to apply in real urban environment to mitigate the risk of pluvial floods (Campisano et al., 2013).
- Predictive control algorithms like model predictive control (MPC) have proven to be an efficient method for controlling UDS lack of adaptive, robust, decentralized and distributed application (García et al., 2015).
- Most of the predictive control systems developed have centralized nature and are designed to control system elements in series, i.e., consecutive tanks and need therefore actuators to be placed to the main collectors, which makes the implementation technically and financially challenging (Saraswat et al., 2016).
- There is lack of solutions available for decentralized inlet control that could be developed gradually and do not need extensive underground works for implementation, i.e., construction of tanks and chambers.

Static solutions to dynamic problem

Cities have traditionally responded to the increasing demands in the stormwater sector by expanding grey infrastructure, i.e., installing new pipelines, storage tanks and also enlarging existing mains and pumping stations. According to Kerkez et al. (2016), large-scale adaption to tackle the challenges utilizing these traditional methods may lead to overdesigned infrastructure triggering new problems like conveying water too quickly to downstream, floodplain encroachment, increasing runoff volumes and stream erosion.

In addition to the adverse effects of large-scale enlargement, it is also in many cases financially unrealistic. Rebuilding pipelines and constructing underground storage tanks in a dense urban area in the vicinity of other critical infrastructure lines like electricity network is an expensive effort. For example, replacing 20% of the stormwater network in Tallinn, Estonia, to handle larger flowrates will cost more than 100 million euros. In larger cities, the length of the pipeline network is in thousands of kilometres and the cost for such effort is immense. Such construction plan takes decades and means constant disruption of everyday life in the urban environment. Building underground retention tank with the capacity of 250 thousand m^3 to protect Tokyo from floods took 13 years and cost 2 billion dollars (Arguedas Ortiz, 2018).

Therefore, in the world of limited financial resources, the role of scientists and engineers is to seek more efficient, fast and feasible solutions to solve the major challenges ahead. The change has already started in many cities worldwide, for example, extreme rainfall event in 2011 has driven series of innovation and improvement of urban knowledge systems towards better adaption for pluvial flooding in Copenhagen, Denmark (H. M. Madsen et al., 2019).

Low impact development

Low impact development (LID) is a countermeasure against an enlargement of impermeable areas in cities and tackling impact of climate change. LID is typically a set of distributed stormwater control solutions, often named also as “green infrastructure” (GI) created and installed in order to restore natural water cycle in urban areas closer to pre-development conditions (Eckart et al., 2017). In some publications, it is also called as water sensitive urban design (WSUD) or sustainable urban drainage systems (SuDS), as pointed out by Fletcher et al. (2015). Specific examples of LID include, for example, green roofs, rain gardens, bioretention cells, and permeable pavements.

LID solutions can be placed to the watershed either by retrofitting existing grey infrastructure, like covering parking areas with permeable asphalt or using existing green areas like parks and lawns as a part of stormwater conveyance system to foster detention, infiltration and treatment. In terms of performance, LID has shown both high efficiency in runoff reduction (Palla & Gnecco, 2015) and water quality improvement (Eckart et al., 2017). According to these authors, typical runoff reduction is between 50 – 80% and the units are capable of reducing total nitrogen, total phosphorus, total suspended solids and other pollutants in the water.

Besides significant advantages, there are notable limitations and barriers to LID becoming more accepted and widely applied for tackling the water challenges. According to Eckart et al. (2017), the main limitations are related to not having standardized solutions, risk on ground water contamination and dependence on specific site conditions like available free space. Critical analysis is needed to be done prior to introducing any on-ground flood mitigation measures to minimize subtraction of these areas from public space, affecting the quality of everyday living environments of urban citizens (Sörensen et al., 2016).

In addition to that, the main barriers listed in the literature are related to community engagement, lack of familiarity with LID practises, lack of experienced contractors and knowledge about maintenance. Monitoring and evaluation of shortcomings pointed out by Campisano et al. (2013) are the main reasons holding back integration with other stormwater systems in the urban area to maximize their efficiency in the improvement of climate resilience. As a result of these barriers, LID remains a local and fragmented solution for mitigating pluvial flood risks.

Smart city innovation

In the last decades, the concept of “smart city” has become more popular in scientific research, politics and business sector. The term itself was first used in the 1990s and its definition is still evolving. The concept involves a diverse range of things like information technology, business innovation, governance, communities and sustainability (Hollands, 2008). Albino et al. (2015) have listed more than twenty different definitions on “smart city”. The main reason of that variability is that a particular definition depends on the sector – whether social, governance or infrastructure is intended to be “smartened”. Smart city concept has been also presented as an opportunity to address the infrastructure problems and improve their performance through novel technology based solutions (Berglund et al., 2020). This thesis focuses on urban infrastructure, therefore the definition suggested by Marsal-Llacuna et al. (2015) is used as a background of the current research: “*Smart Cities initiative tries to improve urban performance by using data, information and information technologies (IT) to provide more efficient services to citizens, to monitor and optimize existing infrastructure, to increase collaboration amongst different economic actors and to encourage innovative business models in both the private and public sectors*”.

In this definition, the key of the smart city solutions is information and communication technologies (ICT) in conjunction with the Internet of things (IoT), which enables fast wireless data exchange, processing and algorithms to be delivered to the actuators to automatically adjust parameters of an infrastructure object. It is also a holistic method as ubiquitous sensing and modelling allows one to automatically estimate the impact of any particular setting on the whole system in the urban space. Smart city concept can also be divided into hard domains like energy grids, water systems, transportation and soft domains named education, social welfare, administration and governance and economy (Berglund et al., 2020). The common characteristic of these domains is enabling future technologies and bringing together sectors that have previously operated independently (Figure 3). Smart infrastructure represents the hard domain of smart cities and can be defined according to Berglund et al. (2020) based on the core components like:

- connected technologies to create interconnected networks;
- infrastructure system that is smartened;
- environmental systems that provide essential services.

The integration of ICT within the urban environment enables the use of other smart, i.e., self-adaptive technologies like water meters, real-time automated control systems, sensors and citizen warning solutions (Albino et al., 2015). It is also a significant business market estimated to increase to 2 trillion USD by 2025 (Zion Marker Research, 2018).

Figure 3. Wider context of smart infrastructure programs to utilize enabling technologies (Berglund et al., 2020).

Despite the growing interest and market, many authors have pointed out that most of the investments in new smart city technologies focus on transportation and entertainment, while more important and urgent urban challenges like flooding hazards are in many cases neglected (Berglund et al., 2020). Smart stormwater systems are one of the emerging hard domains in smart city technologies (J. Li et al., 2019). Kerkez et al. (2016) define the smart stormwater infrastructure as the system that provides constant information about the flows and is capable of adapting itself in real-time to changing storms and land uses. According to Bartos et al. (2017), the smart stormwater systems are promising high reliability, user friendliness and are also cost efficient compared to the traditional pipe focused solutions.

Smart infrastructure and real time control

An efficient way to improve the performance of any engineering system is to apply some sort of automated control system to existing facilities that will utilize predefined control loops to aid to adapt static infrastructure to dynamic loads and outer disturbances. The first control systems were implemented at the end of the 1960s in the United States (U.S. Environmental Protection Agency, 2006) and have rapidly evolved until today.

Real-time sensing and remote control of environmental systems is not a new idea. Supervisory control and data acquisition (SCADA) has proven its reliability in monitoring and control of water infrastructure and is in use in many water utilities worldwide (Aburawe, 2019). Most of SCADA systems are designed and used to monitor conveyance, treatment and distribution of water. It is a centrally controlled system where data is processed in one main server, control commands can be manual or automatic and the system may incorporate some sort of optimization routines (Gray et al., 2017).

The control can be either:

- **off-line based on heuristics** and expert knowledge without having on-line interference with the system and therefore controlling the actuators according to some pre-set values (García et al., 2015).

- **executed in on-line**, i.e., real-time, which means the process variables are monitored in the system and continuously used to operate actuators in the process (Schuetze et al., 2003). Real-time control (RTC) can be either basic regulatory reactive or more elaborate, predictive system with online models and weather forecasts (Ane Loft Mollerup et al., 2015). Implementation of RTC requires a simplified theoretical representation model of the real system in order to find the actuators' settings (see Figure 4).

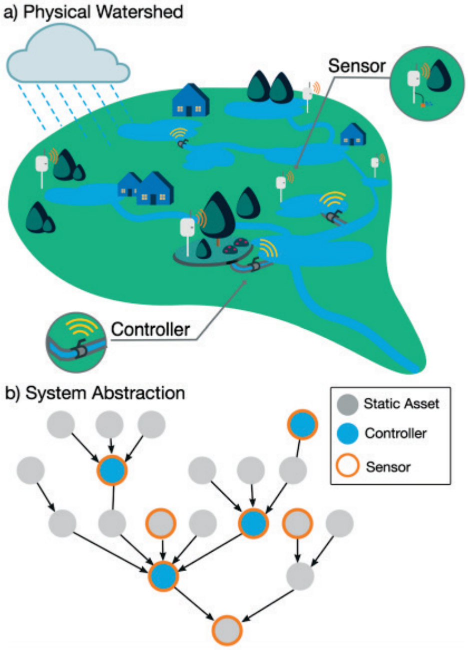

Figure 4 Real physical setup (a) and the abstraction of the system (b) for implementing RTC (Mullapudi et al., 2017).

The example of the first control type is a typical SCADA system used to operate, for example, wastewater treatment plants, pumping stations or water network. As the system is stable with similar diurnal changes and high inertia, fast automatic adaption is typically not needed in the operation (García et al., 2015). On the contrary, real time control systems open a possibility for quick changes to adapt unforeseen rapid processes like cloudbursts in urban areas (Schuetze et al., 2003). Time of concentration from smaller impervious urban catchments can be measured in minutes, therefore fast response is crucial to interfere with operative commands. Therefore, regulatory control systems like model predictive control, allowing creation of pro-active commands for the system, have gained attention in recent years among researchers (Abou Rjeily et al., 2018).

Despite wide usage and popularity in the water industry, there are three main limitations in SCADA that hinder their wider application in stormwater management systems - **interoperability, scalability and security** (Bartos et al., 2017; Kerkez et al., 2016). Traditional SCADA systems are often isolated, having incompatible programming language and therefore incapable of intercommunication (Pliatsios et al., 2020). Most of SCADA has limited possibilities to interfere with modern data analytics software like geographic information systems (GIS), modelling software, open-access databases like weather prediction (Phuyal et al., 2020).

The capacity of SCADA systems to incorporate ubiquitous sensing paradigm to upscale to monitoring of whole urban catchments is the second main deficiency. Sensors are typically placed into few selected locations in the network, like pumping stations and treatment plants. For decentralized systems like stormwater detention utilities or low impact development (LID) sites, the cost and power usage of SCADA is prohibitive (Kerkez et al., 2016).

Although SCADA networks are typically isolated from public networks, the security of such centrally controlled systems remains the third main concern. Many SCADA systems are built on the protocols like such as MODBUS/TCP, EtherNet/IP and DNP317 that have no possibility for authentication (Ghosh & Sampalli, 2019), which means that it is possible to execute unauthorized commands if the system is hacked. Isolation from public networks increases security, but it also prevents utilizing powerful cloud-based data analytic systems and communicates with many sensors scattered along the UDS.

SCADA systems retain their importance in isolated control systems like treatment plants. However, to tackle the challenges of the water industry, new control tools are needed to improve security, expand coverage and integrate control system with other critical infrastructure (Kerkez et al., 2016). Yuan et al. (2019) conclude in the extensive review of automation in urban water systems that adaption of ICT in urban water management is far behind the other process industries, because of four major reasons:

- **economic barriers** like “low” product price of water, profit motives that hinder investment into new technologies, also high cost of remote sensing;
- **technical reasons** like reliability of online sensors, insufficient flexibility in coupling of design and operation, lack of knowledge about real-time control among environmental engineers designing new facilities;
- **regulatory reasons** supporting utilizing public urban space for water detention, opposition of on-line sensors from public authorities traditionally relying on laboratory analyses;
- **the human factor** like barriers in life time education to introduce modern technologies like ICT among utility workers, trusting self-regulatory control systems.

Objective of the thesis

Tackling challenges of urban water systems needs integrated, affordable and reliable engineering solutions. It is evident that none of the challenges related to urban stormwater issues can be solved using just one method like pipe oriented solutions or LIDs. The key of success is integration of different measures into united smart system scattered over urban space. Spatial and constructional diversity on the other hand, needs reliable real-time control systems to harness the maximum capacity of this integration. And last but not least, all the solutions have to be feasible in economic terms and have reliable reputation in order to have acceptance from public authorities.

The main objective of the thesis was to develop a methodology for predictive decentralized real-time control solution for urban stormwater systems that needs minimum computational power, is efficient in terms of flood risk reduction and can be implemented with minimum cost and construction effort.

Implementation of RTC systems on drainage network usually requires considerable investments and tools such as sensor instruments, remote monitoring, mathematical modelling and algorithms. For this reason, RTC potential and benefits must be identified in advance prior to any real investments to justify the feasibility of the system. Therefore, one of the objectives of the work presented in this thesis is to provide a clear methodology for this type of assessment with RTC example implementations on three pilot sites in Publications I, II and III.

Smart drainage systems are seen in the thesis complementary to other methods like LID, grey infrastructure and are meant to augment rather than replace the current infrastructure. The work also aims to widen the smart infrastructure field by creating applicable solutions addressing urgent urban challenges by using the smart city concept. The thesis supports the improvement of terminology and showcases protypes to inspire designers and urban planners to use the solutions in real urban environment.

To achieve the objectives above, the following tasks have been completed:

1. Development of the prototypes of the actuators capable of controlling the inflow to the UDS (Publication I, II and III);
2. Development of the fast model predictive algorithm that needs no optimization for forecasting and needs input only from level sensors (Publication I);
3. Development of a filter and smoothing algorithm for processing sensor data (Publication I);
4. Development of the methodology to automatically identify control locations in an urban drainage system (Publication I);
5. Selection of the best communication technology for the sensors placed into the UDS manholes (Publication IV).

Layout of the thesis

The thesis is written as a dissertation based on four Publications (I, II, III and IV). The research papers are included as separate appendixes 1 to 4 located at the end of the thesis.

Introductory chapter provides a general overview of the field and defines the objectives of the thesis.

Chapter 1 reviews the relevant literature and outlines the main methodology used in the research that is summarized in this thesis. Technologies forming a cornerstone of the real time system as modelling, sensors, data processing, actuators are described in more detail in conjunction with the description of real-time control algorithms and methods for predicting system statuses.

Chapter 2 gives an overview of the methodology and developed predictive RTC solutions.

Finally, **Chapter 3** demonstrates the application of the methodology in Chapter 2 in three pilot sites and draws the conclusions of the analysis, listing research paths needed to be investigated in the future.

Abbreviations

CSO	Combined sewer overflow
DEM	Digital elevation model
DMPC	Distributed model predictive control
GA	Genetic algorithm
GI	Green infrastructure
HiFi	High fidelity (model)
ICT	Information and communication technologies
IoT	Internet of things
LID	Low impact development
MPC	Model predictive control
NPV	Net present value
NPV	Net present value
PFC	Perfluorochemicals
PID	Proportional integral derivative (control)
RCP	Representative Concentration Pathway
RTC	Real time control
SCADA	Supervisory control and data acquisition
SSU	Street storage unit
SuDS	Sustainable urban drainage systems
TC	Total cost
UDS	Urban drainage system
WSUD	Water sensitive urban design
WWTP	Wastewater treatment plant

Symbols

Latin capital letters	
A_L	Area of the lower part of SSU, [m^2]
A_U	Area of the upper part of SSU, [m^2]
B_n	Minutes before the flood event when backflow existence is checked, [min]
C	Set of constraints
D_g	Diameter of the sluice gate, [m]
F_n	Future payment, [EUR]
H	Measured heads, [m]
H_*	Threshold head, [m]
H_1^{i+P}	Predicted upstream head, [m]
H_2^{i+P}	Predicted downstream head, [m]
I_n	Stormwater inlet *n*
L_s	Length of the enlarged pipe section in in-line storage, [m]
P	Prediction horizon, [min]
Q_t	Threshold flow, [l/s]
S_i	Sensor
V_{fl}	Threshold flooding volume, [m^3]
V_s	Volume of the in-line storage, [m^3]
V_{th}	Required storage volume, [m^3]
Y_{full}	Diameter of the orifice, [m]
Z_0	The absolute elevation of the orifice crest, [m]
Latin lower-case letters	
a	Variables
b_i	Boundary
$f_{1(q,t)}$	System hydrograph
$f_{1\text{-}re(q,t)}$	Restricted system curve
$g_i(a)$	Constraint function
h_m	Manhole depth, [m]
h_{max}	Maximum safe water depth in SSU, [m]
h_{th}	Threshold water level, [m]
i	Timestep, [min]
u	System setting
u_n	Control command to change system setting for actuator *n*
w_n	Information exchange between MPC units
x_n	Input data from sensors to MPC
Greek letters	
ω_i	Orifice setting

1 Real-time control of urban drainage systems

Urban drainage systems are typically designed to operate as a passive infrastructure with little possibilities to adapt the system with dynamic and stochastic loads like cloudbursts. Therefore, their potential to handle more intense rainfall events is not fully utilized (Kerkez et al., 2016). If a system operates in the environment with stochastics nature, like stormwater systems in the urban environment, the control decision has to be done quickly, i.e., in real time or even in predictive manner, to respond to the outer changes in time. For that reason, real-time control (RTC) is viewed as an efficient method to reduce the magnitude of disturbances and improve the operation of UDS to adapt the system to changing environmental conditions (van Daal et al., 2017).

An urban drainage system is controlled in real time if the process information like water levels in the pipeline, flows, etc. are monitored on-line and actuators like pumps and gates are operated on the basis of that data. The overall objective of a typical RTC system is to improve the performance of the UDS – reduce the activation of CSOs, ensure a constant load to a WWTP, reduce the risk of floods in case of system's surcharge and trigger controlled floods in the locations where they cause minimum harm (Schütze et al., 2008).

The aim of this chapter is to give a literature review on the typology and components of RTC in order to provide a comprehensive background for the research of RTC systems, current research gaps and developed solutions presented in the thesis in Chapters 2 and 3.

1.1 Hierarchy of UDS control systems

Efficient control setup has to be fully compatible with a real-world situation of the UDS, considering both objectives for a longer and shorter time period. To distinguish between these different time scales, a control hierarchy was proposed by A. L. Mollerup et al. (2017) and further developed by Lund et al. (2018). According to these authors, the hierarchy contains four levels, each of them having slightly different timescale, objectives and tasks (see Figure 5).

The measurements with a time scale of seconds are providing data for the regulatory control layer, which will give commands to the system's actuators within minutes. Regulatory control is the most widely used operational method in the water industry (Yuan et al., 2019). It is typically a simple rule-based-control or proportional-integral-derivative (PID) control algorithm without any disturbance analysis (Ane Loft Mollerup et al., 2015). The second level aims to manage also constraints and interactions between the control loops and consider interactions between different parts of the UDS. This level is typically decentralized, considering interaction between the different control loops. The timescale of this layer is counted in minutes, which is sufficient to run simpler MPC or rule based control algorithms (Svensen et al., 2019).

If more complex objectives are set, an optimization layer is typically included into the control system, which will aid to determine the setpoint trajectories and multi objective control tasks**. Optimization makes the timescale of the process substantially longer, which is a shortcoming in the systems that need fast response to the changing environmental conditions** (Sadler et al., 2019). The highest level of control hierarchy has a substantially longer timescale, which is needed to consider different scenarios of costs and constraints, for example, consider seasonal changes. This is typically solved by rule based control that is switching the system between the preset scenarios (Meneses et al., 2018).

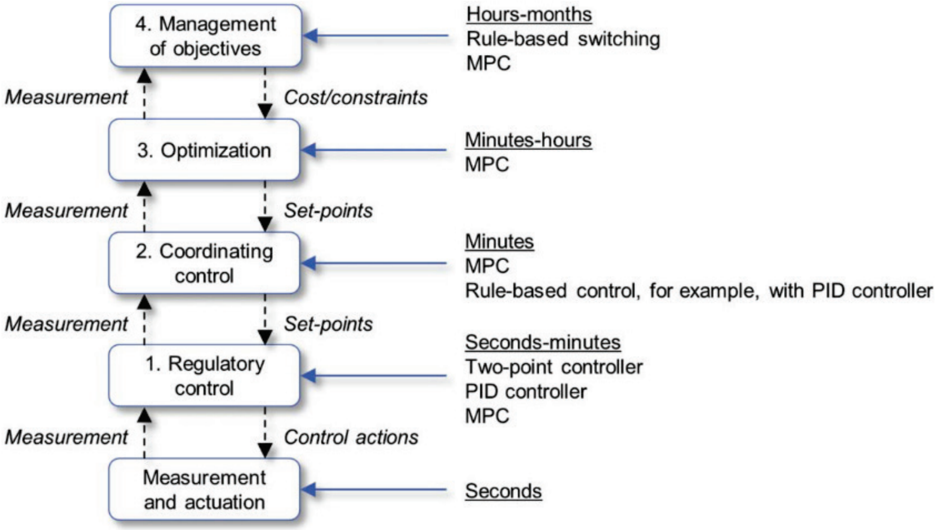

Figure 5 Different timescales of UDS control solutions (Lund et al., 2018).

The control solutions presented in this thesis in Chapter 2 contribute to the first three control layers, starting with a regulatory control in Publication III, developing coordinating and optimization in Publication II and combination of the two first layers in Publication I. The thesis also improves the applicability of MPC systems, demonstrating the solution with a minimum need for optimization (Publication I).

1.2 Basic components of RTC systems

The architecture of any RTC system can be structured as a control loop implemented by hardware components like sensors, actuators, controllers, and a telemetry system (see Figure 6). Sensors collect information about the current status of the system. The communication unit sending the data to the controller is typically in the same compound with the sensor. The controller processes the data and it can also use other data sources like radar information for rainfall prediction to create control actions for the actuator. An actuator is a unit to interfere with the process under control, e.g., regulate the flow in the pipeline. It can be, for example, a movable gate, a valve with an electric motor or a pump. As the actuator is typically not in the vicinity of the control system, it is equipped with a communication unit to send and receive the data between the controller.

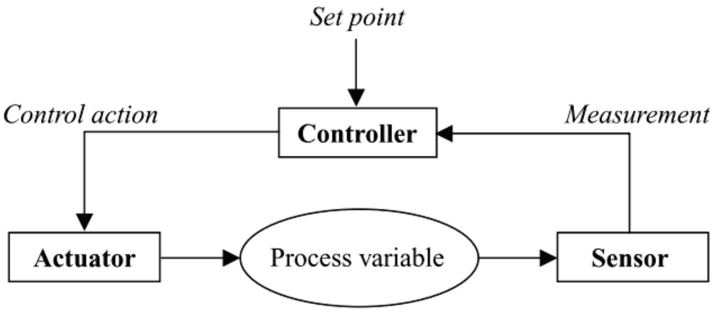

Figure 6. Basic scheme of the control looped system (Campisano et al., 2013).

The type of the control loop of RTC can be either **feedback** or **feedforward** (Schuetze et al., 2003). In the first case, commands are actuated depending on the measured deviations from the setpoint. Feedforward control anticipates the future values of these potential deviations using an inner model of the system and activates controls ahead of time to proactively respond to system changes. Model predictive control (MPC) is a typical example of a feedforward looping (Abou Rjeily et al., 2018).

Typical UDS is a complex system with a large spatial coverage, which means that achieving the management objectives one needs to control simultaneously several locations in the system. There are different control architectures to handle such a situation. These options vary from a centralized system, i.e. SCADA, to decentralized and distributed solutions (García et al., 2015). Centralized control is handled with one common control centre that gives commands to all actuators while in the decentralized type, each actuator has its own control unit that can operate independently (Carbone et al., 2014). The latter one can be developed further by establishing some level of communication between the different controllers (Figure 7), which turns the system to operate in a distributed mode (Christofides et al., 2013).

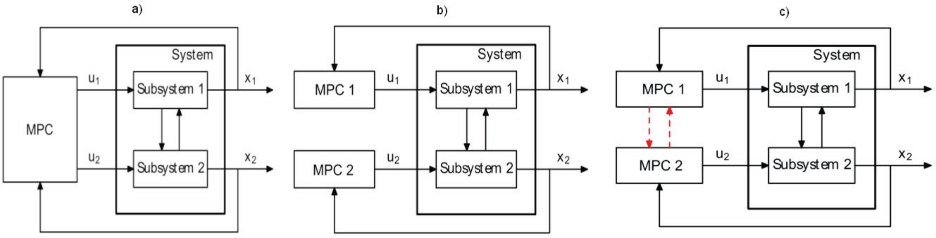

Figure 7 Main types of the control system according to Christofides et al. (2013)*: (a) centralized; (b) decentralized; (c) distributed.*

The research work presented in Chapter 2 contributes to the development and usage of the feedforward type of decentralized (Publication I) and distributed (Publications II, III) control looping utilizing the MPC algorithm. This method has been seen as a promising breakthrough to tackle a challenge of controlling rapidly changing systems like stormwater runoff from the catchments to the underground UDS (Lund et al., 2020).

The work also presents some analysis about signal processing from the sensors to the controller (Publication IV) and suggests design solutions for the actuators (Publications I, II and III).

1.3 Model predictive control

Model predictive control (MPC) is a model-based feedforward control strategy in which the optimal settings are recalculated recursively after new information about the system and new predictions become available (Lund et al., 2018). MPC controller consists typically of four modules: 1) a mathematical model of the system, 2) a cost function to express the control objective, 3) a set of system constraints, and 4) open-loop optimization problem, which is solved at each time instant (Ocampo-Martinez et al., 2013). When applying MPC to UDS, different types of disturbances, for example, rainfall intensities that cannot be directly manipulated by the controller have to be taken into account. According to García et al. (2015), the MPC for UDS can be written as:

$$x(k+1) = Ax(k) + Bu(k) + B_p d(k) \qquad (1)$$

where x denotes the system states, e.g., tank volumes, u is control inputs, e.g., flow through the actuator and d represents measured disturbances, which can be, for example, rainfall intensity or surface runoff. The parameters A, B and B_p describe the system matrix of suitable dimensions and k is the time instant within a previously defined prediction horizon P. Equation (1) is applied for each measurement step, i.e., sampling interval and the whole process is repeated, shifting the prediction horizon by the time instant k (Figure 8).

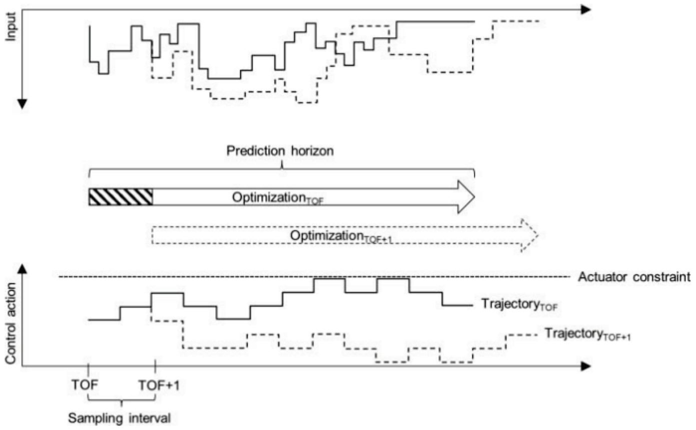

*Figure 8 The receding horizon principle of MPC (TOF denotes a time of forecast) (*Lund et al., 2018).

MPC solutions have been successfully used in industrial applications (Christofides et al., 2013) and several cities such as Barcelona where the technique has shown efficiency in the reduction of CSO overflows in UDS (Ocampo-Martinez et al., 2013). Although MPC theory has been developed into a quite mature stage and is widely used in industrial engineering, some important subjects still remain open in the field of UDS. **These topics are related to adaptive, robust, decentralized and distributed application of MPC** (García et al., 2015). MPC solutions developed and tested in Publications I, II and III contribute to the evolution of the above-named subjects.

1.4 MPC systems for UDS

Most of the current MPC applications in the UDS sector focus on combined sewer systems and have an objective function aiming to reduce CSO overflows during the cloudbursts. For this task, a set of storage tanks (Svensen et al., 2019), in-pipe storage (Garofalo et al., 2017) or detention ponds (Shishegar et al., 2019) are utilized for stormwater peak flow accumulation. The outflow from the compounds is regulated by either controlled gates (Ocampo-Martinez et al., 2013), inflatable dams (Sadler et al., 2020) or valves (Ly et al., 2019).

In these systems, accumulation facilities are typically functioning as a part of the main tunnels, creating interdependent storage cascades, where activation of the upper storage affects imminently the operation of the downstream facilities (Ocampo-Martinez et al., 2013). This setup has several advantages in CSO reduction while closing temporarily the flow in the main tunnel will directly and efficiently affect the spillage volume. Eulogi et al. (2020) have found that the volume reduction in some cases, depending on the design storm, reaches even up to 90%, while others have found more moderate results with an average reduction between 30% and 40% (Piro et al., 2010; Vezzaro & Grum, 2014).

Beside advantages in the CSO flow reduction, the system has also some substantial downsides:

- A need for centralized control system that is capable of analysing the interactions between the control facilities is operating in series (Sun et al., 2020).
- Construction of underground detention tanks is technically and financially challenging. Maintenance of such facilities system needs a lot of effort and is costly (Saraswat et al., 2016).
- The failure of the control system may even accelerate events like flooding and spillages of polluted water into the nature (Duan et al., 2016). Centralized systems are also more vulnerable to cyber threats (Kitchin, 2014) and are more expensive to implement (Berglund et al., 2020).

Simulation and optimization of the inner model for MPC is also challenging in this type of setup because of the high computational cost. According to Shishegar et al. (2018), a mathematical optimization model can be generally described as:

$$max(min)\ f(a) \tag{2}$$

Subject to

$$g_i(a)\{\leq, =, \geq\}b_i \tag{3}$$

$$a_j \in C\ while\ j = 1, 2, \dots, n \tag{4}$$

where *f(a)* is the function that defines the objective of the problem, *a* denotes a set of variables, $g_i(a)$ represents all the functions that together with the boundaries b_i and *C* as a set of constraints determine the constraints for *f(a).* The goal of mathematical optimization is to minimize or maximize the objective function (2). In complex systems like UDS the problem can have several objective functions or with several objectives, which leads to multi-objective optimization that considerably increases the computational time (Monsef et al., 2019).

This means that computational time is longer than sampling interval, which makes it challenging to implement the system in real applications. For example, Abou Rjeily et al. (2018) reached a conclusion that using a genetic algorithm (GA) to find the settings of the gates in a relatively small catchment (30ha) took 10 min with a computer of 60 computing core. Similar results are presented by Sadler et al. (2019) where computational time for 52 ha catchment with using GA for optimization was 132 min per onetime step.

When solving an optimization, the computational time is related to the model size and complexity (Ane Loft Mollerup et al., 2016). Therefore, several simplifications have been developed to make this type of control faster and more feasible. Ocampo-Martinez et al. (2013) used linear virtual tank models instead of simulation of real dynamic processes in tank-pipe systems, while analysis with linear surrogate inner models are suggested by N. S.V. Lund et al. (2020). But even with these diminutions, the computational time and simplifications that drift from the real system can in some cases be limiting factors to apply that solution in larger scale. Moreover, setting up such a control model requires high technical skills in many cases not available in water utility or municipality responsible for stormwater management.

One of the main aims of the research presented in the thesis was to seek solutions for the challenges and shortcomings listed above in order to improve the applicability of MPC for UDS control. In Publications I and III, the focus has been shifted from tunnels and tanks to the inlets that are controlling stormwater flow to underground UDS. Inlet control has several advantages as also concluded by N. S.V. Lund et al. (2020). In this thesis, the idea of controllable inlets has been even more evolved in Publications I and III (see Chapter 2.1).

Controlling inflow from the catchments to the underground UDS opens also possibilities for decentralized control systems while the actuators are not directly situated in the main tunnels as in the case of typical cascading setup (see Chapter2.2). As a decentralized system does not need global settings to be determined at every time step, it was possible to simplify the MPC algorithm and calculate the settings directly, without the need of on-line modelling or optimization (see Chapter 2.3). It improves the computational time (see Publication I) and facilitates the implementation of the control system. Decentralized MPC also improves the reliability of the system while the failure of one or several control units will not affect severely the overall functioning of the UDS (see Publication III).

1.5 Flow prediction and data uncertainty

Forecasting stormwater runoff is one of the key elements of the predictive real time control of UDS with an objective function to reduce the risk of pluvial floods. While any type of forecast is related to a certain amount of uncertainty, it is crucial to decide the proper method and solution for prediction prior to designing RTC for UDS. Commonly, the predictions of the system behavior are made on the basis of long time series, i.e., historical data (Freni et al., 2010) or rainfall on-line measurements (Campisano et al., 2013). However, historical data is not suitable for on-line controlling of urbanized catchments because of the climate change and constant development of urban areas that change the runoff parameters (H. M. Madsen et al., 2019). Measuring rainfall intensities on-line partly overcomes that issue, but this is related to a high uncertainty risk because of a spatial variability of a rainfall event (Tscheikner-Gratl et al., 2016). To overcome that issue, the number of rain-gauges per catchment can be increased (Berne et al., 2004) or gauge data can be combined with radar information to derive information about the spatial distribution in order to reduce the uncertainty (Emmanuel et al., 2015).

Different probabilistic runoff forecasting algorithms have also been developed that address that issue. Löwe et al. (2016) used different mathematical tools like Kalman filter and probability functions for runoff estimation from the sequence of storage tanks, while J. Y. Li & Adams (2000) and Shishegar et al. (2018) developed an analytical probabilistic and stochastic model. These mathematical models are comprehensive, but need a user to define a set of parameters – penalty values, weights and parameters for scaling prior to the computation executed. Authorities responsible for stormwater management might not have full competence to determine these values, which will hinder the real application of these prediction modules.

Different options for simpler and robust predictions have been developed and tested in the thesis (see Chapter 2.3.1) and are presented in the Publications. Predictions are made either on the basis of one local rain-gauge and level measurements from UDS (Publication III), only level measurements from the pipeline (Publication II) or measuring upstream and downstream water levels at the control weir (Publication I).

1.6 Actuators

Actuators are the physical devices that carry out the commands from the control system to react to the changes in UDS. For example, they can close the flow to the downstream of UDS at a flood risk. Nevertheless, they play a crucial role in the control systems; more detailed description of the technical solution is often skipped from research papers. Wong & Kerkez (2018) noticed in their work that controllable gates needed for fast and real-time flow regulation in stormwater systems are still in their infancy. This is mainly because the closing times of typical valves are longer than needed for MPC.

Several research papers have provided sketches about the setup of actuator chambers. Shishegar et al. (2019) proposed gate valves to regulate the outflow from ponds; S.V. Lund et al. (2019) presented a setup of a monitored CSO chamber, RTC equipment is also described by Bartos et al. (2017). In line, gates are sketched by Garofalo et al. (2017) for distributed RTC while many of the authors just provide schemes of the system setup (Sun et al., 2020; Svensen et al., 2019) or photos of the existing facilities (Ocampo-Martinez et al., 2013). Descriptive presentation of the actuators is also quite common in scientific papers (Bilodeau et al., 2018; J. Li et al., 2019; Sørup et al., 2016).

In the thesis, a more detailed presentation of the actuators and related facilities is provided in order to ease the designing and real implementation of the RTC systems in the urban environment. Design parameters with a cross section of the street storage unit (SSU) can be found in Publication I (see Figure 10). 3D drawings for an in-line control chamber are presented in Publication II (see Figure 11). The prototype of adjustable inlet gully was developed for Publication III (see Figure 12).

1.7 Summary

Research papers in the field of UDS have a broad consensus that predictive RTC is an efficient method to alleviate the impacts of climate change and reduce the need of pipeline enlargement. However, most of the effort has been put on the centralized large scale RTC systems, the implementation of which needs substantial financial resources and is technically challenging. Centralized systems are more complicated to tune and manage as the data uncertainty also rises with the increasing complexity and forecast extent. Not all water utilities and municipalities have competence and financial capacity to implement and manage such a control system.

Therefore, decentralized, robust and more universal RTC systems, the MPC of which is computationally less costly, need less sensors for forecast and are easily applicable to existing UDS, will have their place to offer climate mitigative solutions to smaller towns and cities. Development and testing of such RTC systems are the core of the current thesis. The methodology of three Publications (I, II and III) is described in more detail in Chapter 2 and the example applications in pilot sites with the results are analysed in Chapter 3.

2 Decentralized real-time control platform

Highly developed urban areas like central districts of towns and cities have typically a high ratio of impermeable surfaces that are in intense everyday use. Most of the stormwater solutions available to mitigate risks of pluvial floods have limited applicability in these areas while they take valuable space out from the active daily use or need large- scale relocation of underground infrastructure. LID and underground detention tanks are examples of these facilities. Therefore, new efficient and feasible stormwater solutions are needed to improve resilience of UDS in dense urban areas.

Three technical solutions are created and tested in this thesis to aid to fill that gap in the urban environmental engineering:

1. **Street storage units with real-time controlled outflow**, presented in Publication I;
2. **In-line detention with real-time controlled outflow**, presented in Publication II;
3. **On-surface stormwater detention solution with adjustable inlet gully**, presented in Publication III.

All the solutions are operated by the real-time MPC algorithm, can function in distributed manner, i.e., without central control like typical SCADA and use low-energy data transmission presented in Publication IV. The created solutions are designed to complement existing UDS facilities already in place rather than intending to declare the existing infrastructure obsolete. Neither are they opposing green solutions like LID. Moreover, while they utilize a universal real-time algorithm, they can also be applied to control the flow from these green facilities.

In the following Chapters, a summary overview of the methodology provided in Publications I, II, III and IV is presented.

2.1 Actuators and control units

Methodology presented in this thesis differs from a typical RTC structure presented in Figure 6 while the controlled units, i.e., tanks and ponds are not interdependent and directly interfering with the main collectors (Figure 9). This approach has several advantages:

- **RTC can be operated in a decentralized manner**, i.e., without requiring input for each control unit at every time step. This fastens the computational speed significantly and allows skipping computationally intensive optimization algorithms;
- **Decentralized control is more reliable** while failure of a unit will not significantly affect the operation of the main system.
- **Flow in UDS is regulated at the source**, i.e., by adjusting the inflow from the catchments to UDS not by interfering the operation of the main tunnels, i.e., by installing actuators in the pipeline.

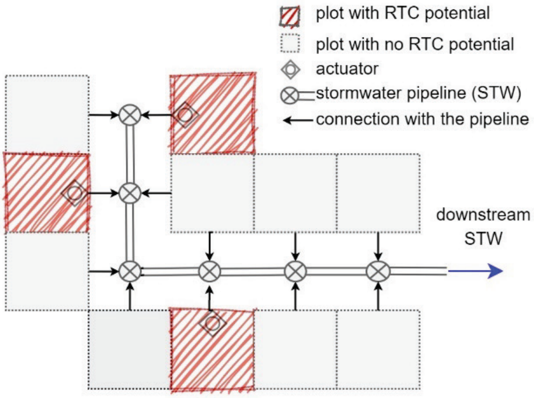

Figure 9 RTC control structure of independent smaller catchments presented in this thesis (Publication I).

2.1.1 Street storage

The idea to utilize street surface for temporal accumulation of excess stormwater in order to reduce peak load to UDS has been successfully used for many decades, for example, in two communities in Chicago, USA (Carr et al., 2001). In this thesis, the idea is developed into the next level by coupling the storage units with real-time outflow control to optimize the filling and depleting of the unit.

Street storage unit (SSU) is a dedicated area in urban space that can be temporarily filled with stormwater, for example, during heavy rainfall events when the underground system is surcharged and additional runoff will cause uncontrolled flooding in the downstream areas. In dry periods or during moderate rain events, the area is dry and can be in active use for citizens, which is a high advantage compared to a typical LID solution. The shape of the unit can vary depending on the urban area that is retrofitted for the storage. This makes the solution flexible and adaptable to various urban conditions. The unit should have two "layers" for water storage in order to distinguish the situation between an extreme and a normal rainfall event. The principal design layout is presented in Figure 10.

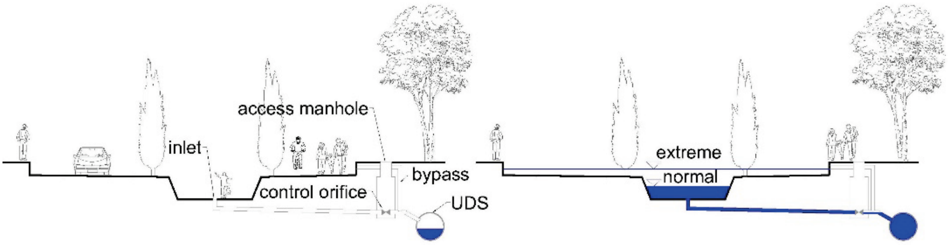

Figure 10 Principal design solution of a street storage unit (Publication I).

The following design parameters should be considered when planning the unit:

- Maximum depth h_{max} safe for pedestrians and pets. The depth h_{max} used in the case study was 1.2 m.
- Area of the upper and the lower part, A_U and A_L respectively.

- Maximum depth of water on the upper level. If this is a street area with traffic, the depth should not exceed 125 mm that has been considered as still a safe level for cars driving up to 26 km/h (Pregnolato et al., 2017).

Control manhole with a sluice gate (adjustable orifice) operated by an electric motor is situated next to the SSU. In the study, the closing time of the actuator, i.e., movement from ω = 0 to position 1 or vice versa was set to one minute, which was sufficient to respond to the sudden changes of heads H_1 and H_2. The manhole is situated between the lowest point of SSU and UDS, allowing control of the outflow from SSU. The unit is equipped with a bypass to avoid the overflow to the surrounding areas at control system's failure.

The manhole has also two water level sensors – one at each side of the sluice gate. The sensors should be capable of measuring water depths at free surface flow and pressure in the pipeline in the case of pressurized flow. Pressure sensors mounted to the bottom of the pipeline were considered in the analysis. A communication unit with a battery is also situated in the manhole. The system can be fed from the grid, battery or using solar panels mounted in the vicinity of the manhole.

2.1.2 In-line storage unit with RTC outflow control

The control unit was designed in Publication II to regulate the outflow from in-line, i.e., extended pipe section used for temporal storage of excessive stormwater flow. The manhole has an emergency overflow for handling extreme weather events and ensuring system operation during any malfunction (see Figure 11).

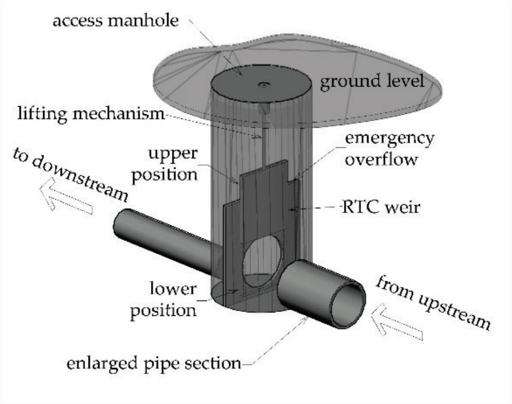

Figure 11 RTC manhole to control outflow from in-line storage unit (Publication II).

An enlarged pipe section upstream of the manhole allows water accumulation. The length of the section can be determined on the basis of the terrain slope and needed volume. Also, the number of RTC manholes in the system depends on the slope of the terrain and can be determined through simple optimization if the hydraulic model of the system is available.

The following design parameters should be considered when planning the unit:

- The length L_s and volume V_s of the enlarged pipe section; this can be determined on the basis of scenario modelling.
- The diameter of the sluice gate D_g, which determines the diameter of the manhole.
- The depth of the manhole, h_m.

Operation of the system is based on the on-line data received from the water level sensors installed at the outlet and at the upstream section of each control manhole. Ultrasonic level sensors can be used to obtain required data. These sensors are preferable as they are situated above the water, which reduces the need for maintenance. As the control manhole will be typically installed with the open-trench method, cables to supply electricity for the motor and communication unit can be installed simultaneously with the installation works. In extreme cases, the water can rise up to the lid of the manhole, activating the bypass. Therefore, all electronics, i.e., the communication unit and the control unit for the gate motor should be either in a watertight casing or installed above the ground.

2.1.3 Adjustable inlet gully

The third option for stormwater inflow control presented in the thesis and in Publication III utilizes existing impermeable surfaces like parking lots for shallow depth water storage. Dedicated areas for controlled flooding are surrounded by shallow barriers like street traffic bumps and curbs, allowing for water storage up to 0.15 m. An adjustable inlet gully was designed to regulate the flow to the underground pipeline system (Figure 12).

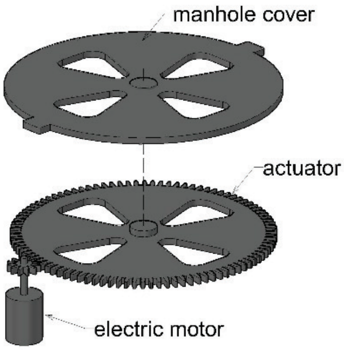

Figure 12 The prototype of an adjustable inlet gully for round lid stormwater manholes (Publication III).

As the upper cover is locked to the manhole crest, the rotation of the lower actuator causes an increase or a decrease of the free opening and thus is capable of regulating the inflow. The full opening of the smart lid corresponds to the capacity of a traditional inlet grid. Therefore, the smart inlet system will not reduce the inlet capacity of the UDS. Importantly, the size of the cover is standardized; therefore, the existing manhole covers can be replaced with adjustable ones without a need to replace the manhole structure.

The following design parameters should be considered when planning the unit:

- Maximum water depth h_{max} should not exceed 125 mm, which has been considered as still a safe level for cars driving up to 26 km/h (Pregnolato et al., 2017).
- The size and shape of the dedicated flood areas considering:
  - the slope of the ground;
  - height and shape of the barriers (street pumps and curbs) should be designed in a way that they cause minimum obstruction for pedestrians and traffic;

  - traffic scheme on the parking lot. It is advisable to keep the main exits dry, i.e., without the storage area.
- Catchment area of one flood zone is between 500 and 1000 m^2

In addition to the actuator, the manhole lid is equipped with a water level measurement sensor capable of registering the water depth above the manhole, the controller and the communication unit. All of the components will be mounted into the body of the inlet gully. The units can be operated off-grid, i.e., by using a solar panel and batteries, which minimizes the need of excavation works, i.e., cutting existing asphalt surface on the parking area.

2.2 Inlet control

The key element of the developed RTC system is the control algorithm that allows prediction of the system's behaviour and adjustment of the settings of the actuators accordingly. The structure and elements of the control system have been improved step-by-step through the Publications, starting from the basic concepts and a single test in Publications II, III and ending with a full-coded script that can control a full set of inlets in Publication I.

The algorithm has decentralized nature, which means that no central control unit is needed and therefore all the control units are capable of operating independently. The solution has no limitations to spatial coverage or number of control units implemented. In addition to that, it has low power footprint and minimum maintenance requirements, which distinguishes this from traditional SCADA systems (Bartos et al., 2017).

The decentralized approach has two main advantages: firstly, higher resilience in case of failures; secondly, lower implementation and maintenance costs. Fast response to the rain events, which is specific to small urban catchments, demands for algorithms that are capable of predicting system statuses in some time ahead to move the actuator into the desired position. Therefore, **model predictive control** (MPC) has been chosen to calculate system settings u. MPC has shown high potential in urban stormwater management but its implementation in distributed mode needs still improvement (García et al., 2015). This thesis aims to contribute in the further development of distributed control algorithms. Developed control algorithms are described in the following paragraphs.

2.2.1 Controlling in-line storage units

The first solution to control the outflow from street storage units to the UDS downstream was developed in Publication II. It utilizes data from the water level sensors and adjusts the movable gates on the basis of pre-set threshold levels (Figure 13). The level measurement sensor S_0 is triggering the system's operation if the pre-set threshold water level h_{th} is exceeded at the outlet. The control manholes are installed in series, with the distance depending on the ground slope and needed storage volume V_{th}. Therefore, first, the distributed model predictive control (DMPC) unit is activated and it tries to predict the future levels in the manhole based on changes measured by the sensors S_0 and S_1. The data transfer from the sensors to the DMPC unit is denoted by x_n and control commands by u_n. As the system operates in series, there is a need for information exchange w_n between the control manholes. This is necessary when the first movable gate controlled by $DMPC_1$ is closed but S_1 shows still a rise in the water level.

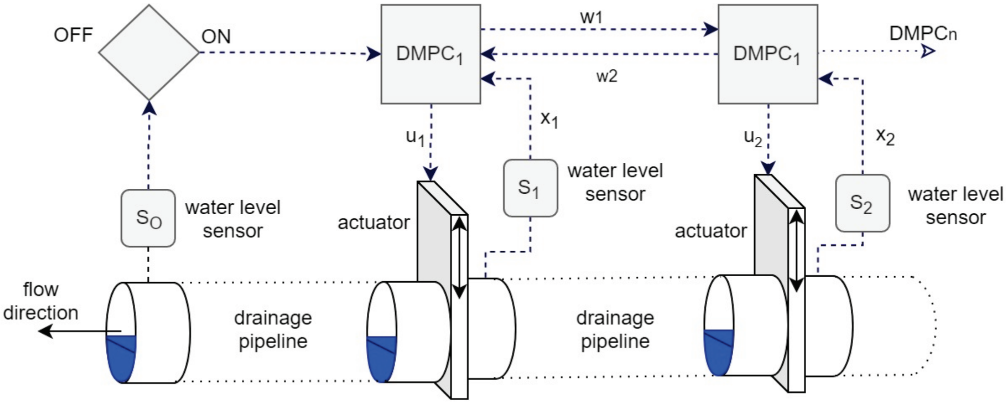

Figure 13 Control scheme designed and tested for in-line street storage units in Publication II.

Cascading operational action is designed for optimal system usage, as in the case of smaller rainfalls, only a few manholes are needed to be activated. This setup also reduces a risk of malfunction and avoids problems typically prevailing in centrally controlled RTC systems (van Daal et al., 2017).

2.2.2 Adjusting inlet gullies

A more complicated distributed control algorithm was developed to adjust series of inlet gullies in the area where a controlled flood could be triggered in dedicated areas for temporal detention of stormwater. The solution is described in Publication III and tested in the parking lot to accumulate temporarily the peak flow.

Similar to in-line storage gates, this solution uses data from the level sensors, but it includes also a rain-gage that monitors the precipitation in real time (see Figure 14). The system will be activated if the threshold water level h_{th} is exceeding the pre-set value. The value of h_{th} can be modelled during the installation phase by using a model of UDS or this can be provided by a local water utility. Rain gage S_1 is continuously measuring rainfall intensities, which allows use of the measured curve $f(q,t)$ for rainfall forecast over the prediction horizon. For that, the drainage model is used to recalculate the restricted curve $f_{1\text{-}re(q,t)}$, i.e., intensities in which case the water elevation at the outlet is below the $h_{th.}$ This curve was set as an objective function to the DPMC algorithm.

At each step, the curve $f_{1\text{-}re(q,t)}$ is scaled for each controllable inlet gully and $DMPC_n$ calculates the setting u_n that is sent to the inlet I_n to match the required inflow rate. The step is repeated after each iteration i. As one floodplain can have several control gullies, the DMPC units exchange their future input trajectories w to ensure similar water levels at I_n.

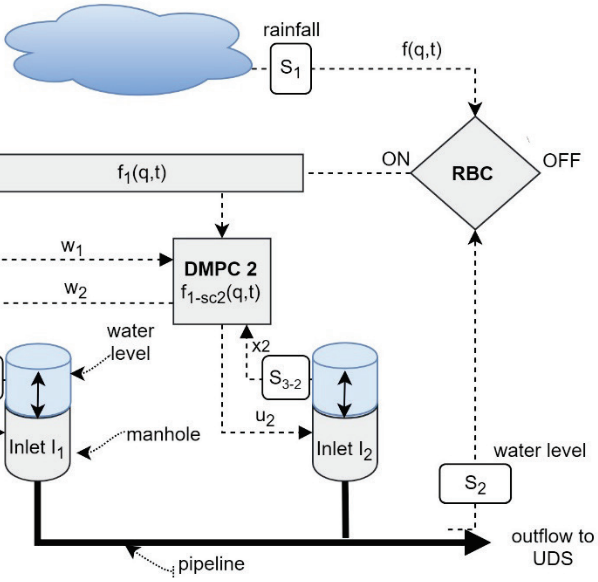

Figure 14 The control scheme for adjustable inlet gullies (Publication III).

If the termination condition is satisfied, i.e., the water level at the outflow is below $f_{1(q,t)}$ and no rainfall is registered by S_1, then all I_n will fully open and the system moves to hibernation mode until the next rain event.

In case of failure, which can happen, for example, if inlets are not fully closed because of the debris or other obstacles, the mismatch between the inlet opening, the system hydrograph $f_{1(q,t)}$ and actual measurements from S_2 will be registered. In this case, all inlets will be opened and a warning message will be sent to the operator.

2.2.3 Regulating outflow from the street storage units

The third solution created and tested in the thesis utilizes dedicated urban areas called street storage units (SSU) to accumulate excess stormwater during a heavy rainfall event. The methodology is described in detail in Publication I. The system uses the data from two level sensors S_1 and S_2 to predict the changes in the flowrate and calculate with the inner orifice model the setting u_1 for the actual actuator (see Figure 15). The system needs also a pre-set limit for the maximum outflow Q_t , which can be iteratively calculated by using the hydraulic model of the UDS or determined by the local water utility. Stormwater can be directed to the SSU by a pipeline or also by an overland flow from the surrounding impermeable areas. The system is equipped with a bypass overflow to ensure runoff even at the actuator's failure.

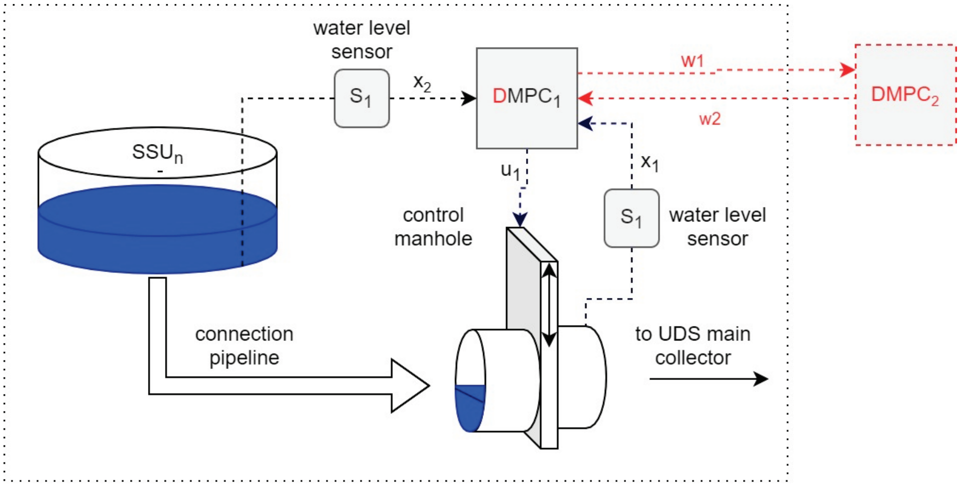

Figure 15 The control scheme developed for SSUs (future development possibilities are denoted with red colour).

The $DMPC_n$ units can also exchange information w_1 and w_2 about their statuses, which is especially important when the SSUs are installed in series, i.e., the operation of the upper SSU affects the flow to the lower unit. This feature can be further developed in the future work.

2.2.4 Selecting locations for SSUs

In the case of in-line storage units presented in Publication II and dedicated shallow flood areas with adjustable inlet gullies in Publication III, control units are typically situated in close vicinity or installed in a clearly distinguishable area like a parking lot. On the contrary, SSUs can be situated over the urban catchment with an area of hundreds of hectares in the locations that have the highest effect on the reduction of the risk and magnitude of urban flooding. Identification of these control locations is not a straightforward effort, therefore a special algorithm was created in Publication I for automated selection of the sites by the aid of the hydraulic model. The principle of the algorithm is presented in Figure 16.

The algorithm is coded in Python3.8 and utilizes *swmmtoolbox* module (Tim Cera, 2013) for reading SWMM5 output binary file. A tailor-made module was also coded to read data from SWMM5 input ascii files. The results are written into csv file that can be easily opened and modified by other common software like MS Excel. The module requires calibrated SWMM5 file that has been simulated with a desired design or future rainfall event, which automatically creates *.out file to store the results.

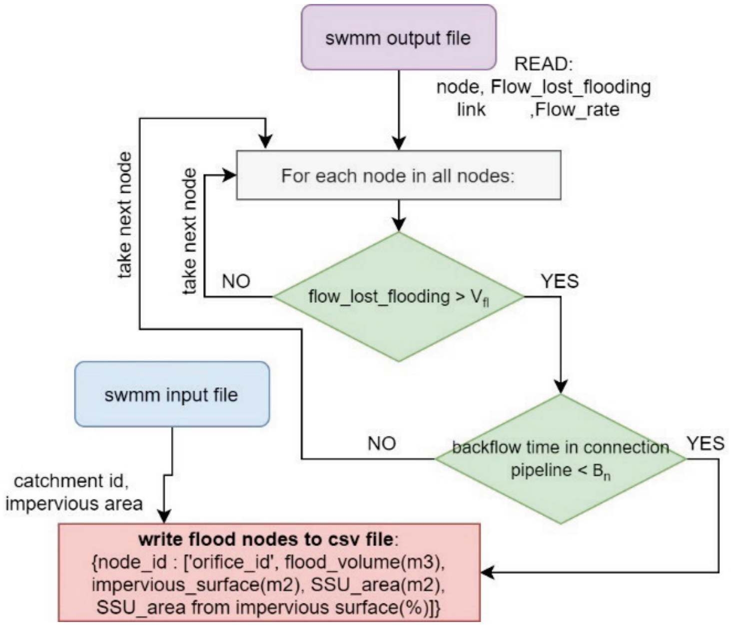

Figure 16 The principle of the selection algorithm used to determine the locations of SSU in an urban catchment.

The user needs to define the threshold flooding value V_{fl} and for how many minutes B_n before the flood event the backflow is checked. If the flooding is caused by the backflow, there is no potential to reduce that with RTC, therefore it is important to filter out these cases from the potential locations.

Testing the module in the pilot case is presented in Publication I.

2.3 Decentralized MPC algorithm

Decentralized predictive control algorithm has been developed and tested in Publications I, II and III. The key feature of the algorithm is that there is no communication between different local controllers, which allows for avoiding costly SCADA type architecture and resembles more to IoT application (S. Li et al., 2015). This means that the controllers have been supplied with a function which allows isolated units to operate achieving an overall objective function of UDS. The setup of the control units is also important while this type of algorithm cannot be used in cases when the control units are directly interdependent, i.e., installed in a sequence.

The structure, objectives and constraints defined as a concept in Publications II and III have been coded in full functionality in Publication I. The main components of the control system are presented in Figure 17.

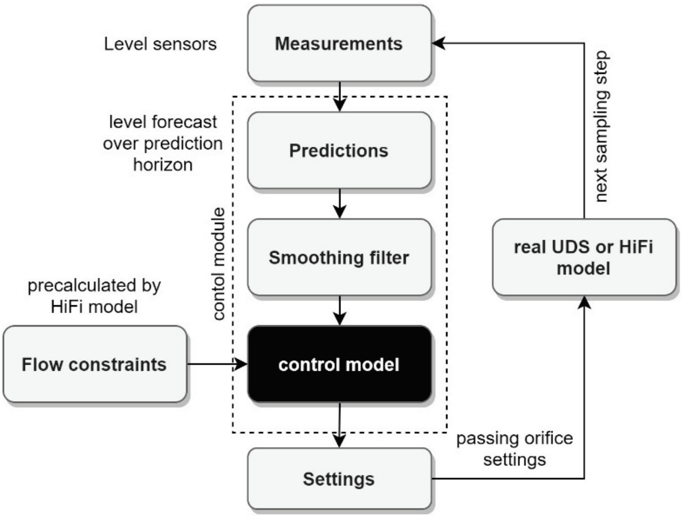

Figure 17 The coded modules of the control system to regulate the outflow from SSU (Publication I).

The prediction and the internal MPC model are two core elements of the control system. In Publication III, the prediction was made on the basis of measured precipitation as the scale of the system (parking lot) is smaller, which guarantees uniform distribution of rainfall. It has been found that even on a small scale, spatial variability of precipitation can translate into large variations in a modelled runoff (Faurès et al., 1995). Therefore, the other two solutions described in Publications II and I utilized only water level measurements to predict system's behaviour and calculate settings for the actuators.

2.3.1 Prediction module

Predicting system's behaviour is necessary to implement pro-active control of UDS. While the solutions presented in this thesis focus on stormwater quantity management, forecasting of flow rates over the prediction horizon *P* has been chosen as an objective of the module. The easiest way to measure current flow in real time is to install a flowmeter to the system. However, due to economic reasons and technical constraints it is more feasible to calculate a flow through the pipeline or orifice object on the basis of measured heads. Ultrasonic or radar sensors are cheaper, easier to install and require less maintenance. In the literature, these are suggested as a substantial alternative to flowmeters as they do not have to be in contact with the water (Campisano et al., 2013).

The module utilizes Python package SciPy 1.0 (Virtanen et al., 2020) for creating a list of predicted heads over the prediction horizon *P* (see Figure 19). As the heads cannot be negative, the control algorithm has been added to check that condition. The scheme of the algorithm derived from Publication I is presented in Figure 18. The user, i.e., the main control module (Figure 17), has to define the prediction horizon *P* and provide an updated list of measured heads *H* at every time step *i* of the receding horizon procedure.

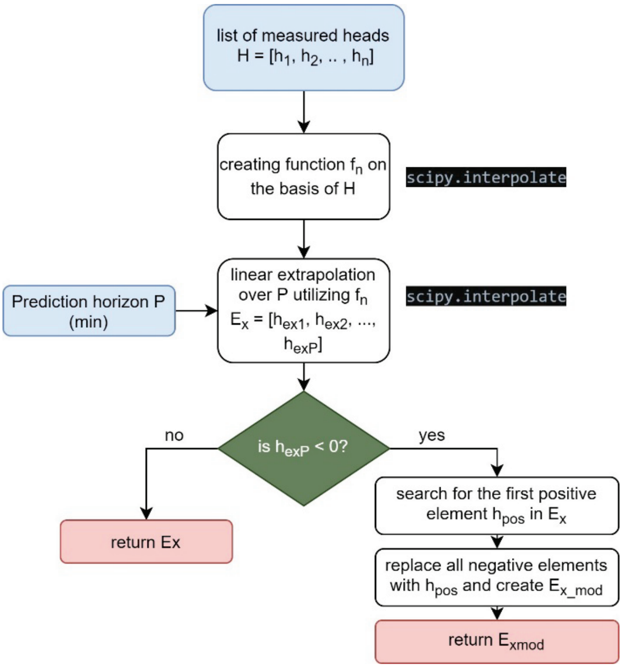

Figure 18 Prediction module for head forecasting. Derived from Publication I.

If the UDS has a backflow, no predictions will be used from the list and the actuator will have a command to move to the position depending on the type of UDS: 1) fully open if the UDS is separate, i.e., the backflow contains only stormwater; 2) fully close in case the system is combined in order to avoid polluted water flowing to the street area.

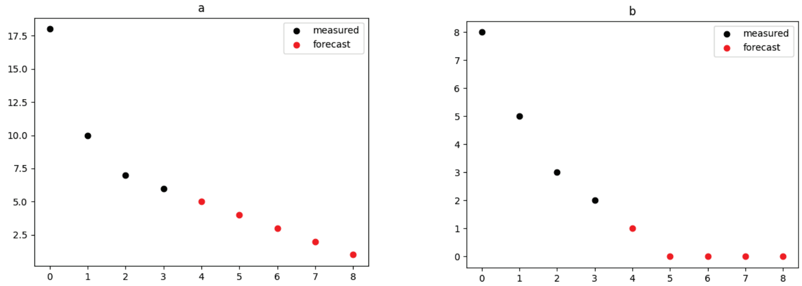

Figure 19 An example of the predicted heads when P = 5 min (a) All h_{exn} values are positive; (b) Four last predicted heads are negative and thus the values are replaced with a positive number and E_{xmod} has been returned.

2.3.2 Smoothing filter

Predictions and measurements have typically a high level of uncertainty, which may affect significantly the simulation and also control algorithms related to the modelling (Dotto et al., 2012). Therefore, a smoothing algorithm was conceptualized in Publications II, III and coded in Python language in Publication I. As the objective was to calculate flowrates on the basis of level sensors, a multivariate approach suggested by Campisano et al. (2013) was chosen to evaluate the interrelation of two different measurement signals. The algorithm is presented in a descriptive way in Publication I and graphically in Figure 20.

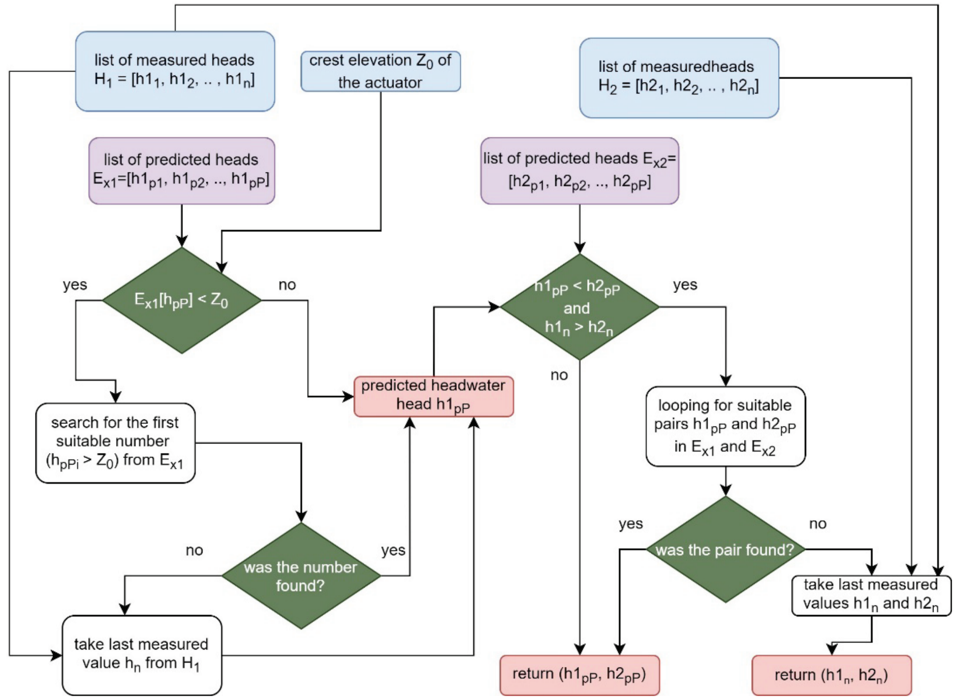

Figure 20 The algorithm for multivariate smoothing of predicted results.

Firstly, it is checked that the head prediction is in line with the actual crest elevation Z_0 of the actuator. In the solutions presented in Publications I, II and III, the crest is equal to the invert of the pipeline and therefore the headwater elevation cannot be physically lower than that of height. Secondly, the condition of sudden backflow is analysed. It is assumed that if the last measurement does not show the backflow, i.e., $h_{1n} > h_{2n}$ but predicted heads ($h_{1pP} < h_{2pP}$), this prediction is discarded in the calculation of the setting.

2.3.3 Internal MPC model

Inner model of the control unit is used in the MPC methodology to calculate system's settings and it should be simple enough to run the model in real time (Lund, Borup, et al., 2019). After a certain sampling interval, the calculation is redone with new forecasts, which allows the control to be adapted to the changes of the system.

In Publications I, II and III, a sluice gate has been chosen for an actuator that is modelled as a sharp-crested orifice. The settings *w*, i.e., the ratio of the opening to the the full diameter of the orifice *i* , are calculated by using the following principal model:

$$\omega_i = M(H_1^{i+P}, H_2^{i+P}, \omega_{i-1}, Q_t) \tag{5}$$

where M denotes the MPC inner model, H_1^{i+P} and H_2^{i+P} are predicted heads over the prediction horizon P at the time step *i*, ω_{i-1} is the orifice setting from the last time step and Q_t is the pre-set threshold flow value. The model considers the situation when the opening is acting like an orifice, i.e., headwater elevation is above the upper edge of the structure and a weir flow that happens if the elevation is below the upper edge. For that, the algorithm calculates the threshold head and evaluates the actual headwater H_1 against that value. It also takes into account submerged tailwater situations.

Threshold head H_* is calculated for each sampling step by using the following formula:

$$H_* = Z_0 + \omega Y_{full} \tag{6}$$

where Z_0 is the absolute elevation of the orifice crest, ω is the setting of the orifice and Y_{full} is the full diameter of the opening. It can be seen from Equation (6) that H_* depends on the orifice opening ω, which is an unknown value and therefore, H_* cannot be directly calculated. One option is to implement an optimization routine to find the threshold value. Another way to overcome that dependency is to take the opening equal to the last setting of the orifice ω_{i-1}. In this study, the latter method was chosen in order to reduce computational burden and ensure that the system could work in real time. The orifice calculation scheme obtained from Publication I is presented in Figure 21.

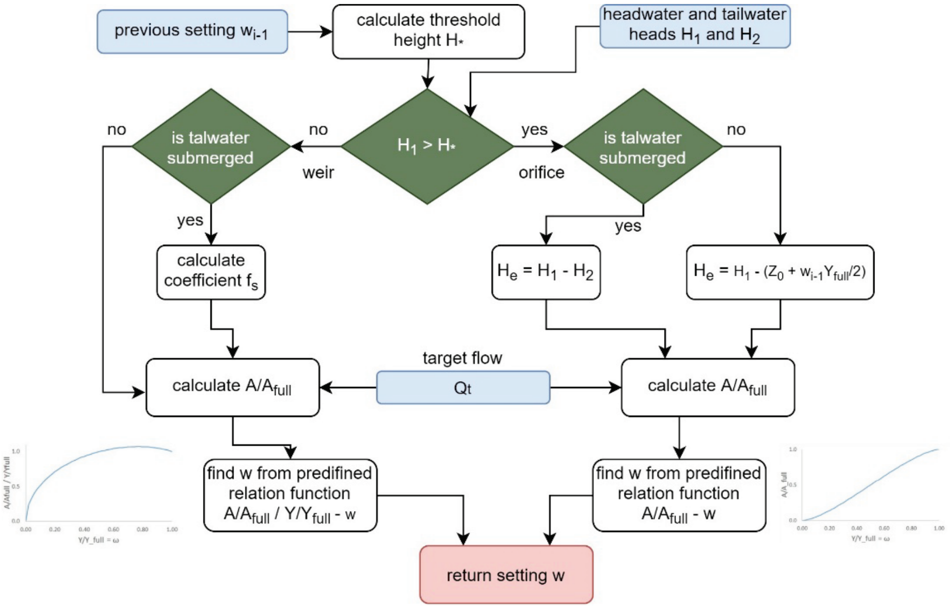

Figure 21 Calculation scheme to find orifice setting by using previous setting w_{i-1} as an input.

If the maximum water depth h_{max} has been reached in the SSU, the opening of the orifice is set to $\omega = 0.1$ to ensure some outflow even if this is exceeding the threshold value Q_t. The calculation scheme was tested with one orifice system by using SWMM5 modelling software (see Figure 22).

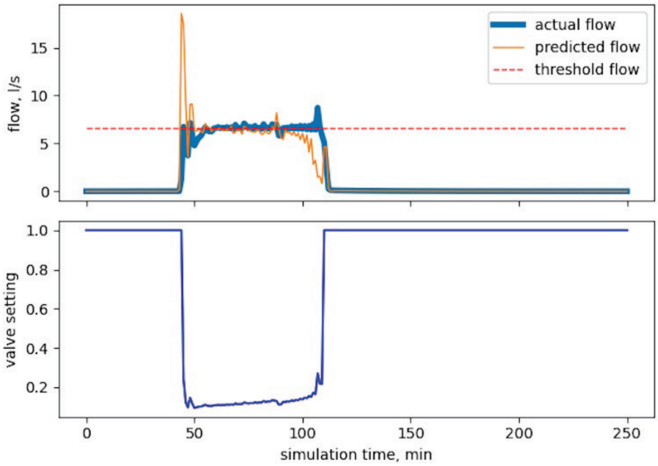

Figure 22 Example calculations of side orifice settings on the basis of the scheme presented in Figure 21 (Publication I).

The main control module utilizes four main rule groups described in Publication I and presented in Figure 23. The control cycle is repeated after each measurement step following the receding horizon principle in order to constantly update the forecasts and adjust the settings. The algorithm works in a decentralized mode, i.e., it needs no feedback from other subsequent control units.

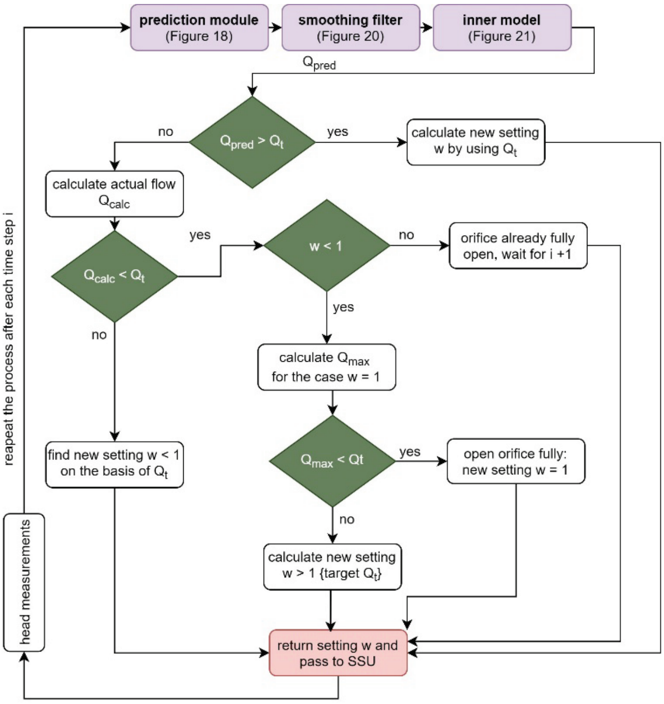

Figure 23 Main rule groups for the main control module (see Figure 17).

In addition to the rules, constraints related to the water depth in the control unit are applied: firstly, to avoid overfilling, which might result in possible spillages and secondly, to allow the valve to be fully open only after the water depth in the street storage is below the pre-set value. This avoids situations when the water flow will rapidly rise because of the sudden opening of the actuator, which may lead to downstream surcharge.

Flow constraint Q_t, i.e., the threshold flow can be fixed over the rain event or may also dynamically change depending on the status of other adjacent control units in the catchment. In the latter case, the system will operate in a distributed mode, i.e., it will get real-time data about the statuses of the adjacent systems. This will be implemented in the future work.

For this thesis, the constant Q_t was calculated for each SSU on the basis of the highest rainfall event that will not cause flooding in the system.

2.3.4 Optimization

Optimization methods were used to find settings of the actuators in Publications II and III. For the smart inlet system presented in Publication III, the stormwater inlets were modelled as bottom orifices and the genetic algorithm (GA) was used in conjunction with the gradient-based method to find the settings in order to shorten the computational time of GA. For each time step *i*, the precipitation was predicted by the MPC algorithm on the basis of the measured rainfall curve and inlet settings were adjusted to match the input rainfall dynamics and satisfy the following optimization constraints: 1) maximum water depth above the rim; 2) maximum allowed outfall from the catchment; 3) similar water depths in all dedicated flood areas. An example of the results of the inlet system optimization is presented in Figure 24.

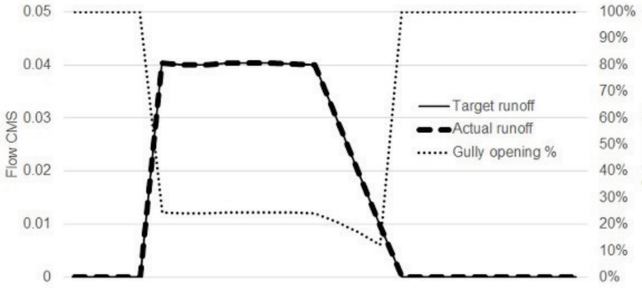

Figure 24 Example of one inlet modelling with optimization of the settings w to match the target runoff (Publication III).

In Publication II, optimization routines were used to find the settings for the actuators regulating the flow from in-line storage tanks to the downstream system. MS Excel spreadsheets with Solver Add-In module were utilized to code the DMPC algorithm and perform necessary optimizations. The following optimization constraints were imposed: 1) outflow should not exceed the threshold level at S_O; 1) maximum level of hydraulic grade line (HGL) at peak moment shall not be less than 0.5 m from the ground level to have some safety distance before the actual flood event; 3) for safety reasons, no actuators should be allowed to be fully closed, i.e., $u \neq 0$. The parameters are presented in Figure 13.

2.4 Communication

Reliable and fast communication is an important element of any RTC system. Wired technologies such as local area networks (LAN) are less vulnerable to interference but their usage is limited for connecting sensors, controllers and actuators in situations of ubiquitous sensing and decentralized control systems (Berglund et al., 2020). Wireless data transmission technologies emerged in recent years have shown their potential in the urban environment, enabling flexibility and feasibility (Wong & Kerkez, 2018). Therefore, the analysis presented in Publication IV focuses on selecting the most feasible solutions to transmit data from the underground sensors installed into UDS manhole (see Figure 25).

The attenuation of electromagnetic (EM) waves in saturated soils has been restricting the development of low-power data transmission for decades. Low power consumption is important while the sensors are operating typically off-grid, in which case electricity is provided by a battery. In many cases, especially when the monitoring manhole is situated in the street area, there are no possibilities to install solar panels for recharging the batteries during daytime.

In Publication IV, a signal loss from a typical concrete manhole with a depth of 3.0 m was modelled and analysed. Signal loss modelling was performed under dry and wet soil conditions. Two low-power wireless technologies – NB-IoT and LoRa where analysed. NB-IoT is a cellular technology based on licensed spectrum, whereas LoRa is a CSS modulation based radio technology that is usually deployed at 868 MHz in Europe and 902-927 MHZ in North-America, respectively. NB-IoT provides better coverage with a high level of scalability due to high maximum coupling loss (MCL) as compared to LoRa. Furthermore, NB-IoT also showed high information rate and low energy consumption and is best suited for underground scenarios.

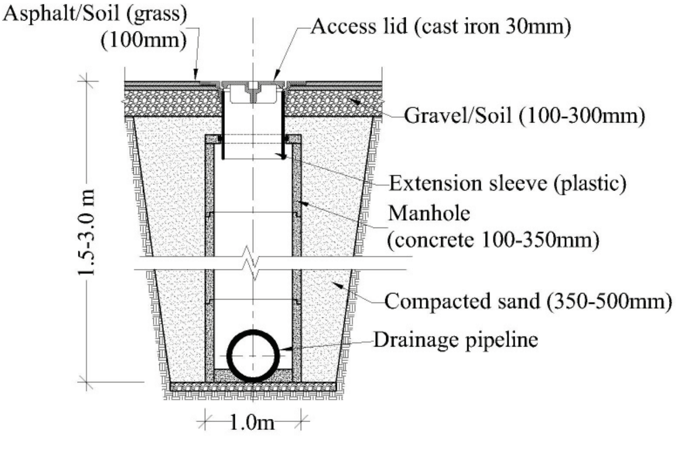

Figure 25 Test manhole used to model signal link loss (Publication IV).

2.5 Conclusions

Different novel technical solutions and predictive real-time control algorithms were presented and described in this chapter. The solutions comprise both inlet control, street storage and in-line flow regulation with an objective to reduce the peak stormwater flow from the catchment to the UDS at cloudbursts. All the developed control algorithms are presented graphically, making it possible for coding in any preferable programming language. The chapter outlines the novelty and additional value of the current work compared to the previous research efforts in the field presented in Chapter 1. It also aims to fill the research gaps listed in the introductory chapter “Addressing the risk of pluvial floods”:

- **Developed MPC algorithm and actuators are universal to function** as an out-of-box solution applicable to any densely developed urban area in order to mitigate the risk of pluvial floods.
- **Developed solution is adaptive**, i.e., allows automatical adjustment of UDS actuator’s parameters to fit the system to changing conditions, i.e., rainfall events. It is also robust, does not need complicated tuning, operates in a decentralized mode without the need of demanding optimization routines and central control system.
- **Developed actuators allow efficient inlet control** without interfering the operation of the main pipeline system, therefore no actuators are needed to be placed into the main collectors.
- **It is possible to implement the decentralized MPC inlet control gradually**, i.e., in conjunction with the urban development projects. Therefore, there is no need of extensive underground works and the construction is financially affordable compared to the enlargement of grey infrastructure for peak flow reduction.

Testing the solutions in real environment is presented in the following chapter. Three pilot sites were selected for the analysis of the economic feasibility, technical advantages and flood risk reduction of the developed systems.

3 Pilot applications

The decentralized RTC solutions were tested and analysed on three pilot areas in Estonia in order to evaluate their performance and compare the efficiency with more traditional flood mitigation measures.

There have been some substantial flood events in pilot area 3 (Publication III) in 2014 and 2017, which have highly disrupted the traffic and businesses and caused damage to the buildings nearby. The other two areas have not faced events with a similar seriousness. However, the risk of flood rises significantly in all pilot areas if we take into account the climate projections, especially higher rainfall intensities forecasted for coming decades (H. M. Madsen et al., 2019). This is in line with the objectives of the thesis – to find feasible solutions for stormwater drainage operation to mitigate the risks of climate change.

High fidelity (HiFi) models of the stormwater systems were used in Publications I, II and III. The HiFi model uses a dynamic rainfall-runoff simulation by utilizing the dynamic wave flow routing method. This allows simulation of backwater effects, pressurized flow, flow reversal, and non-dendritic layouts. The models were created in EPA SWMM5 software that is a widely used modelling freeware for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems (U.S. Environmental Protection Agency, 2021).

More detailed description of the pilots with the analysis of the archived results is presented in the following paragraphs structured by pilot areas.

3.1 System description

3.1.1 Pilot 1

Street storage units with the RTC presented in Publication I were tested in a typical urban district in the City of Rakvere, Estonia (see Figure 26). The town has a separate stormwater collection system with a total length of 7.1 km. Stormwater is conveyed to the system from 287 catchments with an average ground slope of 2.2% and average imperviousness of 65%. Most of the pipeline has been replaced ca 12 years ago and therefore, imminent large-scale construction works to improve the system’s capacity would be unrealistic. Although there have been no major flood events registered so far, climate projections used in the current study show a considerable pluvial flood risk in case any of the climate scenarios forecasted for the region applies (see the flood nodes in Figure 26). Consequently, the objective of the pilot application of SSUs was: 1) to select the most suitable locations of the units; 2) to achieve a maximum reduction in flood nodes, flood duration and volume in the case of an extreme weather event.

The data about the underground pipeline and manholes was obtained from the water utility’s GIS system. Additional geodetic measurements were conducted to fill the data gaps. Stormwater catchments were automatically created on the basis of digital elevation models (DEM) and land-use (CORINE) maps by using GisToSwmm tool (Niemi et al., 2019). The catchments were adjusted on the basis of the input from the local water utility. The model of the existing drainage system was calibrated by using the actual flow and precipitation measurements.

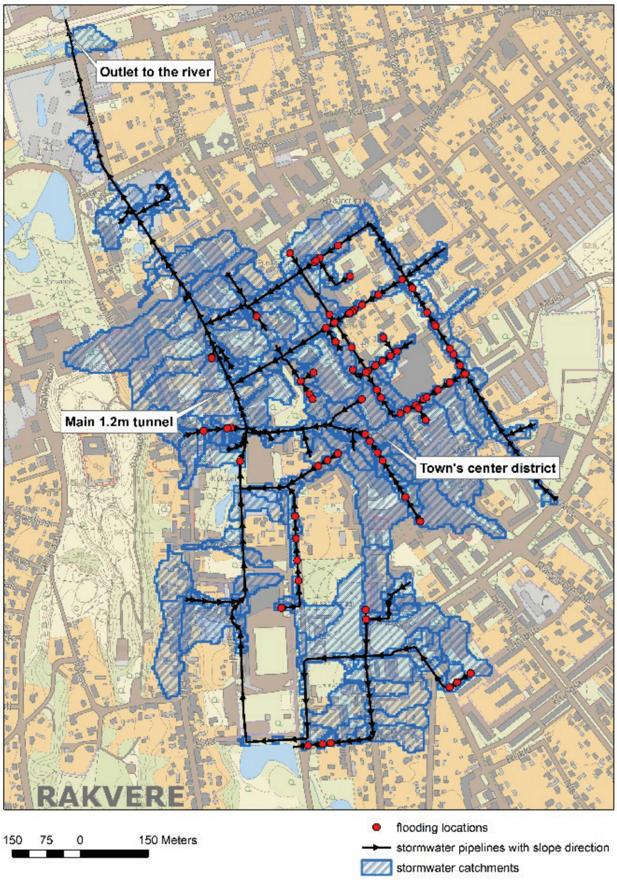

Figure 26 Pilot area selected for Publication I. Flooding nodes demonstrate the impact of the future design storm on existing UDS.

The future design storm was created on the basis of the widely used Representative Concentration Pathway (RCP) methodology (Saldarriaga et al., 2020). Moderate climate projection RCP4.5 was selected and an alternative block methodology suggested by Jato-Espino et al. (2019) was used to construct the RCP4.5 rainfall curve with the return period of two years. This methodology yielded to a curve with a 20-min rainfall with 5-min peak intensity reaching up to 100 mm/h.

The module for the automatic selection of the SSUs described in section 2.2.4 was used to find the location of the units (see Figure 27). Threshold volume V_{th} was taken equal to 0.1 m^3 and the backflow constraint B_n was set to 3 min.

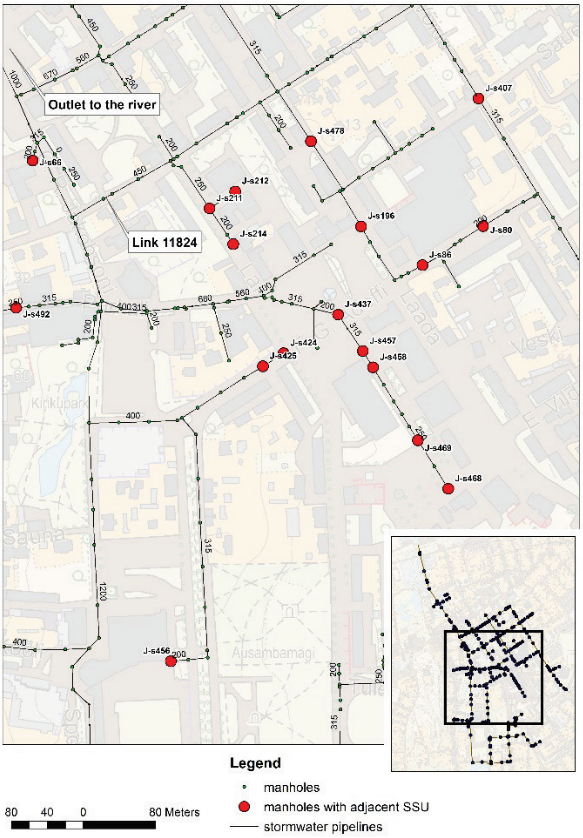

Figure 27 The locations of the street storage units in the pilot area (Publication I).

After simulating the HiFi model with the design storm (see Figure 28), a total of 18 locations (6% of all the inflows/catchments) were determined that satisfied the pre-set conditions. Most of the selected locations are situated at the centre of the pilot area where the ratio of the impermeable surface and the consecutive flood risk is the highest (Figure 27). The area of the upper part of SSUs (A_U) is taken 1000 m^2 and the area of the lower part (A_L) 50 m^2. Maximum depth of the lower part is 1.2 m and upper part 0.3 m, total maximum depth (h_{max}) of all units is 1.5 m. Street storage units form in average 40% of the total area of the selected catchments and 4% of the total area of the pilot district.

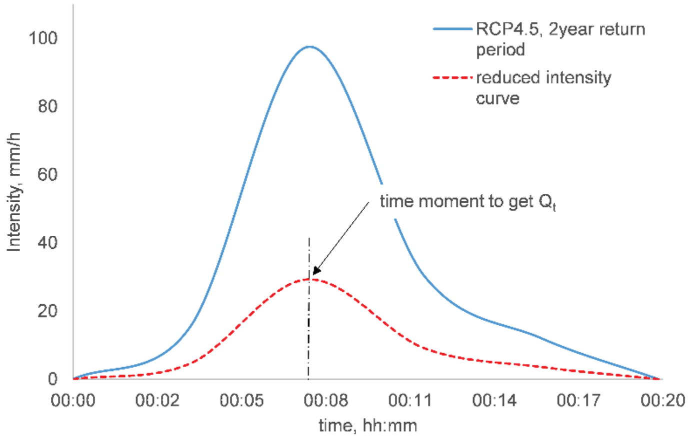

Figure 28 Hydrograph of the design storm and reduced intensity curve to find Qt for each SSU (Publication I).

Threshold flow Q_t needs to be defined by the user for setting up the RTC system (see Figure 28). In this study, Q_t was derived for each SSU from the RCP4.5 curve through an iterative process with the intensities reduced until no flood event was registered during the simulation period.

3.1.2 Pilot 2

Smart in-line storage with RTC in Publication II has been analysed in a 12.5 ha modern urban development area in Tallinn, Estonian capital (see Figure 29). The area was in a planning phase and therefore it was possible to test different methods to reduce the peak outlet from the district to the UDS. During the development, the old obsolete industrial territory will be turned into a modern city environment with 1,600 apartments and offices. As the area will have a high ratio of impermeable surfaces (reaching to merely 100%), the stormwater runoff is considerably higher than it was before the development. Due to the limited capacity of the existing downstream UDS, the water utility has imposed the maximum limit of 300 L/s for the peak runoff. Therefore, the district was ideal to test different peak flow reduction methods.

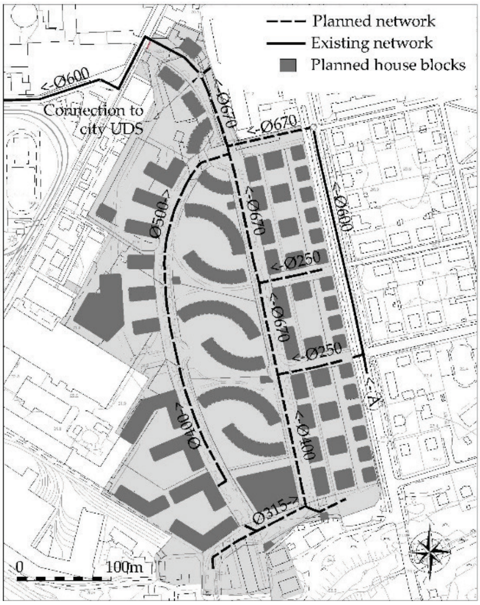

Figure 29 Overview of pilot area 2 (Publication II).

The drainage model and the stormwater catchments of the development district presented in Publication II were built on the basis of detailed design drawings of pipelines and landscaping provided by the developer. The design rainfall defined in Estonian Design Standard (EVS848:2013, 2013) with constant intensity of 28 mm/h in 20 minutes rainfall duration was used. To simulate the parking lot and RTC inlets under an extreme weather event, local extreme rainfall data measured in 2016 in Tallinn was used. This measured rainfall lasted for ca 11 min and the intensity reached up to 125 mm/h. The duration of the peak intensity was ca 1 min.

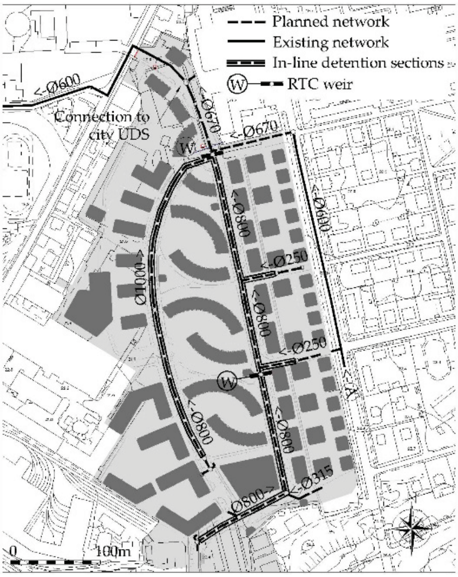

Figure 30 The setup of in-line storage units with the RTC weir (Publication II).

For the in-line storage, 0.9 km of accumulation pipeline was designed with a total volume of 480 m^3 and equipped with two adjustable 300 mm weirs, as presented in Figure 30. Two other technical solutions were created for comparison: 1) the accumulation pipeline with a static orifice and 2) off-line storage tanks with the total volume of 450 m^3.

3.1.3 Pilot 3

In Publication III, dense urban development surrounded by car parking areas in the city of Tallinn, Estonia, was selected for testing RTC controlled inlets to accumulate excess water on large impermeable surfaces (see Figure 31). The area has faced two major flood events in year 2014 and 2017, which shows the vulnerability of the district to more extreme rainfall events.

The ground space area of 12 ha hosts a concert hall, a hockey arena and several shopping and entertainment centres. Seventy per cent of the district is covered with asphalt. The area was developed some decades ago, therefore, RTC inlets could be a feasible way to retrofit the system to meet new climatic conditions. The target was to reduce the peak outflow under extreme weather conditions to 0.5 m^3/s, which corresponds to the peak outflow of the design storm according to Estonian Design Standard (EVS848:2013, 2013).

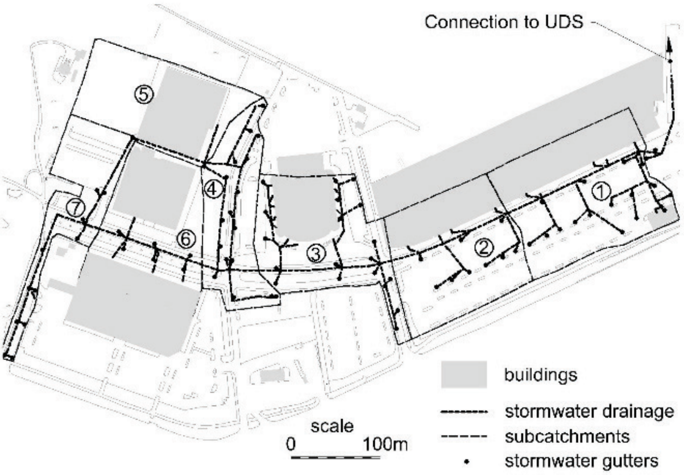

Figure 31 Pilot area for testing smart inlets in Publication III.

Drainage system of the parking lot was modelled on the basis of as-built drawings provided by the local water utility. While the area is compact, the catchments were determined manually on the basis of ground slopes. The model of the existing drainage system was calibrated by using the actual flow and precipitation measurements.

The design rainfall defined in Estonian Design Standard (EVS848:2013, 2013) with the constant intensity of 28 mm/h and duration of 20 min was used as one scenario. To simulate the parking lot and RTC inlets under an extreme weather event, local extreme rainfall data measured in 2016 in Tallinn was applied. This measured rainfall lasted ca 11 min and the intensity reached up to 125 mm/h. The duration of the peak intensity was ca 1 min.

RTC equipped inlet lids were installed to the major stormwater inlets, by first determining the allowable ponded area per inlet. The maximum depth of ponded water was limited to 125 mm, as this is still a safe level for cars driving up to 26 km/h (Pregnolato et al., 2017). Totally, 57 inlets were determined with a total ponded area of 2 ha, which forms only 17% of the total catchment of the pilot area. Selected areas have to be surrounded by a combination of speed bumps and street curbs in order to avoid spillages to the surrounding surfaces at stormwater accumulation.

For scenario 2, the peak flow reduction by using underground detention tanks with the total volume of 1803 m^3 was envisaged. This volume was divided between seven sub-catchments. Detention tanks were calculated on the basis of design rainfall, modelling results, setting the objective peak outflow to 0.5 m^3/s and calculating consequent volumes needed for excess flow storage.

3.2 Hydraulic performance

Hydraulic performance means the ability of a tested solution to either reduce outflow under pre-set threshold level (Publications II and III) or minimize the number of flood nodes and duration by restricting the outflow from SSU-s (Publication I).

3.2.1 Pilot 1

All the scenarios in Publication I were simulated using the same design rainfall RCP4.5 with a duration of 20 min. Flood parameters for the case study area were analysed for four scenarios:

(1) Base scenario, i.e., existing UDS system with no flood control implemented;
(2) SSUs with no control, i.e., outflow with static orifices;
(3) SSUs with RBC applied for street storage units;
(4) SSUs with MPC applied for street storage units.

The results of the simulations are presented in Table 1. It can be seen from the table that despite the fact that no large flood events have historically occurred in Rakvere, changing the rainfall pattern to simulate future precipitation resulted in flooding in 136 nodes (47% of all nodes) with a total flood volume of 950 m^3. Half of these events were considered major, i.e., having flood volume higher than 1 m^3.

Under scenario 2, the connection between SSU and UDS was static, i.e., with fully opened fixed orifice. The opening of the orifice was made changeable under scenarios 3 and 4. Placing the street storage units into the system and connecting the units with UDS will reduce the number of flooding nodes by 13% and the number of major flood nodes by 11%. This is mainly because of the restricted outflow from SSUs, which allowed some accumulation before water is entering to the UDS.

Placing the street storage units into the system (scenario 3) to control runoff, helped to reduce the number of all flooding nodes by 13% and the number of major nodes by 7%. In addition, the mean duration of the flood event was 10 min shorter than in the case of the base scenario. Applying the RBC methodology did not improve the situation significantly compared to the scenario without any control. The RBC algorithm was not able to meet the threshold flow Q_t constraint in any of the storage units; moreover, it even increased the peak runoff merely two times compared to the base scenario, causing new flood events downstream.

Table 1 Results of SSU analysis (Publication I).

Parameter	Unit	Base	SSUs without control	SSUs with RBC	SSUs with MPC
Total number of flood nodes (including SSUs)	pcs	136	119	118	99
Total number of flood nodes $V_f > 1.0$ m^3	pcs	70	62	65	49
Mean flood duration for nodes $V_f > 1.0$ m^3	min	35	29	25	23
Total flood volume, m^3	m^3	950	971	1040	955
Threshold flow (Q_t) constraint satisfied for SSUs	%	0	0	0	89
Peak flow change from SSUs compared to the base scenario	%	-	+93	+93	-77

MPC algorithm (scenario 4) enabled prediction of changes in the water depths up to 5 min ahead and adjust valve position proactively. Therefore, it managed to keep runoff from 16 storage units of 18 below pre-set Q_t. As a result, MPC was able to cut 77% of the peak flow from the controlled catchments, which resulted in 27% reduction in all flood nodes and 30% reduction of major nodes ($V_f > 1.0$ m^3). The mean duration of the flood event for nodes V_f higher than 1 m^3 was 12 min shorter – about the length of the actual rainfall event.

Maximum water depth temporarily stored in the street storage units is an important parameter to assess the suitability to implement the solution in urban landscape with active everyday use. Figure 32 presents the depths measured from the bottom of the lower storage base A_L in the RBC and MPC scenarios. It can be seen from the graph that maximum water levels in the RBC scenario are generally lower than in the case of MPC. However, even in the MPC controlled units, water reaches the upper level storage unit only in seven cases of the total of 18 facilities. This means that the shapes and sizes of the SSUs can be optimized in the future study.

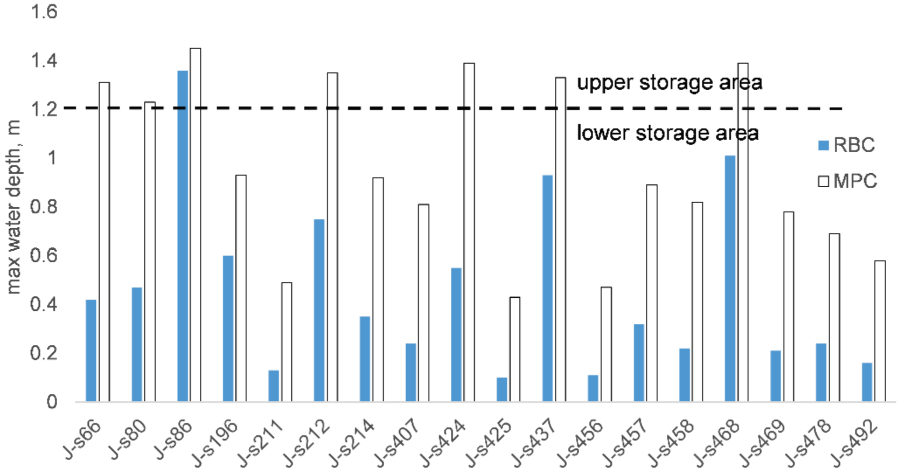

Figure 32 Maximum water depths in SSUs in two options (Publication I).

3.2.2 Pilot 2

The effect of in-line detention with RTC on peak flow reduction was compared to off-line detention tanks and in-line storage with a static orifice (see Figure 33).

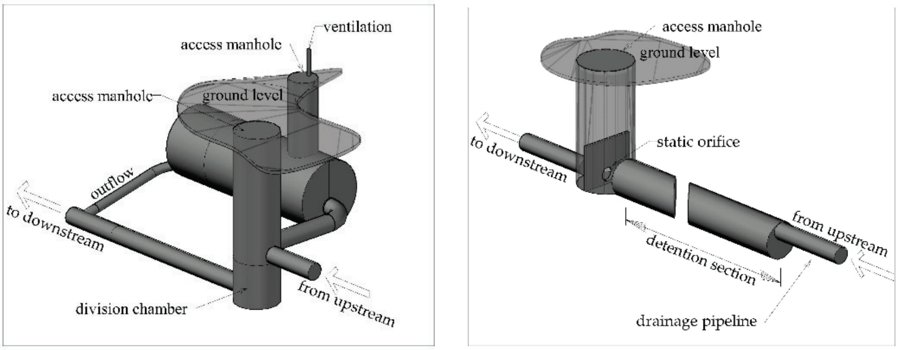

Figure 33 Off-line tanks (left) and in-line storage (right) used in comparison with the RTC system (Publication II).

The results of the analysis of the in-line detention with RTC in Publication II are presented in Figure 34. The objective of the system was to keep the peak flow under 300 L/s, which is the maximum flowrate that the local water utility accepts from the development area. It can be seen that only scenario 4, i.e., in-line detention with RTC, fully satisfies the outflow constraint (300 L/s). It reduces the peak flow by 57%. For the other three, some additional LID facilities had to be foreseen to provide an extra cut, resulting in cost penalties. It is important to note that in-line detention without RTC (option two), on the contrary, has the lowest effect on the peak flow reduction (26%). Traditional off-line detention reduced the peak flow by 39%, which correlates with the data presented in previous studies (Lim et al., 2014; Wang et al., 2017).

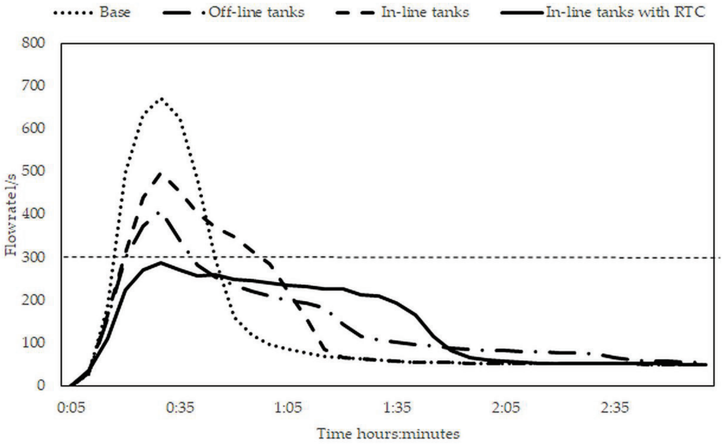

Figure 34 Hydraulic performance of the in-line RTC system (Publication II).

3.2.3 Pilot 3

The results of the analysis of Publication III are presented in Figure 35. It can be seen from the figure that the peak run-off in the case of no flow control will reach up to 1 m^3/s. The curve has a flat top section, which indicates a potential flood event. This occurs as the system's capacity is insufficient to convey all the extreme flow downstream.

As neither control mechanisms nor dedicated ponded areas exist, this flooding is uncontrolled and thus may have negative consequences. The other two options with control show a high efficiency of reducing the peak flow. In both cases, the flow is kept well under 0.5 m^3/s, which is a maximum allowed flow. Smart inlets regulate the flow gradually and this results in progressive flow changes. As a result, it takes 2.5 h to empty the system, which is two times longer than at no flow control. Detention tanks are capturing the rainfall and are emptied after the event; therefore, their flowrate decreases gradually. It takes ca 4 h to deplete the tanks. Maximum ponded depth in the case of control by smart inlet gullies varies from 12 cm to 5.7 cm.

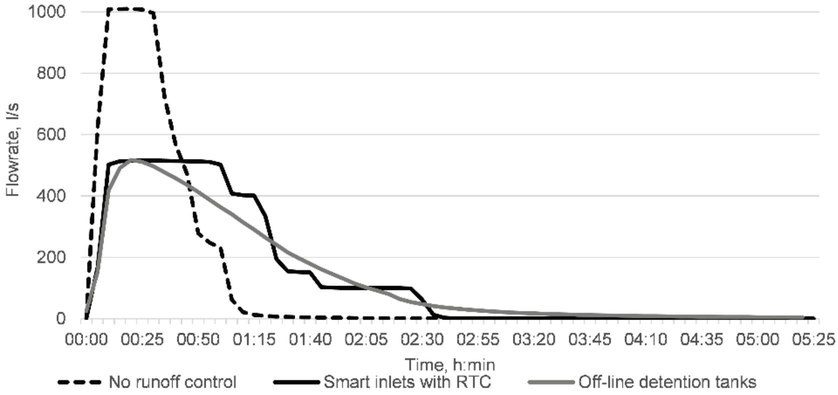

Figure 35 Hydraulic results of controlling the runoff from the parking area (Publication III).

The areas where ponding was allowed by smart inlets and required detention volume in the case tanks would be used instead of the inlets are presented in Table 2.

Table 2 Ponded areas of the smart inlets and volumes of the detention tanks (Publication II).

Sub-catchment	**Total area of the catchment, ha**	**Ponded area, m²**	**Ponded area / catchment area**	**Volume of the detention tanks, m³**
1	2.3	2,800	12%	336
2	1.9	4,093	21%	340
3	1.8	2,753	15%	253
4	1.3	3,247	25%	185
5	1.7	1,961	12%	202
6	1.9	3,928	21%	322
7	1.1	1,988	18%	165
TOTAL	**12.1**	**20,770**	**17%**	**1,803**

It can be seen from the table that only 17% of the catchments need ponding in the case of smart inlets. Tanks with a volume of 1803 m^3 are needed to be installed below the ground to achieve the same detention capacity.

3.3 Economic feasibility

Economic aspects are important to demonstrate the feasibility of the RTC system to the stakeholders and evaluate the solution on the basis of other, more traditional mitigation measures like tanks and enlargement of pipeline. The aspects were considered and feasibility analysed in Publications II and III.

Both investments and maintenance costs of evaluated systems were taken into account in the analysis. Also, indirect costs were considered, reflecting the expenditures of the disturbances during the construction and installation period. For investments and maintenance, the unit prices from the period of preparation of the Publications were used.

Technical components of the options have their unique lifetime. For example, electronic components are expected to last maximum for 5 years and actuators need to be replaced after 15 years, while typical grey structures, i.e., concrete of detention tanks and pipelines, will sustain at least 50 years. To take into account this variability, the net present value (NPV) was calculated for the options. NPV equation converts any future values to the present, thus providing an adequate answer about the actual feasibility of the investment:

$$NPV = \sum_{n=1}^{a} \frac{F_n}{(1+j)^n} \tag{7}$$

where F_n denotes future payment for each period n and j means the interest rate of this specific period n. The following assumptions were made for the calculation of NPV:

1. Calculation period is 50 years.
2. The theoretical natural annual real interest rate is estimated to be around 3%.
3. No price changes of investments were considered, which means that inflation of the investment product is zero and therefore, nominal and real interest rates are the same.

Economic feasibility was calculated for the options analysed in Publications II (pilot 2) and III (pilot 3). Penalty costs, i.e., additional expenditures of the investments were also considered. These costs denote, for example, a need to rebuild some of UDS outside of the pilot area or add some extra LID measures to the properties connected to UDS in the pilot area. Maintenance and components replacement need and costs are considered in the NPV analysis with a time span of 50 years. NPV was not calculated for pilot 1 (Publication I) because no comparable alternatives to SSUs were analysed in the work.

3.3.1 Pilot 2

The results of the cost calculation in Publication II are presented in Figure 36. It can be seen from the figure that the base scenario, i.e., the option with no peak flow control has the highest total cost (TC). This is caused by the high penalties related to the need to rebuild about 0.9 km of the drainage collector downstream of the UDS. In-line tanks with RTC, which were also hydraulically the most efficient mitigative measure, have the lowest TC with no penalties needed to be applied.

Analysis of NPV of all four options showed that over a 50-year period the base scenario has the highest investment value, and the in-line tanks with RTC the lowest. Although the in-line detention with RTC requires electronics and communication units that have a shorter lifespan, it reduces accumulation of sediments to be removed periodically in the other three cases. As a result, NPV of RTC in-line detention is 26% lower than in the base scenario and 5% lower than the in-line solution with no RTC.

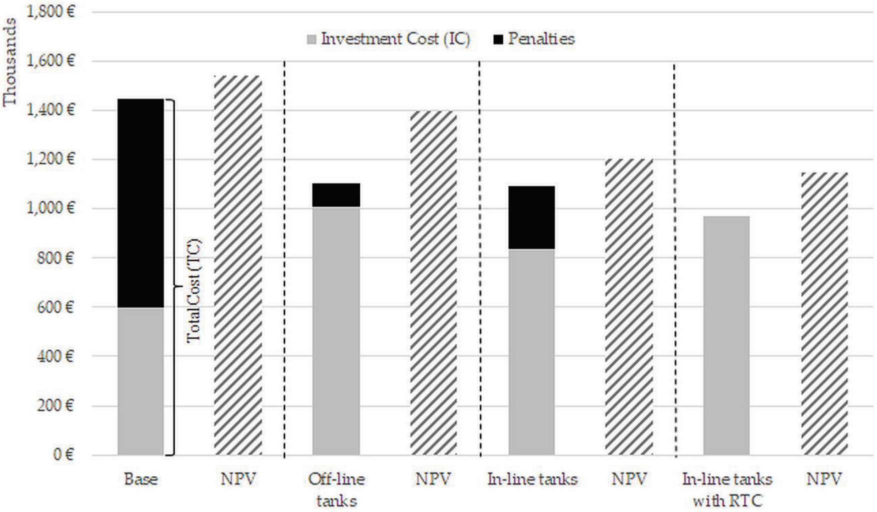

Figure 36 Investment costs (IC), penalties and NPV of the analysed options (Publication II).

3.3.2 Pilot 3

Analysis in Publication III of the feasibility of smart inlets compared to traditional underground storage tanks showed similar results with Publication II (Figure 37). It was concluded that the investment costs of smart inlets are 1.8 times lower than in the case of storage tanks.

Although a smart system has components like electronics that have shorter life span, the NPV of the RTC inlets over a 50-year period is still 19% cheaper than that of detention tanks. Raising the interest rate up to 5% also increases the difference between the two options, thus improving the feasibility of the smart inlet system. On the other hand, the cost of regular cleaning the detention tanks from the sediments will raise the maintenance costs of the tanks.

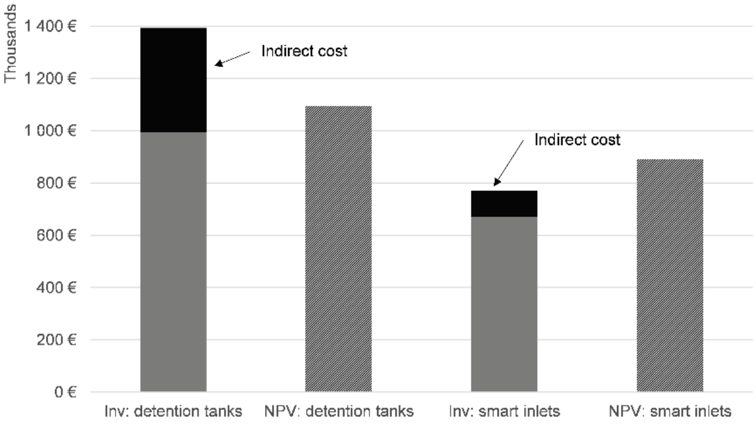

Figure 37 Comparison of investment costs and NPV of two alternatives (Publication III).

In the current study, the cost of a smart lid has been taken relatively conservative, assuming a high cost for new product development. As the quantity of the orders increases, the unit price is expected to decrease. On the other hand, the costs of concrete detention tanks remain relatively stable.

3.4 Discussion

Street storage units analysed in Publication I have typically small catchments, which means that they respond quickly, i.e., in minutes to a rainfall event. Therefore, the computational speed of the MPC algorithm calculations plays a crucial role in an efficient operation. For that reason, storage units are designed to operate in a decentralized mode as optimization of global MPC takes typically considerably longer time than one-minute measurement step used in this study (Zimmer et al., 2015).

The second simplification used to reduce the computational burden was direct calculation of the parameters by the inner model instead of the objective function-based optimization. On the other hand, this simplification allowed use of the non-linear inner model instead of the linear surrogate model typically utilized in MPC systems with in-line actuators (Lund, Madsen, et al., 2019). As a result, the simulation time of the MPC algorithm to adjust 18 independent orifices was only 0.11 sec per one minute measurement step *i* (Intel® Core™ i5-6200U CPU @ 2.30GHz, 2400MHz, 2 cores). This leaves enough time to process the signals to the actuator, get updated data from the sensors and set the actuator to a desired position.

It has to be noted that all the SSUs had similar technical parameters h_{max}, A_U and A_L values. However, Figure 32 reveals that the area of eight units could be reduced as no water reaches the upper layer of the storage system. For other units, the water depth of the upper layer is not exceeding 25 cm, which has been considered as a safe depth for pets and pedestrians (Carr et al., 2001) but might be risky for parking cars and traffic. If the upper levels of the storage units are used for parking, an alarm system should be developed to prevent damage to vehicles. On the other hand, to alleviate the situation where SSUs are already partly filled with water, the safety factor has to be considered when dimensioning the units.

The results of the in-line storage units with RTC (Publication II) showed that if penalties are taken into account, traditional off-line detention tanks are most costly and will not guarantee keeping the peak flow under the threshold level at every time moment. The in-line system with RTC was also designed to mimic the features of off-line tanks, i.e., capability to temporarily cut the water flux during the filling period. However, this feature was not utilized in the case study because the system was capable of reducing the peak flow below the target limit even without completely closing the RTC weir-wall. It is important to note that this may not be the case in other case studies.

The footprint of the off-line tanks and in-line detention is relatively similar (240 m^2 for the case study analysed), but there is a clear advantage in the latter option because the area is evenly distributed along the whole system. This facilitates the installation of the other communications in the street area, e.g., water supply, gas and electricity lines. Moreover, as the off-line tanks analysed in the study have a diameter of 2.4 m, it is not always possible to have them installed at the same level as the invert of the inflow pipeline. This may result in the accumulation of sediments that diminish the capacity of the tank and increase maintenance costs. Sediment transport and deposition have complex behaviour that is not easily characterized with conventional methods and understanding the influence on hydraulic systems requires advanced numerical simulations (Kaur et al., 2017). For that perspective, in-line storage with RTC is considered as the most feasible option to reduce peak runoff from this type of development area. The NPV of the solution is eventually 26% lower compared to the base scenario. This is a clear advantage in a long-term perspective.

Similar conclusions were made in Publication III in the analysis of RTC inlets. The smart inlet system showed high hydraulic performance, capable of reducing the peak flow up to 50%, using only 17% of the catchment area for temporarily ponding. This was achieved with 57 smart inlets at the threshold level of the ponded water of 0.125 m. To reach the same effect with detention tanks, ca 1803 m^3 of underground storage is needed. As a result, the cost of the tanks overtopped the smart solution merely 1.8 times. Although the lifetime of the electronics and sensors is substantially shorter than that of the concrete tanks (5–15 years compared to 50 years) or pumps (15 years), the net present value over a 50-year period of the smart systems was still 19% lower. This is mainly because of lower investment and lower yearly maintenance costs. As a result, the small-scale real-time control strategy with smart inlets seems a promising and feasible solution to be implemented in existing parking areas for peak flow reduction.

4 Final comments

The summary article generalizes the developments and results of four scientific publications on smart urban drainage systems (Publication I, II, III and IV). Although the control solutions of UDS presented in the thesis were tested on three pilots, they are designed to be universal, i.e., applicable in any urban area facing the increasing risks of stormwater systems' overload.

In a wider perspective, the work draws attention to the fact that also above ground structures, like existing permeable surfaces are part of UDS. The three pilot sites are just examples of some of these possibilities. This aspect is often neglected due to different ownerships and interests. Typically, in such areas, the water utility operates the underground UDS while the landowner is responsible for maintaining above ground spaces, i.e., stormwater catchments. This division hinders the implementation of more efficient stormwater solutions like LIDs, SSUs or floodplains on parking lots. The thesis clearly demonstrates that the co-operation between these two parties can yield beneficial impact on handling an urban stormwater run-off. This is an important step towards integrated view on improving the resilience of urban areas.

This thesis as any other research work has its limitations and possibilities for future work. The developed decentralized MPC algorithm has potential to operate also in a distributed mode, i.e., the controllers are exchanging the information about the statuses and adjusting their actions according to that. This will be tested in future research. Distributed mode can open new opportunities, for example, to reduce the dimensions of SSUs (Publication I), volume of in-line storage (Publication II) and size of the floodplains (Publication III) and increase the efficiency to reduce the peak flow. The research was based on the virtual sensors that were simulated by the HiFi model. The next step comprises installation of real sensors into UDS and testing of the performance of the MPC algorithm using specially designed, i.e., fast actuators. The author of the thesis dreams to have one fully functional smart stormwater system built into an urban area in the coming years.

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Abstract

Decentralized real-time control platform for urban drainage systems in climate proof smart cities

A technical solution is developed in the thesis to control stormwater runoff from above ground catchments to an urban drainage system (UDS) in order to alleviate the risk of pipeline surcharge during intense rainfall events. The surcharge can lead to pluvial flood or activation of combined sewer overflow (CSO), both of which will have negative consequences on urban environment.

The core of this work is the development of decentralized model predictive control algorithm (MPC) that can be implemented to control inflows to existing UDS with minimum cost and effort. The algorithm allows foreseeing the impact of rainfall event or other disturbance affecting the flow in the pipelines and adjusting the actuators just in time to capture the peak flow. This reduces the risk of flooding downstream. Decentralized operation makes the control points independent and less vulnerable to major failures. The developed MPC algorithm utilizes the dynamic inner model of the actuator but needs no simultaneous modelling of UDS or computationally costly optimization routines. This is a clear advantage compared to most of the MPC systems designed.

Urban stormwater services face major challenges in coming decades. These are related to urbanization, climate change and deterioration of the infrastructure. Urban areas have responded to the increasing demands by enlarging the underground grey facilities, i.e., installing new pipelines and detention tanks and enlarging the capacity of existing systems. Due to the large extent of the challenges, this method is prone to failure. Therefore, new smarter solutions that comprise also above-ground facilities and allow automatic control of the inflow to UDS are needed. Most of the control systems available have centralized nature and are not capable for predicting UDS parameters, like water levels in pipelines. This makes it difficult to apply the control to the whole urban catchment with numerous inlets that respond quickly, i.e., in minutes to rainfall event.

The decentralized MPC created in this work is universal and robust, allowing the implementation of any type of inlet control in an urban catchment. The algorithm has been successfully tested in three pilot areas to control adjustable gullies, real-time controlled manholes and street storage units. The results show that the solution is capable of reducing the peak flow more than 50%, keeping the inflow to UDS below the pre-set threshold level and reducing the number of flood nodes by 30%. Predictive control algorithm is computationally faster than most of the solutions available, for example, the calculation of the settings of 18 decentralised orifices took only 0.11 s, which is sufficient for typical control step of 1 min. The solutions are also economically feasible both in terms of investments and maintenance costs, being in average 20% cheaper than traditional methods for flood risk reduction. Therefore, the developed smart stormwater system is feasible, robust and an efficient method to increase the resilience of urban areas.

Lühikokkuvõte
Sademeveesüsteemide detsentraliseeritud juhtimissüsteemi platvorm kliimakindlates tarkades linnades

Doktoritöös loodi lahendus linna sademevee süsteemide sissevoolude juhtimiseks eesmärgiga vähendada isevoolse torustiku ülekoormusega seotud riske. Ülekoormus, sh torustiku täistäitele üleminek võib kaasa tuua üleujutuse või ühisvoolse kanalisatsiooni ülevoolu rakendumise. Mõlemal olukorral on negatiivsed tagajärjed linnakeskkonnale.

Töö tuumaks on mudelipõhise ennustusvõimekusega juhtimisalgoritmi loomine, mida on võimalik rakendada olemasoleval sademevee süsteemil vähima maksumuse ja töömahuga. Algoritm võimaldab ette ennustada vihma või muu häiringu mõju sademevee süsteemi torustiku vooluhulkadele ning anda täituritele ette seaded tippvooluhulga piiramiseks. See toob kaasa üleujutusohu vähenemise linna süsteemis. Algoritmil on detsentraliseeritud ülesehitus, mis võimaldab juhtida sissevoolusid sõltumatult ning teeb süsteemi rikete suhtes töökindlamaks. Välja arendatud mudelipõhise ennustusvõimekusega algoritm kasutab täituri seadete leidmiseks dünaamilist mudelit, kuid ei vaja kogu süsteemi reaalajas modelleerimist või arvutuslikult mahukat optimeerimist. See on oluline eelis võrreldes teiste olemasolevate ennustusvõimekusega algoritmidega.

Linna veesüsteemide toimimist mõjutavad lähi kümnenditel olulisel määral nii urbaniseerumine, kliima muutused kui ka taristu tehnilise seisukorra halvenemine. Tavapäraselt on linnakeskkonnas nende mõjuteguritega hakkama saamiseks laiendatud või suurendatud olemasolevat sademevee süsteemi, paigaldades uusi torustikke ja mahuteid või suurendades olemasolevate torustike läbilaskevõimet. Eespool nimetatud mõjutegurite koosmõju on aga sellise ulatusega, et tavapärasel viisil ei ole enam võimalik süsteeme muutuvate oludega kohandada. Sellest tulenevalt otsitakse uusi nutikaid lahendusi, mis kaasaksid ka maapealset linnaruumi ning võimaldaksid kontrollida veekogust, mida torustikku juhitakse. Olemasolevate juhtimissüsteemide kasutamine sellisel moel on aga oluliselt raskendatud, kuna need on tsentraalsed, ei võimalda ennustada süsteemi käitumist ning neid on keeruline rakendada sissevoolude kontrolliks, mis asuvad suurel maa-alal kogu linna valgala ulatuses.

Doktoritöös loodud detsentraliseeritud mudelipõhise ennustusvõimekusega algoritm on vaba eelkirjeldatud puudustest ja see on sobilik mistahes tüüpi sademevee sissevoolude juhtimiseks. Algoritmi katsetati kolmel pilootalal, et juhtida reguleeritavaid restkaeve, maa-aluseid kontrollkaeve ja tänava pinnas asetsevaid akumulatsioonimahuteid. Tulemustest selgus, et kontrollalgoritm on võimeline vähendama tippvooluhulka kuni 50%, hoidma vee sissevoolu torustikku püsivalt alla ette antud piirmäära ja vähendama üle ujutanud kaevude arvu kuni 30%. Algoritm on ajaliselt kiirem kui enamus olemasolevaid lahendusi. Näiteks 18 tänavareservuaari seadete arvutus võttis aega 0,11 sekundit ühe minutilise ajasammu kohta. Välja töötatud lahendus on lisaks tehnilistele eeldustele ka majanduslikult tasuv. Analüüsides nii investeeringute kui püsikulude suurust, on lahendus umbes 20% odavam kui tavapärased üleujutuse riski vähendamise meetodid. Seega on doktoritöös välja arendatud lahendus teostatav, töökindel ja majanduslikult soodne ja sobib linnade kliimakindluse tõstmiseks.

Appendix 1

Publication I
Kändler, N.; Annus, I.; Vassiljev. (2021). **Controlling peak runoff from plots by coupling street storage with distributed real time control**. Urban Water Journal. In press.

Controlling peak runoff from plots by coupling street storage with distributed real time control

Nils Kändler[a]*, Ivar Annus[a] and Anatoli Vassiljev[a]

[a]*Department of Civil Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia*

Provide full correspondence details here including e-mail for the *corresponding author

Nils Kändler

Researcher

Department of Civil Engineering and Architecture

Tallinn University of Technology

Mobile: +372 5266 701

nils.kandler@taltech.ee

www.taltech.ee/en

Controlling peak runoff from plots by coupling street storage with distributed real time control

A technical solution is developed to control stormwater runoff from plots in order to mitigate pluvial flood risk. Climate change alters precipitation patterns, which increase a risk for urban drainage systems (UDS) operating above their design limits. Therefore, feasible solutions are needed to retrofit UDSs to new climate conditions. In this study, street storage units (SSU) are coupled with a predictive real-time control algorithm to temporarily accumulate stormwater and thus minimise the risk of UDS surcharge. SSUs are operated in distributed mode and do not directly affect the flow in the pipeline, which makes the system less vulnerable to failures. SSUs are fully usable for citizens in dry periods. The results showed that control of 6% key inflows with SSUs reduced the number of flood nodes by 30% during an extreme weather event. The solution was successfully tested in Rakvere town, Estonia.

Keywords: off-line storage; street storage; RTC; DMPC; flood mitigation

Introduction

Urban water services face major challenges in coming decades due to the global effects of climate change. Altered precipitation patterns and extreme weather events pose stress on urban water infrastructure, especially on stormwater systems typically designed on the basis of historical climate information. According to the analysis by Rosenberger et al. (2021) the climate projections for 2040-2068 demonstrate that persistent development without any compensation measures will lead to severe problems in stormwater management. Rebuilding the pipeline networks to meet new meteorological conditions is financially unrealistic due to a large extent of the effort (García et al. 2014). There are many methods currently under research that could bring relief to this challenge. Low impact development (LID) and underground detention tanks (DT) are some of these methods that have proven their importance and benefits in reducing the flood risks (Li, Yan, and Duan 2019). It is pointed out by S.V. Lund et al. (2019) that integration of these new solutions with exiting UDS infrastructure and applying real-time control (RTC) to operate the whole system will significantly improve the flood resilience. Therefore, future cities must apply integrated solutions and harness the advantages of instrumentation and control to mitigate climate risks (Yuan et al. 2019). In this process, smart infrastructure plays a key role to bridge gaps between facilities currently designed and operated mainly under a fragmented approach (Berglund et al. 2020). For example, engineers planning underground stormwater pipelines seldom participate in the design of streets, roofs and other areas contributing highly to stormwater runoff. That leaves a great potential of joint design effort to increase the capacity of stormwater systems with minimum cost and effort, i.e., underground works unharnessed.

Real time control (RTC) of urban drainage systems (UDS) is considered one of the most feasible alternatives to construction-focused solutions (Beeneken et al. 2013). RTC systems in stormwater networks are typically designed to operate the assets by monitoring the system in real time, either applying local control or system-wide control options (García et al. 2015). According to Abou Rjeily et al. (2018), the algorithms of RTC systems can be classified as heuristic, i.e., based solely on an operator's experience or optimisation-based rules that in some cases can also predict the system statuses ahead to create proactive control commands. For the latter method, the model predictive control (MPC) algorithms have demonstrated high potential in many studies (e.g., Abou Rjeily et al., 2018; Madsen, Falk and Halvgaard, 2018; Shishegar, Duchesne and Pelletier, 2018; Lund et al., 2020). MPC is an adaptive control strategy in which optimal settings are found recursively after new data from the UDS become available at each measurement step. The key aspects of MPC are receding horizon principle, which allows recursive updating of both prediction and control horizon and the internal MPC model optimised based on the objective function to find the best control settings (Nadia Schou Vorndran Lund et al. 2018).

In most cases, RTC algorithms have been developed and analysed for in-line control and storage operated in centrally controlled mode (Eulogi et al. 2020; Lim et al. 2014; Svensen, Niemann, and Poulsen 2019). However, distributed RTC systems that are not directly interfering with the main collectors are still in a wider context unexplored (Abou Rjeily et al. 2018).

The concept of street storage units (SSU) as an effective off-line measure to mitigate flood risk was developed decades ago but most of the systems implemented are using either centrally controlled operative systems or have static weirs designed for flow regulation (Carr, Esposito, and Walesh 2001). Nevertheless, the SSU solution has proven to be an effective method to reduce a peak flow from streets and parking lots to underground pipeline systems (N. S.V. Lund et al. 2020). SSU is a dedicated area in urban landscape where excess stormwater can be temporarily accumulated if an underground pipeline is surcharged. This method differs from tanks and barrels while during dry periods, the SSU is fully usable for citizens and traffic. This is an important aspect while free space is usually scarce in dense urban environment. It is also conceptually different from in-line storage systems like actuators harnessing the capacity of the pipelines while off-line solutions need no actuators to be placed into the main collectors. As pointed out by Garofalo et al. (2017), this is a clear advantage since the risk of UDS malfunction at an actuator's failure is minimum.

The main aim of this study is to develop a novel solution to regulate runoff in real time from street areas to the underground pipeline system. For that, off-line STUs are coupled with distributed RTC algorithms. According to Schuetze et al. (2003), local control is economically feasible for smaller UDS. In this paper, we will provide principal design parameters and a control algorithm to develop such systems in any smaller municipality with a separate stormwater system. The solution was tested in a small-size town Rakvere, Estonia. This work also contributes to widening the RTC concept by exploring its application at the control systems operating in distributed mode. The algorithm is fully coded in Python language and utilises *pyswmm* and *swmmtoolbox* modules to interact with the HiFi model created in EPASWMM5.1. The HiFi model uses a dynamic rainfall-runoff simulation by utilizing a dynamic wave flow routing method. This allows to simulate backwater effects, pressurized flow, flow reversal, and non-dendritic layouts.

Methodology

Dense urban areas like central districts of towns and cities have typically a high ratio of impermeable surfaces, i.e., streets, parking lots, squares that are in intense everyday use. Therefore, there are limited options to pursue low impact development (LID) practices for stormwater management as this takes valuable space out from active daily use. On the other hand, sealed surfaces have a great potential for temporary stormwater storage during cloudbursts (Zischg et al. 2018). In this case, the usage of urban space is limited only during short periods of time, typically less than an hour and can be freely used by citizens in dry periods. Our previous research focusing on parking lots (Kändler et al. 2020) showed strong feasibility of the street storage solution compared to traditional underground storage expansion methods. In this study, we expand our previous results over the whole urban catchment and analyse more universal street storage options that could be applied in various places with impermeable surface like roofs, streets, squares etc. The novelty of the idea is to control runoff from small catchments that play an important role in triggering flood events downstream of the system (Figure 1). This allows leaving the main pipeline system free from actuators, i.e., valves, gates or weirs, which reduces the risk of major failure due to obstacles in the collectors, i.e., malfunctioning weirs and gates.

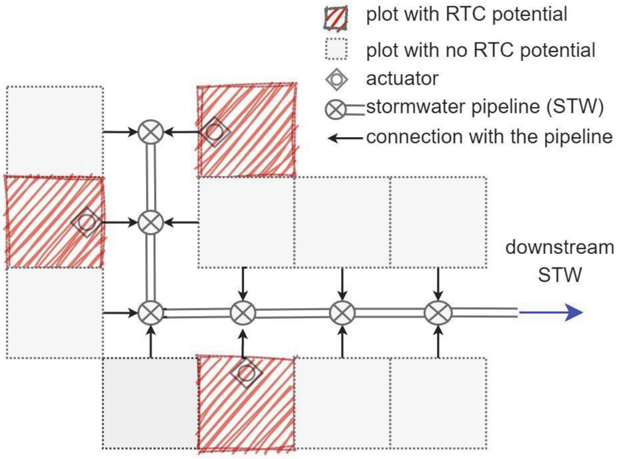

Figure 1. Principal scheme of street storage placement and interaction to main UDS.

The key aspect of the analysed solution is to find a feasible amount of catchments, i.e., plots where the control could be applied with minimum cost and effort. It would be of course most effective to regulate inflows from all the sub-catchments/plots in the dense urban area, but this would be economically unfeasible.

In addition to physical requirements for construction, i.e., landscaping to create barriers for storage, the flow control algorithm plays an important role in the efficiency of the system. A centrally controlled system has its advantages but in many cases it is too expensive to implement (Campisano et al. 2013). Therefore, a system was designed with independent units capable of operating without central control station, but exchanging information about the statuses between adjacent units.

Moreover, as the catchments are small, the time of concentration is short, which underlines the need for flow prediction to capture the peak flow at the right moment.

Model predictive control (MPC) is utilised for that task. All the elements of the storage and the control system are described in the following paragraphs.

Street storage

Street storage unit (SSU) is a dedicated area in urban space that can be temporarily filled with stormwater during heavy rainfall events when the underground system is surcharged and additional runoff will cause uncontrolled flooding in downstream areas. In dry periods or during moderate rain events, the area is dry and can be in active use for citizens. For the study, a two-level storage area was designed (Figure 2).

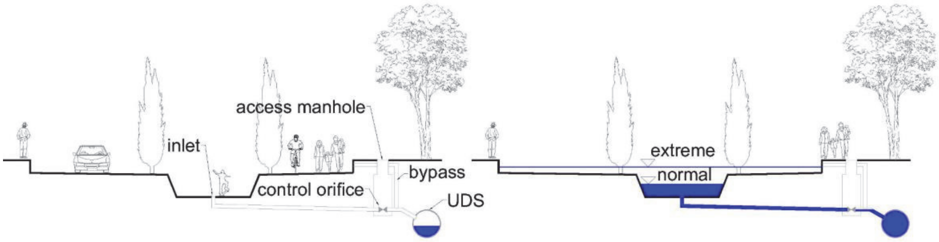

Figure 2. Street storage unit during dry periods (left) and rain events (right).

The lower level of the storage will be filled during normal rainfall events, while the upper section with a significantly larger area is used to capture extreme cloudbursts. Two parameters: maximum depth h_{max} and the area of the upper and lower part, A_U and A_L respectively are defined for street storage design. Both depend on the specific location of the system and design intensity of an extreme rainfall. To determine h_{max} , one should take also into account a safety factor of water depth to pedestrians and traffic. Parameters A_U and A_L should be selected to fit the unit best into the urban landscape and the storage can be filled during rain events without additional pipeline built, i.e., utilising only surface flow.

Actuator

The key element of the system is a flow control device that is capable of regulating runoff from SSU to the underground stormwater pipeline. This device can be either a sluice gate or a valve capable of adjusting dynamical positions between the fully closed and the fully opened statuses. For this study, a sluice valve was selected and the unit was modelled as a side orifice with a circular opening. Depending on the rainfall intensity and water depth in the street storage unit and pipeline, the valve can operate as a weir under gravity flow, i.e., flow with free surface or surcharged orifice under pressure flow condition. A flow with a partly filled pipe, i.e., a gravity flow occurs especially at the beginning and at the end of a rain event, while filling and emptying of the area has typically a full pipe with pressurized flow conditions. As the time of concentration for small catchments is short, i.e., counted in minutes, it is important to take into account both flow regimes in order to accurately predict and calculate gate settings. For that, threshold head H_* is calculated for each time step i:

$$H_* = z_0 + \omega D \tag{1}$$

where z_0 is the elevation of the bottom of the gate opening, D is the full diameter of the gate and ω is the setting of the orifice. As the setting is not known at the beginning of the time step, setting from the previous time step ω_{i-1} is used as an initial guess. The dynamic model of the actuator decides which equation to utilise for the flow calculation, evaluating upstream head H_1 against the threshold head H_*:

$$Q = \begin{cases} orifice\ model & , if\ H_1 > H_* \\ weir\ model & , if\ H_1 < H_* \end{cases} \tag{2}$$

Tailwater conditions are also checked and relevant adjustments applied for time-steps with submerged tailwater to improve the accuracy of the results. In our study, the closing time of the actuator, i.e. movement from $w = 0$ to position 1 or vice versa was set to one minute which was sufficient to respond to the sudden changes of heads H_1 and H_2.

Control algorithm

Local RTC algorithm is an engine to operate the actuator. The algorithm has distributed nature. This means that no central control unit is needed, all the SSUs are capable of operating independently. This approach has two main advantages: firstly, higher resilience in case of failures; secondly, lower implementation and maintenance costs. Highly developed areas have typically shorter time of concentration, which means that the catchments respond quickly to a rainfall event filling the SSUs within a couple of minutes. For regulating outflow from this type of SSUs one needs to predict system statuses in some time ahead to move the actuator into desired position. For that reason, model predictive control (MPC) has been chosen to calculate system settings. MPC has shown high potential in urban stormwater management but its implementation in distributed mode needs still improvement (García et al. 2015).

Due to economic reasons, it was decided that only the data that the algorithm receives from the UDS to determine the valve settings are regarded as water elevations before (H_1) and after (H_2) of the actuator of each SSU. Installation of flowmeters is technically complicated while accurate information is needed for both pressure and free surface flow, flowmeters need sufficient length of straight pipe segment and need to be accessible for maintenance. This requires additional investments, i.e., larger control manhole with an access ladder. Flowmeters, typically installed on the invert of the pipeline, also need to be regularly cleaned to free the sensors from sediments that will raise the maintenance cost of the system.

The control algorithm consists of six modules presented in Figure 3. Measurement data from level sensors H_1 and H_2 is imported into the prediction module that analyses the elevation trends and makes predictions over the prediction horizon P. Predictions and measurements typically contain disturbances (Yuan et al. 2019). Therefore, automated custom filter module is created to smooth the prediction data for the control module.

The control module needs an additional parameter to define maximum allowed, i.e., threshold runoff from the SSU. This threshold flow Q_t can be either pre-set by water utility on the basis of modelling results or calculated dynamically after each time step i, taking into account the statuses of adjacent SSUs. The module takes Q_t as an objective operational goal and runs the orifice model to calculate new settings for the sluice valves. The setting ω is exported to the valve control unit and the valve is adjusted accordingly. In this research, the high fidelity (HiFi) model with a pre-set Q_t was used to mimic the processes of a real UDS.

The process of calculating the settings for n SSUs $\omega_{1..n}$ is repeated after each measurement step i, as illustrated in Figure 3.

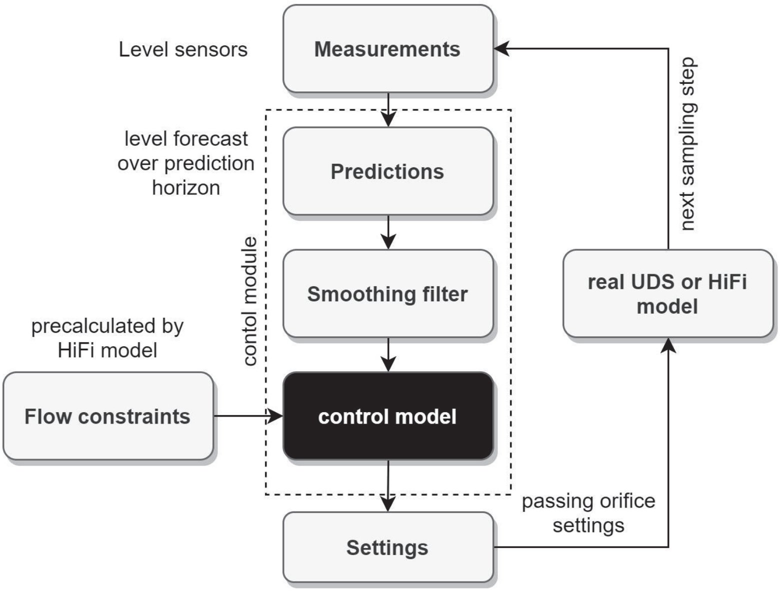

Figure 3. Architecture of the process scheme.

Prediction module

The purpose of the module is to utilise the measured head data to create an arrow of predicted values over the prediction horizon P with a step equal to the measurement step i. For small catchments, P can be taken equal to the time of concentration (i.e., the time needed for water to flow from the most remote point in a catchment to the outlet), which is typically between 3 to 10 minutes. The measurement step i used in the study is 1 min. This is the recursive step when new prediction is created and passed to the subsequent module. With a defined P and S, the linear extrapolation method showed the most reliable and stable results compared to other methods for predicting measurement data (Dotto et al. 2014). The result of the prediction is passed to the smoothing filter as an array in a form of $[x_1, x_2, \ldots, x_n]$, where x represents the predicted value, x_n is the last value of the prediction horizon P and $x_1 - x_2$ is the measurement step i. This prediction array is used by a smoothing filter to discard predictions that do not meet the constraints.

Smoothing filter

There are various methods available to filter the measurement data, i.e., handle disturbances. For example, Kalman filter is widely used in environmental engineering for sensor data smoothing (S.V. Lund et al. 2019). For this study, a custom filter was created in order to evaluate not only one prediction array as typically possible in existing filters but two arrays of H_1 and H_2 predictions simultaneously. This gives additional possibilities to filter out improbable changes in head differences, i.e., sudden backflow etc. The filter analyses two main possible deviations in the prediction array:

(1) H_1^{i+P} cannot be negative neither lower than z_0;

(2) H_1^{i+P} cannot be smaller than H_2^{i+P} if $H_1^i > H_2^i$.

If any of these conditions is violated, previous element x_{i-1} from the prediction array is taken as x_n and filtering is recursively repeated. If none of the elements in the prediction array meet the conditions, the last actually measured value H_1^i and H_2^i is taken as a prediction for this measurement step i. If the UDS has a backflow, i.e. $H_1^i < H_2^i$ no predictions will be used and the actuator will move to the next position depending on the type of UDS: 1) fully open if the UDS is separate, i.e. the backflow contains only stormwater; 2) fully close in case the system is combined in order to avoid polluted water flowing to the street area.

Internal MPC model

To calculate the side orifice predicted flow Q_{pred} on the basis of predicted heads H_1^{i+P} and H_2^{i+P}, the non-linear internal model is used. The flow is evaluated against the threshold flow Q_t as an objective and a new setting will be calculated for the orifice taking into account the current status, water levels and change in heads. Valve setting ω is calculated for every measurement step i using principal model:

$$\omega_i = M(H_1^{i+P}, H_2^{i+P}, \omega_{i-1}, Q_t) \,, \tag{3}$$

where M denotes the MPC inner model, H_1^{i+P} and H_2^{i+P} are predicted heads over the prediction horizon P at the time step i, ω_{i-1} is the orifice setting from the last time step and Q_t is the pre-set threshold flow value. The simulation starts with a fully opened valve, i.e. $w = 1$. The following main rule groups are applied for control:

(1) If $Q_{pred} > 0$ and $Q_{pred} > Q_t$, then start closing the valve by calculating a new setting ω;

(2) If $0 < Q_{pred} < Q_t$ and $Q_{calc} < Q_t$, then start opening the orifice by calculating Q_{max} possible. If $Q_{max} < Q_t$ valve can be fully opened, else a new setting ω is calculated;

(3) If $0 < Q_{pred} < Q_t$ and $Q_{calc} > Q_t$, then a new setting ω is calculated for the orifice to ensure that the threshold flow Q_t is met,

where Q_{calc} denotes the calculated flowrate on the basis of measured heads H_1 and H_2.

In addition to the rules, constraints related to the water depth in the street storage are applied: firstly, to avoid overfilling, which might result in possible spillages and secondly, allow the valve to be fully open only after the water depth in the storage is less than 0.2 m. This avoids situations when the water flow will rapidly rise because of the large difference between H_1 and H_2, which may lead to downstream surcharge. If maximum water depth h_{max} has been reached in SSU, the valve will be set to minimum opening $w = 0.1$ to ensure some depletion even if the outflow is exceeding the threshold value Q_t.

Flow constraint Q_t, i.e., threshold flow can be fixed over the rain event or may also dynamically change depending on the status of other adjacent street storage units in the catchment. For this study, constant Q_t was calculated for each node on the basis of the highest rainfall event that will not cause flood in the system.

The setting ω calculated by the internal MPC model is either passed to the real actuator in the drainage system or to the HiFi model for testing.

Identifying control locations

Choosing the locations where the storage units should be placed affects significantly the overall efficiency of the control system (Saldarriaga et al. 2020). Several research papers have addressed different methodologies for site selection (Eulogi *et al.*, 2020), sizing the units and determining the optimal number of facilities per catchment (Cunha et al. 2016). In this study, the HiFi model with extreme precipitation was simulated and the following criteria were determined for searching the optimum locations:

(1) Suitable free space, i.e., impermeable area that has potential to be retrofitted into street storage units;

(2) Node flood total volume V_f is larger than the threshold volume V_{th};

(3) Flow direction from the SSU to the UDS is positive, i.e., flood is caused by the runoff from the catchment, not by backflow from the underground system. Node was excluded from the selection if any backflow occurred up to B_n minutes prior to the maximum flood rate;

(4) Number of selected locations should not exceed 10% of all the inflow nodes, i.e., properties or street areas connected to UDS.

Our analysis for the case study showed that the threshold volume V_{th} should not be less than 0.1 m^3. This avoids including nodes with smaller floods, the control of which would have limited effect on flood reduction. Street storage units collect and accumulate water only from the surrounding areas, i.e., their catchment is relatively small with the time of concentration counted in minutes. Therefore, after the evaluation of the results, the backflow constraint B_n was set to 3 minutes.

Case study

The street storage with the RTC system was tested in an Estonian town, Rakvere (Figure 4). The municipality with its history of over nine centuries has ca 10 thousand inhabitants today. The central part of the town selected for the pilot area has fully separate stormwater system. This is also a heritage area, which poses restrictions on wide-scale construction works like enlargement of pipelines or construction of underground storage tanks. The total length of the pipeline is ca 7.1 km and diameters vary from 0.2 to 1.2 meters. The stormwater system of the central part of the area is connected to the main 1.2 m stormwater tunnel at the west side of the town. The outlet of the system is the Selja river that carries the water into the Baltic Sea. Totally, 287 stormwater catchments with connection to UDS are situated in the pilot district with a total area of 41.9 ha, average ground slope of 2.2% and average imperviousness of 65%. Some larger buildings have their roofs directly connected to the pipeline system, others direct flow to the street where it is captured by stormwater inlets. The moderate size of the catchments and UDS makes the pilot suitable for testing the solution that could be feasible for small municipalities.

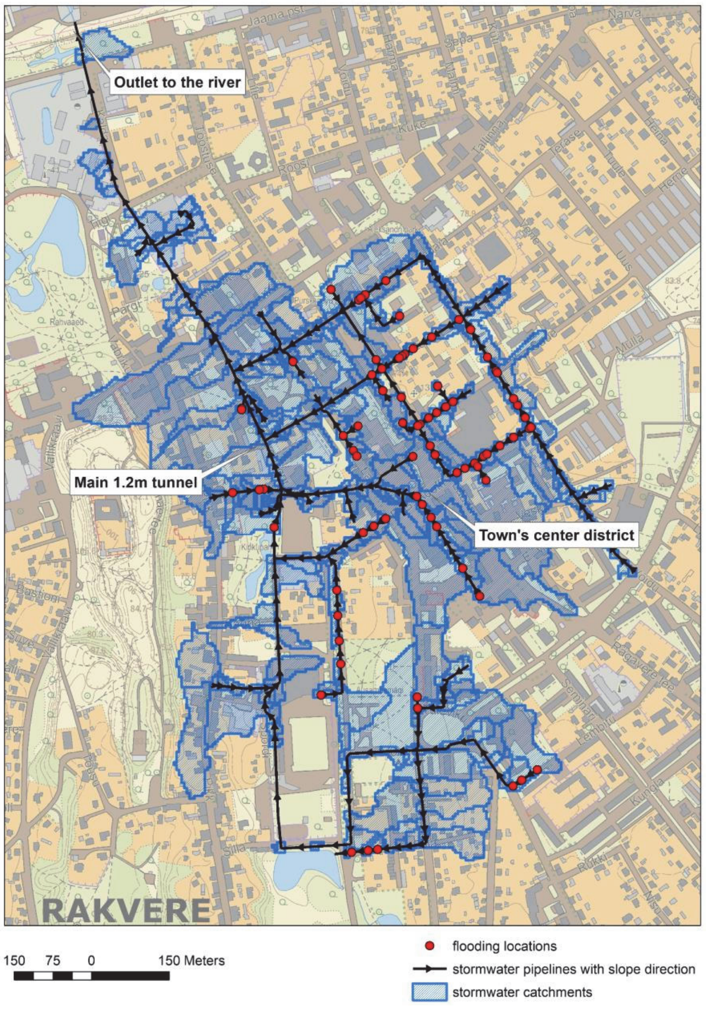

Figure 4. Pilot area in Rakvere, Estonia.

Major rehabilitation of the stormwater system in Rakvere was accomplished in years 2015 – 2018. This system is expected to operate during the next 50 years, making the pilot case a suitable case for situations when other mitigative measures instead of pipeline-focused solutions have to be implemented to handle increasing flowrates.

The HiFi model of the stormwater system created in SWMM5.0 software has been compiled in ongoing Interreg BSR NOAH project (https://projects.interreg-baltic.eu/projects/noah-178.html). The model is calibrated on the basis of flow and precipitation measurements. The SSU control algorithm is designed to operate without simultaneous modelling of UDS.

Design storm

Currently no major historical flood events caused by the surcharge of the stormwater system have been registered in the pilot area. However, the risk of flood rises significantly if we take into account the climate projections, especially higher rainfall intensities forecasted for coming decades (H. Madsen et al. 2014). In this analysis, future design storm was created on the basis of the widely used Representative Concentration Pathway (RCP) methodology (Saldarriaga et al. 2020; H. Madsen et al. 2014). Moderate climate projection RCP4.5 was selected and an alternative block methodology suggested by Jato-Espino et al. (2019) was used to construct the RCP4.5 rainfall curve with the return period of two years (Figure 5). This corresponds to the design rainfall suggested by Estonian Design Standard (EVS848:2013 2013) with a return period of 20 years. This return period is used to design UDS when there is a high risk of damage to the buildings and basements because of the pluvial flood.

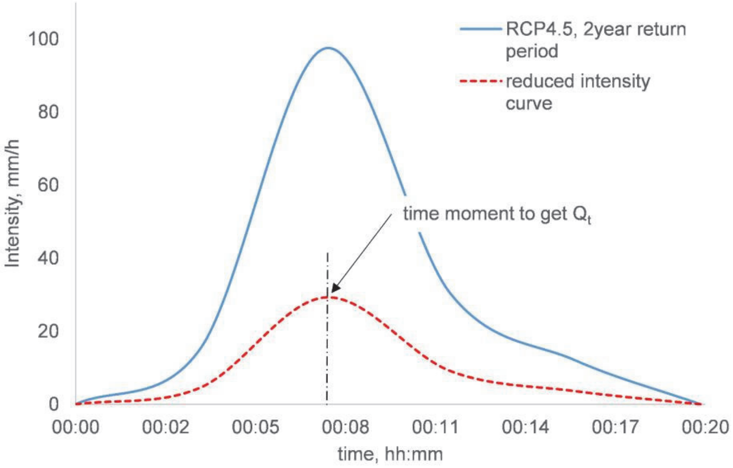

Figure 5. Hydrograph of the design storm and reduced intensity curve to find Q_t *for each SSU.*

The RTC system developed also needs Q_t (threshold flow, i.e., maximum flow from plots to the underground pipeline with no pluvial flooding) to be predefined for each plot connected to the pipeline system. Local water utility typically determines Q_t on the basis of historical data and experience. In this study, Q_t was derived from the RCP4.5 curve through an iterative process with the intensities reduced until no flood event was registered during the simulation period. The curve for Q_t is presented in Figure 5.

Street storage units

Identifying control locations is the first step in planning and implementing a street storage RTC system. For the pilot case, the threshold volume V_{th} was taken equal to 0.1 m^3 and the backflow constraint B_n was set to 3 minutes. After simulating the HiFi model with the design storm, a total of 18 locations (6% of all the inflows/catchments) were determined that satisfied the pre-set conditions. Most of the selected locations are situated at the centre of the pilot area where the ratio of the impermeable surface and the consecutive flood risk is the highest (Figure 6). Selected area represents typical dense urban space that has limited room to construct, for example, low impact development solutions or other mitigative facilities that will reduce the neighbourhood in an active use of citizens.

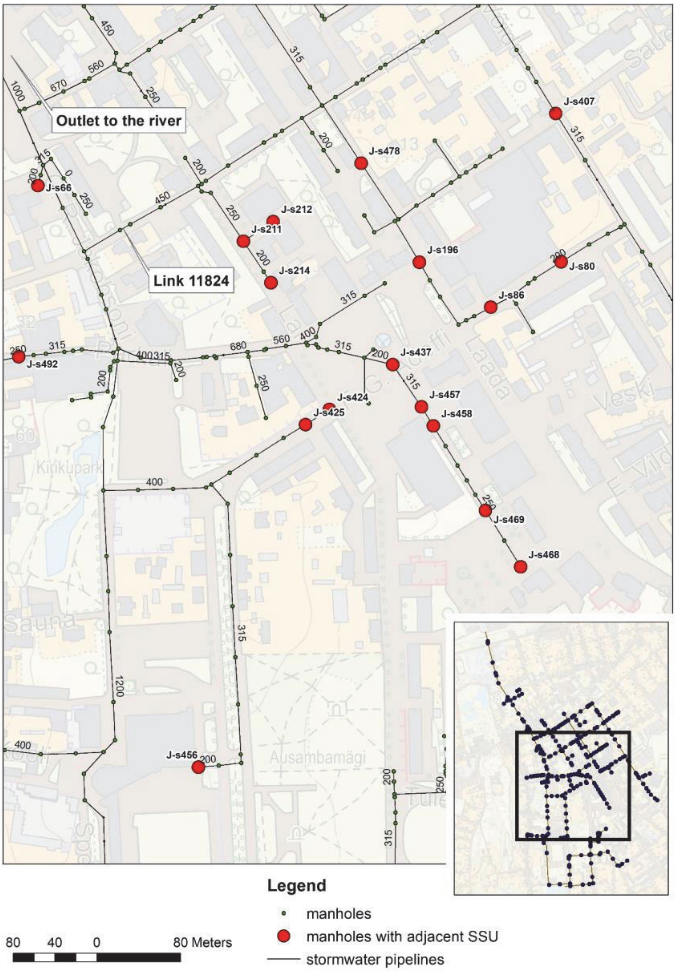

Figure 6. The locations of the street storage units in the pilot area.

Dimensions of the storage units play an important role in both the capability of temporal flow accumulation and also smooth fitting into urban landscape. For the case study, all the units were determined using the unified dimensions. The area of the upper part (A_U) is taken 1000 m^2 and the area of the lower part (A_L) 50 m^2. Maximum depth of the lower part is 1.2 m and upper part 0.3 m, total maximum depth (h_{max}) of all units is

1.5 m. Street storage units form in average 40% of the total area of the selected catchments and 4% of the total area of the pilot district. It is important to note that this area is excluded from the urban space available in everyday use only in case of bigger rain events. Diameter (D) of the actuators was calculated on the basis of runoff and it varies from 0.2 m to 0.5 m.

RBC algorithm

RBC is a type of a regulatory control algorithm which is the simplest operating method for any water system and is therefore widely used by water utilities (Mollerup et al. 2015; Yuan et al. 2019). The RBC was used to give a comparison to developed control system and support the communication of its advantages to the stakeholders. The RBC uses the following algorithm:

(1) If the water level H_1^i at the downstream side of the control orifice rises above the predetermined upper level h_u, the orifice will fully close;

(2) If the water level H_2^i at the downstream side of the control orifice is falling below the predetermined lower level h_l, the orifice will fully open;

(3) Orifice opening speed is j times slower than closing speed.

The rule (3) assures that accumulated water that is held in the street storage unit is not suddenly released to the underground system causing risk of surcharge. The following values were determined for the parameters as a result of a simple search algorithm: h_u was taken equal to 0.2 m, h_l was set to 0.1 m and j is 5 times slower than closing the orifice.

Results and discussion

In this study, two technical solutions were analysed to retrofit the existing stormwater system in order to increase its resilience to future flood events. All the results were calculated using the HiFi model that mimics the actual behaviour of the UDS. After construction of SSUs, the HiFi model can be replaced with data derived from the real system. In the latter case, the HiFi model can be used for data validation and calculating preliminary settings, i.e., Q_t and dimension of the SSUs. Flood parameters for the case study area were analysed for four scenarios:

1. Base scenario, i.e., existing UDS with no flood control implemented;
2. SSUs with no control, i.e. outflow with static orifices;
3. SSUs with RBC applied;
4. SSUs with MPC applied.

Despite the relatively new UDS that has so far operated without triggering any major pluvial floods, modelling of future storms showed serious concern about high flood risk in coming decades. These results are presented as the base scenario. Therefore, street storage units capturing water from the surrounding plots with a high ratio of impermeable surfaces were placed to the urban space and connected to the existing pipeline system. In case of scenario two this connection was static, i.e. with fully opened fixed orifice. The opening of the orifice was made changeable in case of scenarios three and four. Dimensions of the existing pipeline were not changed, no storage tanks and actuators to utilise in-line storage capacity were used.

The simple RBC algorithm developed for the study needs only one sensor at the downstream side of the actuator to close or open the valve depending on the pre-set water levels h_u and h_l. This option has no possibility to predict the system's status. This is a serious shortcoming while time of concentration t_c in this type of catchments is very short, typically measured in minutes. For example t_c varies from 0.66 min to 3.39 min with average value of 1.58 min in case of Rakvere catchments. Therefore, it is not possible to reactively act fast enough to prevent peak flow exceeding the threshold flow Q_t to enter the UDS already surcharged. Moreover, it was found that opening the valve on the basis of only one sensor causes substantial peak in runoff that even increases the peak flow from the controlled catchment compared to the base scenario.

On the other hand, MPC needs one level sensor on both sides of the actuator in order to satisfy the objective function by calculating the settings with the inner model. Prediction horizon P that is set to 5 min showed a reasonable forecast to proactively react to the rapidly changing flowrate. Typical setting curve and resulting flows from SSU are presented in Figure 7. It can be seen from the figure that at the beginning of the rainfall – when the flowrate increases rapidly, the prediction module shows high forecasted change in the flowrate minutes ahead, making it possible to adjust the orifice to cut the flow into a desired threshold range. In every measurement step i, the forecast over the prediction horizon P is renewed and a new setting is calculated accordingly. After the end of the rain event, the system slowly releases the water accumulated and returns to the initial status to be ready for the next event.

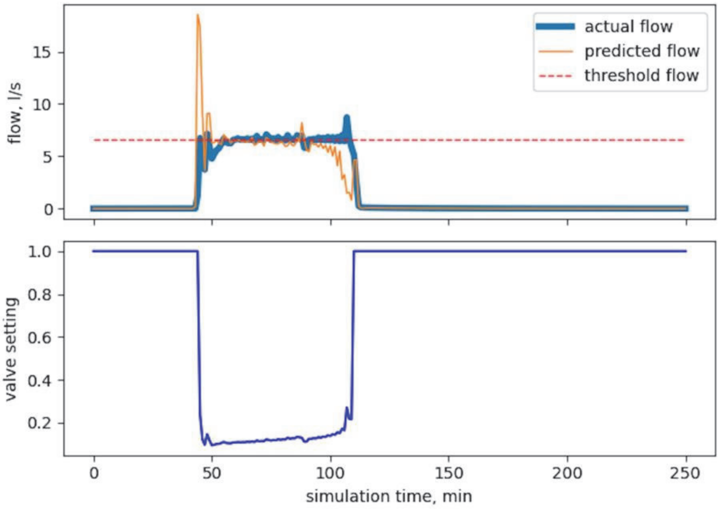

Figure 7. Predicted flowrate, actual flowrate and actuator settings for one control unit.

All the scenarios were simulated using the same rainfall event (see Figure 5). The results of the simulations are presented in Table 1. It can be seen from the table that despite the fact that no large flood events have historically occurred in Rakvere, changing the rainfall pattern to simulate future precipitation resulted in flooding in 47% of all nodes with a total flood volume of 950 m^3. Half of these events were considered major, i.e. having flood volume V_{flood} higher than 1 m^3. Because of the surcharge of the underground pipeline system, a 20-min rainfall caused water to stay on the ground up to 100 min until it finally drained to the pipeline.

Table 1. Results of simulating the effect of street storage units in flood mitigation.

Parameter	**Unit**	**Base**	**SSUs without control**	**SSUs with RBC**	**SSUs with MPC**
Total number of flood nodes (including SSUs)	pcs	136	119	118	99
Total number of flood nodes $V_f > 1.0$ m^3	pcs	70	62	65	49
Mean flood duration for nodes $V_f > 1.0$ m^3	min	35	29	25	23
Total flood volume, m^3	m^3	950	971	1040	955
Threshold flow (Q_t) constraint satisfied for SSUs	%	0	0	0	89
Peak flow change from SSUs compared to the base scenario	%	-	+93	+93	-77

Placing the street storage units into the system and connecting the units with UDS will reduce the number of flooding nodes by 13% and the number of major flood nodes by 11%. This is mainly because of the restricted outflow from SSUs which allowed some accumulation before water is entering to the UDS. Applying the RBC methodology for runoff regulation did not improve the situation significantly compared to SSUs without a control. It shortened the flooding duration about 4 minutes but increased the number of major flood nodes. In addition, the mean duration of the flood event for both static SSUs and SSUs with RTC was 10 min shorter than in the case of the base scenario. However, the RTC algorithm, neither SSUs with no control were able to meet the threshold flow Q_t

constraint in any of the storage units; moreover, these even increased the peak runoff merely two times compared to the base scenario.

Fourth scenario, SSUs with MPC algorithm enabled to predict changes in the water depths up to 5 min ahead which allows to adjust valve position proactively. Therefore, it managed to keep runoff from 16 storage units of 18 below pre-set Q_t. As a result, MPC was able to cut 77% of the peak flow from the controlled catchments, which resulted in 27% reduction in all flood nodes and 30% reduction of major nodes ($V_f > 1.0$ m^3). The mean duration of the flood event for nodes V_f higher than 1 m^3 was 12 min shorter – about the length of the actual rainfall event.

Selecting the locations and dimensions for detention facilities plays a critical role in the effectiveness of the control system in flood risk reduction (Duan, Li, and Yan 2016; Li et al. 2015). The algorithm used in this study to automatically detect the sites for SSUs showed relatively high efficiency, as 6% of the inlet plots selected in the pilot area managed to reduce the number of flood nodes by 30%. Constructing 18 street storage units with a maximum area of 1000 m^2 is economically realistic compared to the option to enlarge system capacity by installing tanks and larger pipelines. Street storage systems are designed to operate independently, i.e., in distributed mode; therefore, the failure of one unit has minimum impact on the system operation compared to the malfunction of in-line actuators.

Maximum water depth temporarily stored in the street storage units is an important parameter to assess the suitability to implement the solution in urban landscape with active everyday use. Figure 8 presents the depths measured from the bottom of the lower storage base A_L in the RBC and MPC scenarios. It can be seen from the graph that maximum water levels in the RBC scenario are generally lower than in the case of MPC. However, even in the MPC controlled units, water reaches into the upper level storage unit only in seven cases of the total of 18 facilities. The locations of the SSUs can be found from Figure 6. To alleviate the situation where SSUs are already partly filled with a water, safety factor has to be considered when designing the units. It can be seen from the Figure 8 that water level in the most of the SSUs do not reach to the upper level, leaving unused capacity for the cases of the next storm event occurring less than 60 minutes (average time to deplete the units) after the previous rainfall.

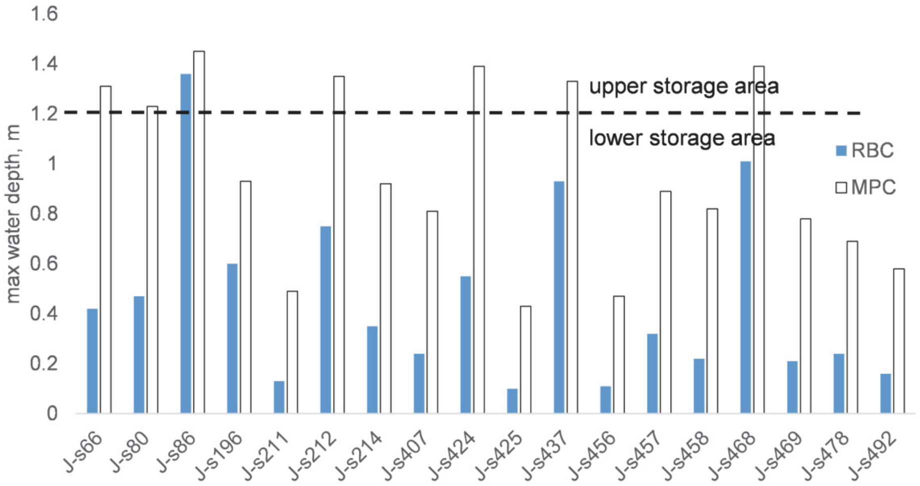

Figure 8. Highest water depths in street storage units (dashed line represents the border between the upper and lower part of the unit).

It has to be noted that all the SSUs had similar technical parameters h_{max}, A_U and A_L values. However, one can observe from Figure 7 that the area of eight units could be reduced as no water reaches the upper layer of the storage system. For other units, the water depth of the upper layer is not exceeding 25 cm, which has been considered as safe depth for pets and pedestrians (Carr, Esposito, and Walesh 2001) but might be risky for parking cars and traffic. If the upper levels of the storage units are used for parking, an alarm system should be developed to prevent damage to vehicles.

The effect of regulating inflow to the stormwater system by distributed street storage units on runoff from the catchment was also analysed. Runoff curve from the central part of the pilot area (see conduit 11824 from Figure 6) is shown in Figure 9. It can be seen from the graph that neither MPC nor RBC is cutting substantially the peak flow. This is mainly because only 6% of all the inflows are controlled. However, MPC is significantly shortening the peak flow period. As RBC is not able to predict the system status, it affects the runoff at the end of the rain event, causing an increase in the flowrate while opening the valves to deplete the street storage units. SSUs with no control slightly reduce the length of the peak, but will not affect the situation at the end of the runoff.

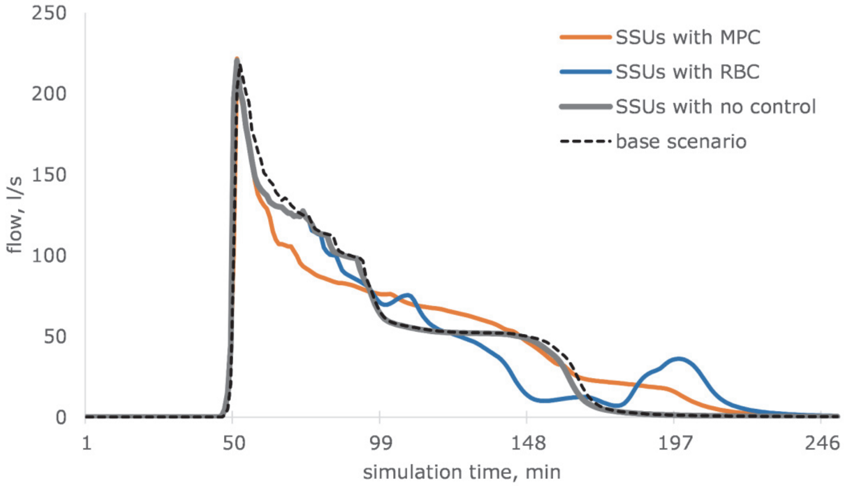

Figure 9. Flow comparison from the outlet of the central part of the catchment in conduit 11824 (the location is presented in Figure 6).

Street storage units have typically small catchments with quick response to a rainfall event. Therefore, the computational speed of the MPC algorithm calculations plays an important role in an efficient operation. For that reason, storage units are designed to operate in distributed mode as optimisation of global MPC takes typically considerably longer time than one-minute measurement step used in this study (Zimmer et al. 2015). The second simplification used to reduce the computational burden was direct calculation of the parameters by the inner model instead of the objective function-based optimisation. On the other hand, this simplification allowed us to use the non-linear inner model instead of the linear surrogate model typically utilised in MPC systems with in-line actuators (S.V. Lund et al. 2019). As a result, the simulation time of the MPC algorithm to adjust 18 independent orifices was only 0.11 sec per one minute measurement step *i* (Intel® Core™ i5-6200U CPU @ 2.30GHz, 2400MHz, 2 cores). This leaves enough time to process the signals to the actuator, get updated data from the sensors and set the actuator to a desired position.

Conclusion

Climate change forces utilities and municipalities to find solutions to reduce pluvial flood risk caused by changing precipitation patterns. In this study, a novel system was developed and tested to regulate inflows from the adjacent catchments to the underground UDS. This method reduces the need for pipeline-oriented rehabilitation solutions, like enlargement of the sections or harnessing in-line storage capacity that are typically most expensive and technically challenging. The core of the created solution is a novel real time control algorithm that operates in a distributed manner and is capable of predicting flows on the basis of data derived from level sensors.

Analysis of the pilot catchment representing typical small UDS showed high efficiency of the solution, whereas controlling 6% of the inflows reduced the number of flood nodes at extreme rainfall event merely 1/3. Main advantages of our system are: firstly, off-line control that needs no obstacles, i.e., actuators placed into the main conduits; secondly, no need for underground pipeline enlargement works and thirdly, no areas are needed to be excluded from the active use in urban space for stormwater storage. Street storage units can be designed as one integral part of urban landscape even increasing the diversity of quite monotone street environment. Skate parks and areas for resting from urban busy lifestyle are just some options to utilise the street storage units in dry periods.

Further research and development activities are needed to develop a distributed MPC algorithm, making it possible to communicate between adjacent SSUs in order to optimise the storage durations. This allows testing of SSUs with adaptive threshold flow and thus makes the units "smarter". Also, custom fit SSUs, including both roofs and other surfaces above a street level, could be embedded to the methodology. We are also seeking possibilities for pilot testing in real urban environment, which requires also governance, regulations and social factors to be considered. In future cities more interactions are expected to be established between citizens, urban space and urban water systems. This research aims to support that inevitable trend.

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Appendix 2

Publication II
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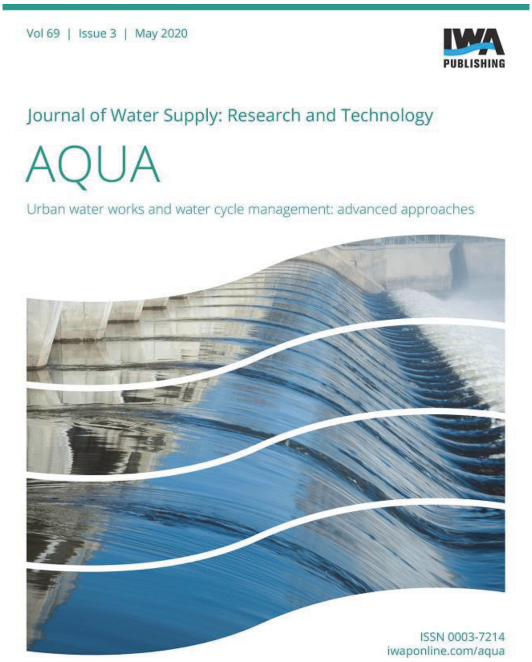

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Real time controlled sustainable urban drainage systems in dense urban areas

Nils Kändler, Ivar Annus, Anatoli Vassiljev and Raido Puust

ABSTRACT

Stormwater runoff from urban catchments is affected by the changing climate and rapid urban development. Intensity of rainstorms is expected to increase in Northern Europe, and sealing off surfaces reduces natural stormwater management. Both trends increase stormwater peak runoff volume that urban stormwater systems (UDS) have to tackle. Pipeline systems have typically limited capacity, therefore measures must be foreseen to reduce runoff from new developed areas to existing UDS in order to avoid surcharge. There are several solutions available to tackle this challenge, e.g. low impact development (LID), best management practices (BMP) or stormwater real time control measures (RTC). In our study, a new concept of a smart in-line storage system is developed and evaluated on the background of traditional in-line and off-line detention solutions. The system is operated by real time controlled actuators with an ability to predict rainfall dynamics. This solution does not need an advanced and expensive centralised control system; it is easy to implement and install. The concept has been successfully tested in a 12.5 ha urban development area in Tallinn, the Estonian capital. Our analysis results show a significant potential and economic feasibility in the reduction of peak flow from dense urban areas with limited free construction space.

Key words | control manholes, in-line storage, real time control, smart urban drainage systems, sustainable urban drainage system

Nils Kändler (corresponding author)
Ivar Annus
Anatoli Vassiljev
Raido Puust
Department of Civil Engineering and Architecture,
Tallinn University of Technology,
Tallinn 19086,
Estonia
E-mail: *nils.kandler@taltech.ee*

INTRODUCTION

Changing climate and densification of built-up areas will have a considerable impact on urban areas. One of the effects of this trend on urban areas in Northern Europe is the increase of stormwater peak intensities during rain events (Madsen *et al.* 2014). Current urban drainage systems (UDS) are usually not designed to cope with such extremes. In these cases, intense rainfall will cause the system to become surcharged, which will consequently trigger pluvial floods. Rapid urbanisation that is disrupting the natural stormwater cycle is accelerating the problem even more. As a result of these trends, urban areas are considered highly vulnerable to climate change (Tapia *et al.* 2017).

There are usually limited financial resources available to enlarge the UDS to handle higher flow rates. Therefore, special attention has to be paid if new development districts are planned to connect to the existing system. There are several options available to alleviate the pressure on existing UDS and therefore reduce the risk of surcharge at downstream. According to Fletcher *et al.* (2015), these can be broadly divided into structural and non-structural measures, both of which are underpinned with mitigation of changes in flow regime and improvement of water quality. Low impact development (LID) is considered by many authors as one of the efficient structural methods, while best management practices (BMP) contribute to the non-structural category (Joksimovic & Alam 2014; Saraswat *et al.* 2016).

LID can also be characterised as a small scale stormwater treatment facility located near the source (Fletcher

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et al. 2015). These techniques are usually divided into two groups: (1) green solutions, e.g. above ground bioretention systems and (2) grey solutions, e.g. underground concrete structures. Green solutions, also referred to as sustainable urban design systems (SUDS), attempt to restore a natural hydrologic budget (Joksimovic & Alam 2014) while underground detention facilities aim to accumulate the peak flow and discharge this into the system with a certain time lag (Andrés-Doménech *et al.* 2012). In this study, we focused on the improvement of underground LID structures, e.g. grey infrastructure, considering green solutions as a valuable additional measure in stormwater management.

Underground LID solutions aim to increase spare capacity in the system to accumulate excessive flow rates. The extra volume can be achieved by adding off-line or in-line underground storage into the UDS. Typical off-line facilities are detention tanks, having a connection to the mains, while free capacity of the drainage network has often been considered as in-line storage. Although effectiveness of off-line facilities is the objective of many recent studies (Lim *et al.* 2014; Thomas *et al.* 2016; Wang *et al.* 2017), in-line solutions are mainly considered as a possibility of utilising the excess capacity of the pipeline, not specially designed for storage (Garofalo *et al.* 2017). In this study, we intend to change this paradigm to include storage and flow control into the design as an additional objective.

Real time control (RTC) methodology that emerged with the development of information and communication technology (ICT) aims to bridge the structural and non-structural measures into one comprehensive solution (Beeneken *et al.* 2013). This is achieved by installing active network elements, e.g. weirs and valves, into the UDS. These actuators will be automatically adjusted on the basis of the data from the network sensors and thus allow UDS to be adaptable for different loading conditions. Therefore, RTC is seen as a key technology to improve the operation of UDS (García *et al.* 2015).

The main objective of our work is to find the most feasible solution to reduce stormwater peak runoff volume from compact real-estate development areas situated within a highly urbanised catchment. The paper is based on the results obtained in Kändler *et al.* (2018) with significant improvements to the overall analysis. The advantages of LID in-line reservoirs are coupled with RTC architecture to create a smart and sustainable solution for peak flow reduction from newly developed dense urban areas.

METHODOLOGY

Redevelopment of obsolete areas into new living and business districts is a constant process in every city. As these places are typically surrounded by highly urbanised catchments, constraints have to be imposed for the stormwater runoff into the existing UDS in order to avoid network surcharge.

In many cases, due to limited free space available, it is not possible to choose full-scale SUDS for flow mitigation, since these require notably more space than grey solutions (Fletcher *et al.* 2015). Free construction space is usually scarce in these areas because other underground communications and developers attempt to gain profit by maximising the building footprints.

Underground storage containing either off-line detention tanks or enlarged pipe sections for in-line storage are considered a feasible option to alleviate the stormwater runoff problem (Piro *et al.* 2010). Off-line detention tanks are usually cylinder shaped plastic or concrete underground barrels installed in the network with a connection to the UDS (Figure 1(a)). A diversion chamber is used to direct water either to the pipeline downstream or to the detention tank. After being filled, the tank will empty if the hydraulic grade line (HGL) in the system has lowered below a water level in the barrel. It was assumed in our study that the volume of the tanks will be compiled from 50 m^3 plastic cylinders, as these have manageable dimensions for transportation and installation. It would be technically challenging to install larger barrels below the street area because of the limited free space. It was also assumed that the tanks will be filled and emptied only by gravity flow.

In-line storage facilities are typically enlarged pipe sections designed to be part of the network (Figure 1(b)). Outflow from these sections is restricted by a fixed orifice, i.e. a pipe section with a smaller diameter. During a rainstorm, these pipe sections will fill with water, hence reducing the peak flow at the outlet. Distinct from off-line storage solutions, water is always flowing through the system. In our study, it was assumed that the maximum

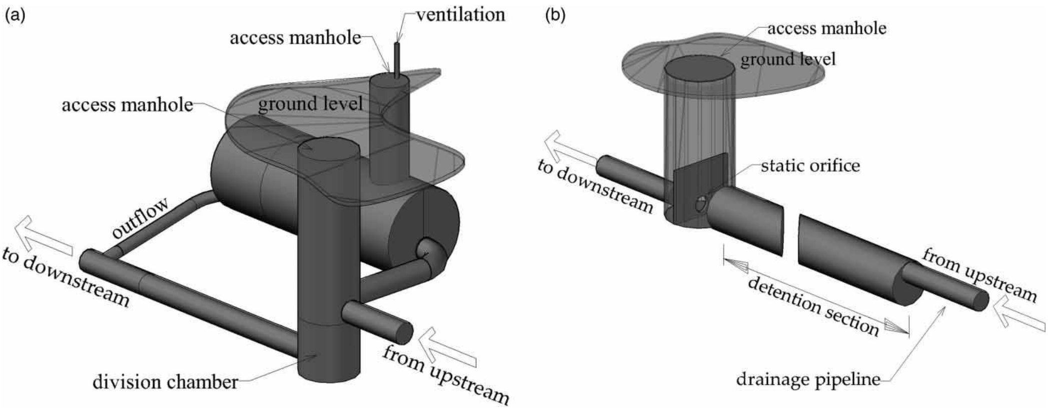

Figure 1 | Underground stormwater detention solutions: (a) off-line detention tank; (b) in-line detention tank with a static orifice.

diameter of these enlarged sections should not exceed 1 m, as larger conduits would significantly hinder installation of other communications in the street area.

An in-line storage system was coupled with an RTC solution to create a smart in-line storage unit. An RTC weir is designed to close the flow completely in order to harness the useful feature of off-line tanks. The system consists of an RTC manhole, a control algorithm, an optimisation and telemetry system which are described in more detail in the following paragraphs.

RTC manhole

A stormwater manhole with an adjustable weir is the key part of the developed system. The position of the weir changes the cross-section of the free opening and thus regulates the flow through the manhole (Figure 2). The position of the weir is changed by a threaded rod turned by an electric motor. The manhole also has an emergency overflow for handling extreme weather events and ensuring system operation during any malfunction.

An enlarged pipe section upstream of the manhole allows water accumulation. The length of the section can be determined on the basis of the terrain slope. Also, the number of RTC manholes in the system depends on the slope of the terrain and can be determined through simple optimisation if the hydraulic model of the system is available. If the terrain, i.e. the pipe slope, is significant, it is advisable to install control manholes in sequence in order to maximise the storage capacity. The RTC weir is equipped with a communication unit to exchange information with adjacent manholes and update the control curve. As stormwater systems will be built during the development of the area, simultaneously, trench works can be easily supplied with electricity from the grid system as the connection cables are installed.

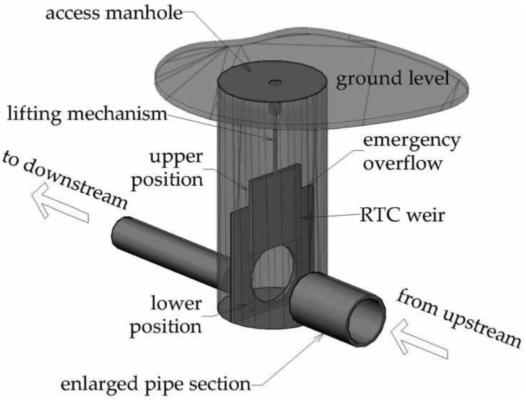

Figure 2 | In-line detention tank with an RTC weir.

Control algorithm

Operation of the system is based on the on-line data received from the water level sensors installed at the outlet and at the upstream section of each control manhole. The distributed mode predictive control (DMPC) algorithm is used to create the control curve for each weir-wall. DMPC is an optimisation-based solution capable of predicting a system status, i.e. relationship between the water level and the gate opening. This is first needed to eliminate measurement errors of the level sensors and second, to make the system's response to a rainfall hydrograph proactive.

Figure 3 presents the principal operational scheme of the control system. It can be seen from the scheme that no central control unit is needed and therefore each control manhole can operate independently, exchanging the information about the water levels and gate positions. Level sensors are used instead of flow measurements to reduce errors caused by sediments in the pipeline and reduce the cost of the system.

The following implementation strategy was used:

1. The level measurement sensor S_O is activating the system if the determined threshold level, i.e. flow rate out from the area, is achieved.
2. The control manhole closest to S_O starts to function, measuring the water height S_1 at the upstream. This information x_1 is fed to the DMPC$_1$ unit and the respective operational curve u_1 is calculated and sent to the actuator.
3. If the weir-wall has reached a lower position but the water level at S_1 is still increasing, the second control manhole DMPC$_2$ is activated upstream. For that, DMPC$_1$ is exchanging the status information w_1. Information x_2 about the water level upstream of the manhole is fed to the DMPC$_2$ unit to calculate the necessary adjustments u_2 for the actuator.
4. As the flow through the gate depends on the water levels upstream ($S_1 \dots S_n$), the position, i.e. the control curve of the weir-walls, is calculated by DMPC$_n$ units for each time step.
5. When the rainfall is over, weir-walls will open in reverse order from activation. Weir-wall DMPC$_n$ at the upstream is sending information w_{n-1} to the downstream unit. Water levels are constantly measured to avoid exceeding the required peak outflow at S_O.

Cascading operational action is designed for optimal system usage, as in the case of smaller rainfalls, only a few manholes are needed to be activated. This setup also reduces a risk of malfunction and avoids problems typically prevailing in centrally controlled RTC systems (van Daal *et al.* 2017).

Optimisation

Distributed model predictive control is an optimisation based control algorithm. Therefore, manipulated variables have to be optimised at each time step, taking into account the system prediction in order to have the model parameters fit to the actual targets, i.e. weir-wall positions.

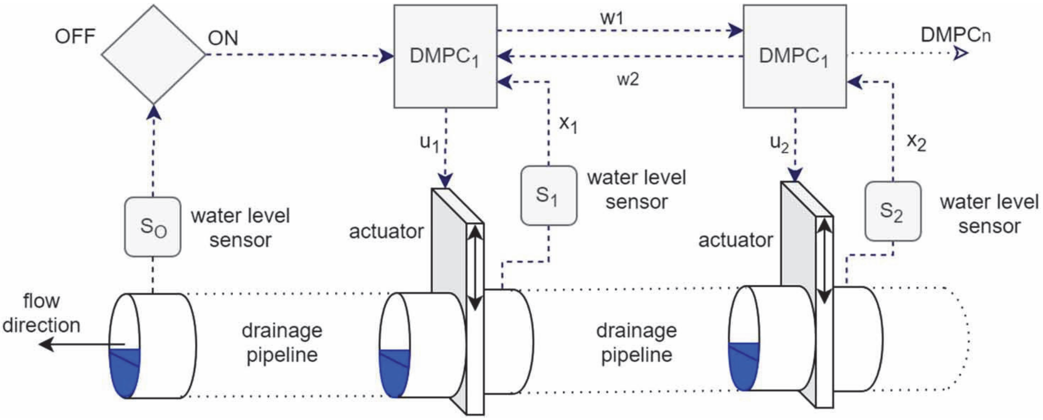

Figure 3 | Architecture of the control algorithm.

MS Excel spreadsheets with Solver Add-In module were utilised to code DMPC algorithm and perform necessary optimisations.

Optimisation results were tested and evaluated with EPA SWMM 5.1 software through a step-by-step process as presented in Figure 4. Water levels were calculated by the software and a new control curve was developed for each time step, i.e. runoff moment using the DMPC algorithm. Weir-walls were modelled as transverse weirs with a discharge coefficient of 1.84. The control curve calculated by the DMPC algorithm was imported to the modelling software to set the height of the weir-wall. The following optimisation constraints were imposed: (i) outflow should not exceed the threshold level at S_O; (ii) maximum level of HGL shall be at peak moment not less than 0.5 m from the ground level; (iii) for safety reasons, no weir-walls should be allowed to be fully closed.

Telemetry system

Reliable communication is a key issue to ensure the smooth operation of the system. As the stormwater system will be built in conjunction with the area development, both cable-wired and wireless communication could be used. We chose the latter method in our study.

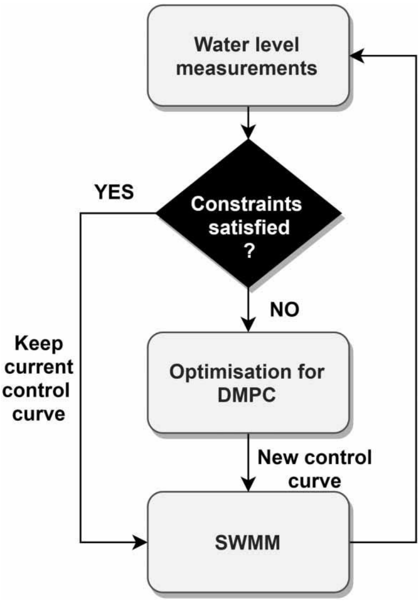

Figure 4 | The process scheme of the optimisation process.

The weakening of an electromagnetic signal in soils with high moisture content and different structure layers (asphalt, gravel, sand) is so significant that communication with underground structures has been considered infeasible for decades. It has been found by Malik *et al.* (2018) that new low-power long-range communication technologies such as narrowband internet of things (NB-IoT) are opening new possibilities for underground data connections and are therefore especially suitable for urban drainage systems. These technologies have sufficiently low energy consumption, wide signal coverage and a suitable information rate for the described RTC system.

Economic aspects

The developed RTC in-line detention was compared with the traditional methods, such as off-line tanks and in-line detention, in economic terms to highlight the advantages of the solution. All three options were evaluated in reference to the scenario with no flow reduction measures implemented.

Two cost components were used to find the feasible solution (Table 1). The first component is the investment cost (IC) that includes the infrastructure cost (pipes, manholes, equipment, etc.) and the cost for the construction works.

Table 1 | Cost components for the economic analysis

Component Investment Cost (IC)	Specification	Cost
Pipeline	Diameter 0.1–0.4 m	230–350 EUR/m
Pipeline	Diameter 0.5–1.0 m	400–750 EUR/m
Detention tank	50 m^3	58,720 EUR/pcs
Weir manhole	Adjustable weir with communication unit	40,000 EUR/pcs
RTC	Sensors and control unit	50,000 EUR/pcs
Penalties		
Exceeding the target flow	per 1 m^3	895 EUR/m^3
Replacement of the downstream pipeline	Diameter >1.0 m	800 EUR/m

The second component, named as ‘penalty’, was imposed to consider the case when the technical solution appeared does not fully meet the design constraints and therefore extra investment is needed outside the street area, e.g. adding additional retention tanks on the plots. Penalty for the base scenario, i.e. with no LID used, takes into account the replacement of the pipeline outside the development area in order to allow higher volumes to pass.

Each system needs maintenance, which can be expressed as a cost per year. For example, stormwater pipelines need yearly cleaning from sediments and regular service is required for the weir-wall components. In addition, technical components have their unique lifetime, i.e. they need replacement after a certain period. Our consideration was that electronic components are expected to last up to 10 years, the pipeline, including manholes, need some restoration after 20 years and detention tanks need some repairs after 30 years of operation.

To take into account this variability, the net present value (NPV) for evaluated options was calculated as follows:

$$NPV = \sum_{n=1}^{a} \frac{F_n}{(1+i)^n} \tag{1}$$

This method converts any future values to the present, thus providing an adequate answer about the feasibility of the investment. For that future payment F_n for each period n is summarised and subtracted with an interest rate i of this specific period n. Several assumptions were made for the calculation of NPV:

1. Calculation period a was taken 50 years.
2. Theoretical natural annual real interest rate was estimated to be around 3%.
3. No price changes of investments were considered, i.e. inflation of the investment product is zero and therefore nominal and real interest rates are the same.

RESULTS

The developed RTC in-line detention system was tested and evaluated on the background of traditional off-line and in-line solutions in a 12.5-ha modern urban development area in Tallinn, Estonian capital (Figure 5). A base scenario with no LID imposed was taken as a reference to the other three options.

During the development, the old obsolete industrial territory will be turned into modern city environment with 1,600 apartments and offices. The build-up ratio of the plots is merely 100%, comprising both living blocks and underground parking garages. Taking into account street areas, including some pedestrian streets with minor greenery, the rate of impermeable surfaces is merely 90%. The infiltration and evaporation in the catchment areas were neglected to be in line with the cold climate conditions. A constant flow of 50 L/s, representing the infiltration from the upstream catchment areas, was applied to point A (Figure 5).

Standard design rainfall with a return period of two years, intensity of 28 mm/h and duration of 20 minutes was applied for the study on the basis of Estonian Design Standard (2013). As the catchment area is compact, unified rain intensity was used for the whole area.

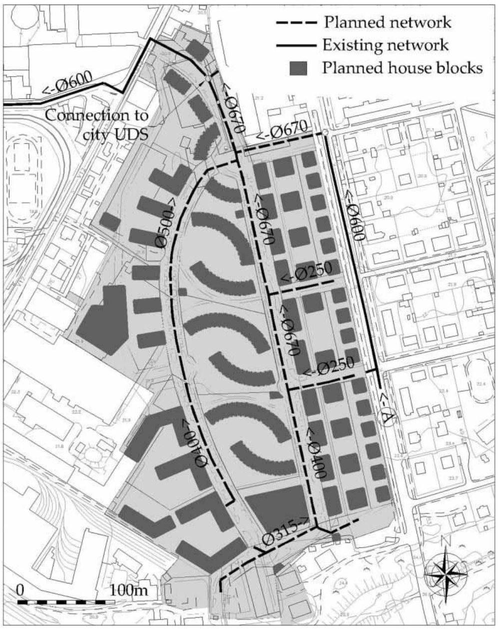

Figure 5 | Urban development area in Tallinn with the base scenario (no flow reduction applied).

Due to the limited capacity of the existing downstream UDS, the water utility has imposed the maximum limit of 300 L/s for the peak runoff. Calculations showed that under the base scenario, i.e. no LID foreseen, the peak runoff from the catchment will be 670 L/s, which is more than two times higher than that allowed.

Simple optimisation was performed to set up technical details for the three LID scenarios. The following optimisation constraints were considered for placing off-line and in-line storage units: (i) availability of free space for the construction and technical applicability, as described in the methodology; (ii) minimum IC; (iii) highest resilience, i.e. distance between the ground level and HGL is >0.5 m at the peak flow.

Nine off-line storage tanks with a total volume of 450 m^3 were placed at the locations shown in Figure 6(a). As the storage tanks will cut off some of the peak flow rate, it was possible to use a smaller pipeline than in the base scenario presented in Figure 5. For the scenario of in-line storage, 0.9 km of accumulation pipeline was designed with a total volume of 480 m^3 (Figure 6(b)). A fixed orifice with a diameter of 300 mm was installed at the outflow to restrict the flow. For the fourth scenario the section was replaced with the RTC weir and one additional weir was installed to the middle of the main conduit section, as presented in Figure 6(b).

The results of the analysis of the four scenarios are presented in Figure 7. It can be seen that only the fourth scenario, i.e. in-line detention with RTC, fully satisfies the outflow constraint (300 L/s). It reduces the peak flow by 57%. For the other three, some LID facilities had to be foreseen to provide an additional cut, resulting in penalties. It is important to note that in-line detention without RTC (option two), on the contrary, has the lowest effect on the peak flow reduction (26%). Traditional off-line detention reduced the peak flow by 39%, which correlates with the numbers presented in previous studies (Lim *et al.* 2014; Wang *et al.* 2017).

Figure 6 | Technical solutions for the peak flow reduction: (a) off-line detention tanks; (b) in-line detention with RTC.

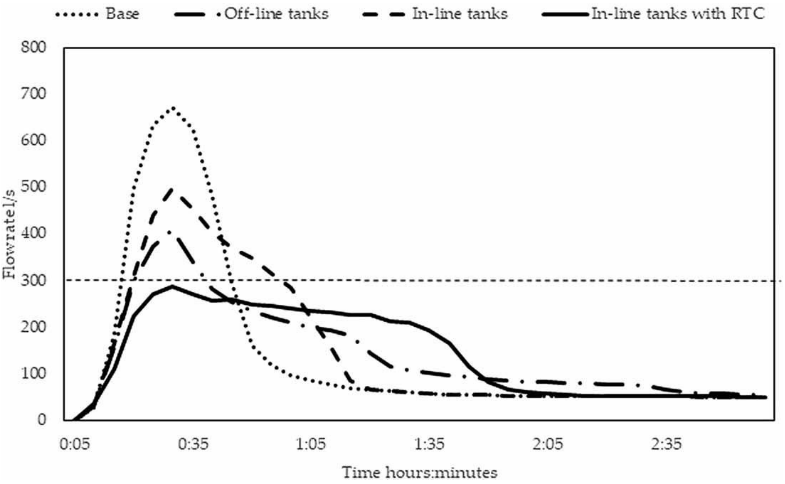

Figure 7 | Peak flow graph of a 3-hour period for the different scenarios (300 L/s threshold presented with dashed line).

Results from the economic analysis are presented in Figure 8. It is quite obvious that the base scenario has the lowest IC, as this solution has no costly facilities conceived for flow detention. The IC of the other three options is on average 47% higher, which may lead to the decision that any flow detention is infeasible because of economic reasons. However, this conclusion is misleading since adding penalty costs to IC changes the sequence of total costs (TC) significantly. As can be seen from Figure 8, the base scenario has actually the highest penalty costs, which leads to the highest TC. High penalty cost stems from the need to rebuild about 0.9 km of the drainage collector downstream of the UDS to reduce the risk of network surcharge. For the other two options, the penalty cost was calculated on the basis of additional LID facilities needed on the plots. As RTC in-line storage is meeting the flow constraints, no penalty costs were applied.

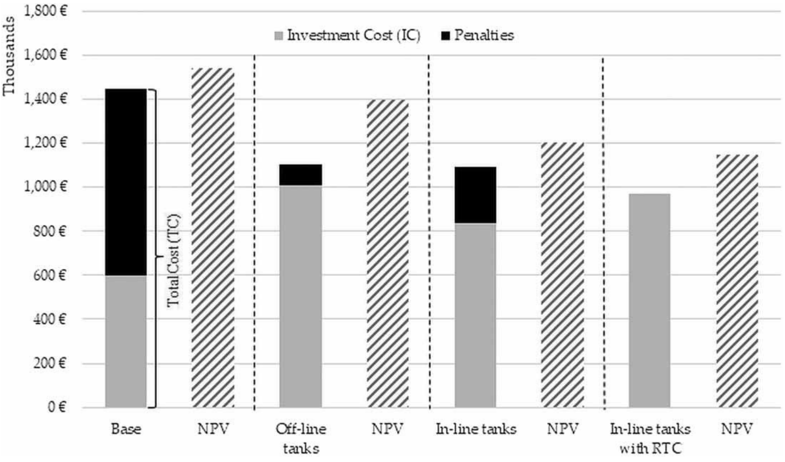

Figure 8 | Investment costs (IC), penalties and NPV of the analysed options.

It can be seen from the results that in-line tanks without RTC and off-line tanks have similar total costs. The penalty cost of the in-line tanks is the highest compared to other two options because of the substantial investments needed for an additional LID on the plots to cut the peak flow below the target level (300 L/s). It is also important to note that as the RTC in-line detention has no penalties, its total cost becomes, on average, 12% lower than that of the other two options, making the solution the most feasible.

Analysis of NPV of all four options showed that the base scenario has the highest investment value, and the in-line tanks with RTC the lowest, over a 50-year period. Although the in-line detention with RTC requires electronics that have a shorter lifespan, it reduces accumulation of sediments to be removed periodically in the other three cases. As a result, NPV of RTC in-line detention is 26% lower than in the base scenario and 5% lower than the in-line solution with no RTC.

DISCUSSION

Although it may seem that the traditional UDS are the most cost effective solution for new developments in dense urban areas, the results of our study show that if the penalty costs are taken into account, this option is actually the most costly. Upgrading the downstream UDS network needs much effort and adds additional economic burden to the option. Therefore, in terms of hydraulics and cost efficiency, the most feasible options are traditional off-line storage facilities and in-line detention with RTC. The TC of these solutions is merely a quarter lower than the traditional UDS (base scenario). It should be noted that the traditional in-line detention system showed a relatively low impact on the peak flow reduction and is therefore falling behind the other two with a comparatively high penalty cost.

The in-line system with RTC was also designed to mimic the features of off-line tanks, i.e. capability to temporarily cut the water flux during the filling period. However, this feature was not utilised in the case study because the system was capable of reducing the peak flow below the target limit even without completely closing the RTC weir-wall. It is important to note that this may not be the case in other case studies.

The footprint of the off-line tanks and in-line detention is relatively similar (240 m^2 for the case study analysed), but there is a clear advantage in the latter option because the area is evenly distributed along the whole system. This facilitates the installation of the other communications in the street area, e.g. water supply, gas and electricity lines. Moreover, as the off-line tanks analysed in the study have a diameter of 2.4 m, it is not always possible to have them installed at the same level as the invert of the inflow pipeline. This may result in the accumulation of sediments that diminish the capacity of the tank and increase maintenance costs. Sediment transport and deposition have complex behaviour that is not easily characterised with conventional methods and understanding the influence on hydraulic systems requires advanced numerical simulations (Kaur *et al.* 2017). For that perspective, in-line storage with RTC is considered as the most feasible option to reduce peak runoff from this type of development area. The NPV of the solution is eventually 26% lower compared to the base scenario. This is a clear advantage in a long-term perspective.

CONCLUSION

A new decentralised real time controlled in-line detention system was developed to reduce the peak runoff from the urban catchment to the existing UDS downstream. The system has independently operated control manholes that are capable of exchanging information between each other and pro-actively adapt to the changing stormwater runoff hydrograph. The solution is easy to apply as neither a central control unit nor extra personnel are needed. As the system is situated completely underground, it is suitable for the locations of cold climate, especially for Northern Europe with moderate terrain conditions and smaller catchment areas where the infiltration capacity of the soil is non-existent.

The RTC in-line detention system was compared with two traditional solutions – off-line storage tanks and in-line detention facilities, and the base scenario – a system with no runoff control. Penalty rules were used to analyse actual indirect costs.

The methodology was tested in a 12.5-ha development area in Tallinn, Estonian capital. It was found that the in-line detention with RTC has the highest cut in the peak flow, the lowest total cost and the lowest investment costs over a 50-year period. Apart from that, the solution also has many other advantages, including better sedimentation removal and smaller construction footprint, which is particularly important in dense urban areas.

Future research will focus on more advanced optimisation methods, coding the solution in Python language and analysis of the different precipitation intensities, i.e. operation under extreme weather conditions.

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Appendix 3

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RESEARCH ARTICLE

Peak flow reduction from small catchments using smart inlets

Nils Kändler, Ivar Annus, Anatoli Vassiljev and Raido Puust

Department of Civil Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia

ABSTRACT
A concept for reducing stormwater peak run-off from existing small urban catchments is developed. Stormwater inflow from the ground to the pipeline is managed by smart gullies. The gullies are real-time controlled and therefore capable of predicting the weather conditions. Drainage facilities are usually unable to cope with excessive flows that exceed their design limits. This results in pluvial floods and activation of combined sewer overflows, both of which have negative consequences. Northern Europe is expecting to receive more intense rainstorms in the future; therefore, innovative solutions are needed for flow management. The inlet control presented in our work is financially feasible and efficient to be applied to small catchments with substantial permeable surfaces to reduce the peak run-off. The control system is autonomous; therefore, it is suitable for sites scattered around the urban catchment. The concept was successfully tested in a 12 ha catchment area in Tallinn, Estonia.

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KEYWORDS
Urban drainage system; real time control; stormwater inlet control; controlled floods

Introduction

Stormwater systems in urban areas are facing greater stress due to fast spatial developments and expectations to receive more intense rainstorms in the coming decades (Langeveld, Schilperoort, and Weijers 2013). Sealing off the permeable surfaces accelerates the run-off response of the urban drainage system (UDS) and rises the risk of system surcharge. According to the trend analysis of extreme precipitations in Europe, the frequency of these events will increase in the future (Madsen et al. 2014). This means that UDS has to operate outside its design limits more often. As pointed out by Bazin et al. (2014), the volume of water exceeding system capacity will be released through street manholes and will consequently cause overland flow. The activation of combined sewer overflows (CSO) leading untreated wastewater into the nature is the other way of the system response. In some cases, backflow may occur, which can result in flooding the basements of buildings. According to Sörensen et al. (2016), these events have negative consequences and should, therefore, be avoided.

Cities and towns have traditionally responded to the increasing demand by enlarging the capacity of the UDS. Taking into account the rapid urbanisation and climate trends, this endeavour seems financially unrealistic (Bruijn et al. 2017). Therefore, several solutions are under investigation to develop feasible options for urban run-off reduction (Houdeshel et al. 2011; Joksimovic and Alam 2014) and avoidance of CSO activation (Cembrano et al. 2004; García et al. 2014; Mollerup et al. 2017). Low impact development (LID) attempting to restore natural water cycle in urban catchments (Joksimovic and Alam 2014) and real-time control (RTC) of UDS that aims to improve the operation of the existing stormwater facilities (Beeneken et al. 2013) are the two main categories of this research effort.

Although numerous sources provide recommendations for designing LID and RTC for new catchment areas, methods for retrofitting existing systems situated on small-scale compact districts with substantial imperviousness still need to be improved (Campisano et al. 2013). Moreover, according to Beeneken et al. (2013), typical RTC systems are feasible to be implemented on large-scale UDSs and therefore appear unsuitable for small catchments with high build-up ratio. In addition, Eckart, McPhee, and Bolisetti (2017) have found that insufficient information on operation and maintenance is one of the factors that impede wider implementation of LID solutions.

Our study attempts to fill this gap by developing a concept for a feasible small-scale RTC system that utilises the storage capacity of the existing impermeable surfaces. The solution merges RTC and LID best practices into a new run-off control solution that could be applied with a minimum construction effort to retrofit existing compact impermeable areas.

In the following sections the concept of smart inlets, including technical and economic considerations, is reviewed. The target was to find the most feasible solution that affiliates minimum construction and management costs. The method is applied for the caste study, and the outcome of the analysis is evaluated in the Results section. Main conclusions are presented in the discussion section along with directions for future research.

Materials and methods

Parking lots situated around shopping centres are a good example of a small catchment with high build-up ratio. The surface of these spaces is usually efficiently utilised and sealed with a watertight layer, which leaves limited options to implement full-scale LID solutions. As these areas contribute highly to urban run-off, it is evident that municipalities are trying to motivate landowners for peak run-off reduction. Because of limited technical solutions available for feasible applications to the small-scale catchments, this endeavour is prone to failure (Bach et al. 2014).

CONTACT Nils Kändler ✉ nils.kandler@taltech.ee

The overall stormwater drainage system in these areas is typically designed to capture and direct the rainfall to the outlet at the downstream as fast as possible. For that purpose, surface is inclined towards the gullies that are directly connected to the manholes and underground drainage pipeline. This design target clearly contradicts modern urban drainage management principles that focus on stormwater run-off control (Eckart, McPhee, and Bolisetti 2017). It has been found that holding water upstream of the system for a limited period will reduce the peak flow and thus improve system's resilience (Thomas et al. 2016). To follow this approach, we developed a technical concept by applying for recent advances in small-scale affordable RTC solutions, i.e. sensors, actuators and algorithms and utilised the advances of LID detention methodology.

The solution is named as 'smart inlet system' to distinguish it from typical urban scale RTC solutions (Kändler et al. 2018). The smart inlet system consists of adjustable manhole gullies operated automatically by control algorithms that are utilising optimisation techniques and can communicate via an innovative telemetry system.

Impermeable areas like streets and parking lots commonly have pedestrian walkways to ensure a safe route for people. Quite often, speed bumps are used to calm down the traffic. With some modification, these structures are also suitable to form barriers for stormwater ponding, i.e. water accumulation on the surface. Typically, the catchment area of one inlet is between 500 and 1000 m^2, which allows designing surface ponding areas with volumes up to 100 m^3. Therefore, the smart inlet can efficiently use the existing surface for the temporal accumulation of excessive flowrates without a need for additional underground tanks.

This concept is featured by significant differences from the traditional effort of constructing special underground barrels with pumping stations to accommodate the excess water. As the water depth on the ground has to be kept on the safe level for pedestrians and traffic, the size of the ponded area is crucial to have sufficient capacity for the on-surface storage. The target was to find the most feasible solution that involves minimum construction effort and lowest management costs.

Actuators

The key elements of the smart inlet system are the manhole inlet gullies that have capability to regulate the opening size and thus control the inflow from the ground surface to the underground pipeline. The principle of the gully is presented in Figure 1.

An electric motor is turning the actuator by the aid of the gearwheel. For example, a 12 V direct current (DC) gear motor can be used in the actuator, which firstly, ensures electrical safety as the system is situated in the hostile environment and secondly, guarantees low energy consumption. This is crucial since the target is to make the units operative as off-grid facilities, i.e. having no connection to the power line. The power supply is taken from the battery that is charged by the solar-panel situated on the manhole cover. All the equipment mounted on the lid must be waterproof in order to ensure operation in underwater conditions.

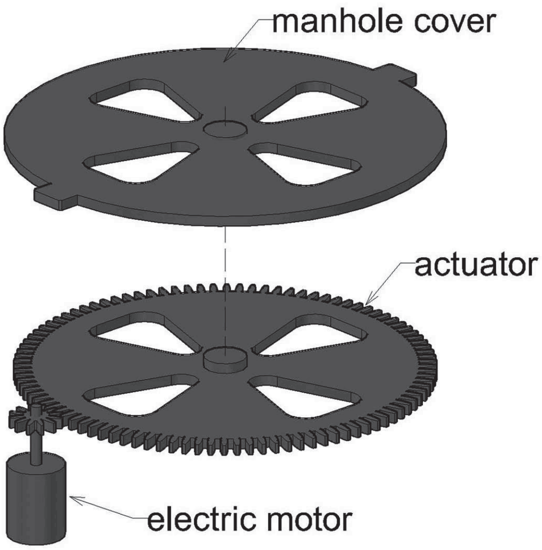

Figure 1. The principal technical solution of the adjustable inlet gully.

As the upper cover is locked to the manhole crest, the rotation of the lower actuator causes an increase or a decrease of the free opening and thus is capable of regulating the inflow. The full opening of the smart lid corresponds to the capacity of a traditional inlet grid. Therefore, the smart inlet system will not reduce the inlet capacity of the UDS. Importantly, the size of the cover is standardised; therefore, the existing manhole covers can be replaced with adjustable ones without a need to replace the manhole structure.

In addition to the actuator, the manhole lid is equipped with the water level measurement sensor capable of registering the depth above the manhole, controller and communication unit. All of the components will be mounted into the body of the inlet gully.

RTC control algorithm

Real-time control algorithm is a crucial component of the smart inlet system. There are several options available for the algorithm, e.g. rule-based control (RBC), proportional-integral-derivative (PID) and model predictive control (MPC). These algorithms are commonly used in industrial processes. In our work, an attempt was made to apply the solutions into infrastructure facilities and develop an autonomous control system that has no need for intervention of a human operator.

As the objective is to have independent, i.e. decentralised operative stormwater inlet gullies, the MPC algorithm was chosen to drive the system. The objective of MPC in the UDS operation is to compute in a predictive way the set of manipulated variables to achieve the optimum performance of the system according to the pre-set constraints and operation targets (Ocampo-Martinez et al. 2013). This has a clear advantage over the traditional proportional-integral-derivative (PID) control algorithm that is capable of handling only one constant and is therefore not suitable for the cases where there are dynamic interactions between system components, i.e. rainfall, water depth and flow (Zimmer et al. 2015).

MPC can be implemented by utilising a centralised or decentralised, i.e. a distributed structure. In the first option, the system has one global control unit that aggregates data from components and calculates manipulated variables, while the latter brings the control algorithm to the component level. This is especially useful if the time lag between the system status input, i.e. the water level and the manipulated variable output, i.e. the actuator setting, is critical. Therefore, distributed model predictive control (DMPC) is widely seen as a feasible option to operate UDS (García et al. 2015; Garofalo et al. 2017).

RBC control is added to the system for DMPC activation. This helps to keep all smart manhole covers in hibernation mode during the dry period, thus saving the battery lifetime. The concept of the system is presented in Figure 2.

The smart inlet system uses the following implementation strategy:

(1) RBC switches on the RTC system if the rain sensor S_1 registers a rainfall above a threshold value, and the water level measured by the sensor S_2 has exceeded the pre-set.
(2) Model predictive algorithm (MPA) uses the measured rainfall dynamics f(q,t) to predict the receding horizon: firstly, to calculate the full hydrograph $f_{1(q,t)}$ for the system and secondly, to scale the hydrograph $f_{1(q,t)}$ to determine the outflow under the pre-set maximum rate. This restricted hydrograph $f_{1\text{-}re(q,t)}$ will be set for the objective function of the DMPC.
(3) At each iteration i (i > 1):

- Hydrograph $f_{1\text{-}re(q,t)}$ is scaled to $f_{1\text{-}sc(q,t)}$ for each inlet I_n on the basis of the properties of the specific catchment area.
- DMPC of the inlet is sending the command (u) to the inlet I_n actuator to keep the inflow matching the hydrograph $f_{1\text{-}sc(q,t)}$. Water depth above the rim is constantly measured by the sensor $S_{3\text{-}n}$, and the pre-set maximum safe depth is used as an optimisation constraint c.
- DMPC receives back state measurements (x) to make necessary adjustments in (u).
- DMPC units exchange their future input trajectories (w) to ensure similar water levels at I_n.

(1) When new precipitation and water elevation measurements are received from sensors S_1 and S_2 at time (t), the procedure is repeated from step 2.
(2) If the termination condition is satisfied, i.e. the water level at the outflow is below $f_{1(q,t)}$ and no rainfall is registered by S_1, then all I_n will be fully opened and RBC switches RTC to hibernation mode until the next rain event occurs and brings the system back to step 1.

To set-up the system, the user has to determine the acceptable maximum surface water level in every inlet and the desired outflow from the system. In the case of extreme rainfall event exceeding the limits of RTC, the following consequences will occur: 1) MPC algorithm controlling the openings

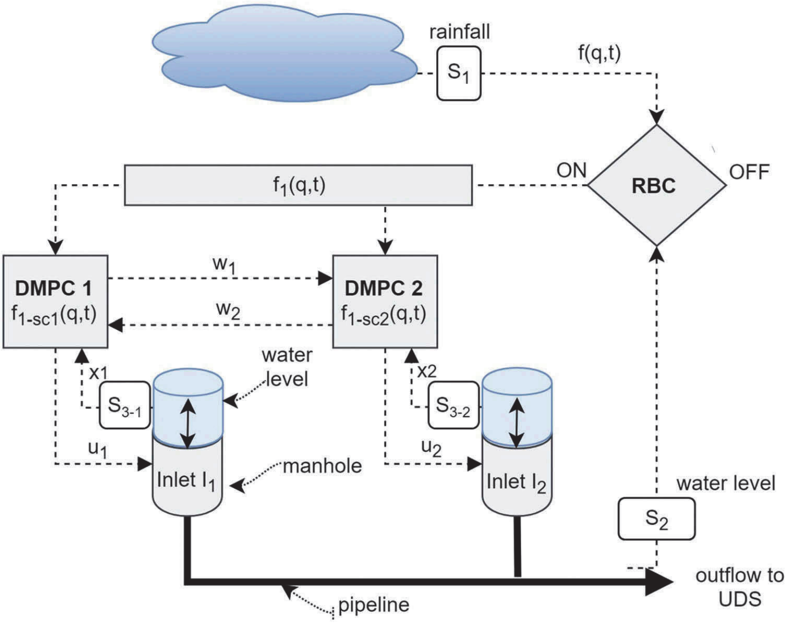

Figure 2. Concept of the real-time control (RTC) strategy of the stormwater run-off from a parking lot (Kändler et al. 2018).

of the gullies will strictly follow the constraint of the maximum water level. If this depth is exceeded in the case of fully opened inlets, spillage will occur from this flood plain to the side areas. 2) As not all the gullies are under RTC control, the rest of the inlets will be used for capturing this flow. Naturally, this can happen only if there is a spare capacity in the underground system.

At RTC system failure, i.e. the inlets are improperly closed or blocked, the MPC unit recognises a mismatch between the inlet opening, system hydrograph $f_1(q,t)$ and actual measurements from S_2. In this case, all inlets will be opened and a warning message will be sent to the operator, i.e. water company or property owner about the risk of flood in the downstream of the system. Malfunctioning inlets will be listed in order to facilitate the maintenance.

Optimisation

Distributed model predictive control (DMPC) is an optimisation-based control algorithm. This means that manipulated variables have to be optimised at each time step, taking into account the system prediction in order to have the model parameters fit to the actual targets. For the smart inlet system concept, the genetic algorithm (GA) was used in conjunction with the gradient-based method in order to shorten the computational time of GA. An example of DMPC optimisation in the case of one stormwater inlet is presented in Figure 3.

It can be seen from Figure 3 that the gully opening, i.e. orifice, is adjusted automatically with an adjustable setting rate from 1 (fully open) to 0 (fully closed) on the basis of the target hydrograph $f_{1\text{-sc}(q,t)}$ delivered for the manhole. Setting step 0.1 was chosen for the gully adjustment. During the rain event, the water level was kept constantly above the rim at the pre-set target (0.125 m in our case). When the rain event is over, the manhole opens itself fully.

The gullies were modelled as orifices; therefore, water height above the orifice and the ratio of orifice opening determined the flow through the manhole. Typical orifice discharge coefficient $C = 0.65$ was used for inlets. This coefficient was kept constant over the setting curve of the manholes.

EPA SWMM 5.1 software was used to test the control strategy and evaluate the optimisation results. The process scheme of the control system is presented in Figure 4.

The control system was modelled in SWMM 5.1 through the step-by-step process, which took into account thresholds, e.g. maximum water level above the rim and target maximum flowrate at the outfall. For each time step, the precipitation was predicted by the MPC algorithm and orifice settings were adjusted to match the input rainfall dynamics and satisfy the optimisation constraints: 1) maximum water depth above the rim; 2) maximum allowed outfall from the catchment; 3) similar water depths in all dedicated flood areas.

Telemetry system

Communication system between the inlets is a key part of the system. As the goal was to have minimum disturbances in the area, i.e. avoid construction of communication cables, an innovative wireless system has been considered for the concept. Lack of efficient communication with sensors in the underground UDS is one of the main deficiencies preventing a wide application of RTC both in small and large-scale catchments (Campisano et al. 2013). The attenuation of electromagnetic (EM) waves in soils with high moisture content and different structure layers (concrete, gravel, sand) is so significant that communication through the soil has been considered infeasible for decades. Legacy (2G, 3G) machine-to-machine (M2M) would enable the establishment of the link over short distances, but these technologies are not energy efficient and therefore battery powered operation would be limited.

It has been found by Malik et al. (2018) that new low-power long-range communication technologies like narrowband internet of things (NB-IoT) are opening new possibilities for underground data connections and are therefore especially suitable for urban drainage systems. These technologies have sufficiently low energy consumption, wide signal coverage and a suitable information rate for the described RTC system. Composite materials can be used to manufacture the smart lid actuator in order to reduce the attenuation.

Economic aspects

Economic aspects are important to demonstrate the feasibility of the smart inlet system to the stakeholders. Therefore, both investment and maintenance costs were taken into account in the analysis. In addition, indirect costs were determined, reflecting the expenditures of the disturbances in the area during the construction and installation period. Usually, the parking lots surround lively hubs of shopping and entertainment centres, therefore interfering the traffic has probably a negative impact on business activities.

LID underground detention tanks typically used to accommodate excessive run-off from small catchments are used as a comparative alternative. The tanks have proven their efficiency in urban drainage systems (Andrés-Doménech, Montanari, and Marco 2012). But also some downsides like cost, accumulation of sedimentation and maintenance difficulties are widely acknowledged (Blecken et al. 2017). Despite that, the solution is robust enough to be widely used in UDS for run-off reduction and therefore represents an adequate background to more 'smart' systems. The cost components of the two alternatives are presented in Tables 1 and 2.

Additional costs comprise the adjustment or construction of speed humps and street curbs. These are needed to form barriers

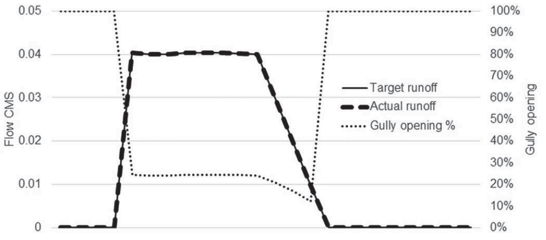

Figure 3. Example of the DMPC algorithm driving the opening of the gully to match the flow with the target flow curve.

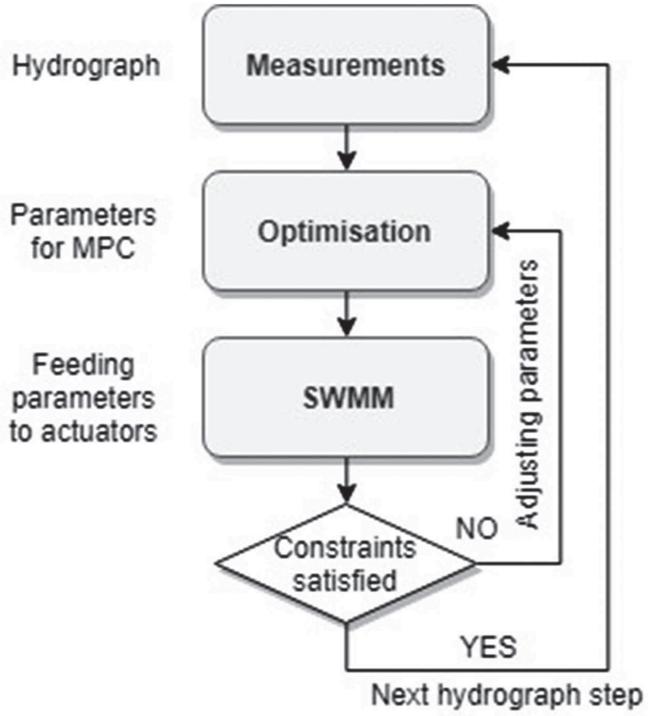

Figure 4. The process scheme of the drainage model.

Table 1. Cost components of smart inlet system.

Component	Specification	Unit	Cost, EUR	Cost reference
Investment cost				
Smart inlet gully	Actuator, control system and battery	EUR/pcs	8000	Calculated on the basis of the components, including composite lid structure
Sensors and central control unit	Rain gauge, outflow measurement, central RBC unit, programming	lump sum	110,000	Calculated on the basis of the components, includes programming 50 thousand EUR
Additional costs	Speed bumps	EUR/pcs	1500	Manufacturer's data
	Street curbs	EUR/meter	50	Manufacturer's data
Indirect costs	Disturbances of business activities	EUR/week	50,000	Cost of theoretical revenue due to limited parking possibilities
Maintenance cost	Maintenance of sensors and actuators	EUR/manhole/year	50	Cleaning the manhole from sediments

to prevent overland flow from ponded areas. On the other hand, these can also be used for safe pathways for pedestrians in case the smart inlet system is active and triggers controlled floods.

Technical components of both options have their unique lifetime. For example, electronic components are expected to last maximum for 5 years and actuators need to be replaced after 15 years, while structures, i.e. concrete of detention tanks, will sustain at least 50 years. To take into account this variability, the net present value (NPV) was calculated for both options. NPV equation converts any future values to the present, thus providing an adequate answer about the feasibility of the investment. The value is calculated as follows:

$$NPV = \sum_{n=1}^{a} \frac{F_n}{(1+i)^n} \tag{1}$$

NPV converts all economic transactions over the certain horizon from n to a to equivalent values in the present. For that future payment F_n for each period, n is summarised and subtracted with an interest rate i of this specific period n. Several assumptions were made for the calculation of NPV:

(1) Calculation period was taken 50 years.
(2) Different interest rates were analysed to test the robustness of the calculation. The theoretical natural annual real

Table 2. Cost components of traditional LID detention tanks.

Component	Specification	Unit	Cost, EUR	Cost reference
Investment cost				
Tank	Concrete tank with access manholes	EUR/m^3	500	Procurement results in Estonia 2016–2018
Pumps	Pumps and pipelines	EUR/tank	2000	Manufacturer's data
Additional costs	Ground works and asphalt pavement	EUR/m^2	80	Manufacturer's data
Indirect costs	Disturbances of business activities	EUR/week	50,000	Cost of theoretical revenue due to limited parking possibilities
Maintenance cost	Maintenance of sensors and actuators	EUR/tank/year	500	Cleaning the tank from sediments, water utility information

interest rate is estimated to be around 3%, and it is confirmed by empirical long-term average values. However, according to Kei-Mu and Jing (2016), as the real return varies over time, showing higher values in the 1980s and lower values after the 2008–2009 recession, interest rates from 2% to 5% were used in sensitivity tests.

(3) No price changes of investments were considered, which means that inflation of the investment product is zero and therefore nominal and real interest rates are the same.

Case study

Catchment

The concept of a smart inlet system was tested in a typical dense urban development surrounded by car parking areas in the city of Tallinn, Estonia. The ground space area of 12 ha has a concert hall, a hockey arena and several shopping and entertainment centres. Seventy per cent of the district is covered with asphalt and cobblestone pavement and is reserved for traffic and parking. The ground has a moderate 1% slope from east to west.

The catchment has one outflow connection to the town's UDS. As the downstream system is a combined type of a sewer running along the coastline, it is crucial to limit the peak outflow to the UDS in order to reduce the risk of CSO activation. Therefore, the catchment is highly suitable for testing the developed smart inlet concept.

System description

The system consists of seven sub-catchments, including both rooftops and asphalt pavement. The length of the UDS pipeline is ca 3 km, containing a total of 83 stormwater inlet gullies and 108 manholes for maintenance and connections. The stormwater collection system from the rooftops is directly connected to the underground drainage. The system is operating fully on gravity flow, i.e. no pumping is used to convey water to the downstream. The diameters of the main pipelines vary from 0.2 to 0.56 m. There are no methods currently applied for peak flow reduction, i.e. the whole system is designed and built to channel captured water downstream as fast as possible. The stormwater drainage system is presented in Figure 5.

The model of the stormwater drainage has been created and calibrated during a study by Koppel et al. (2014). No information was available about the rainfall intensity and return period used to design the system; therefore, the iterative analysis was performed to determine the parameters. The

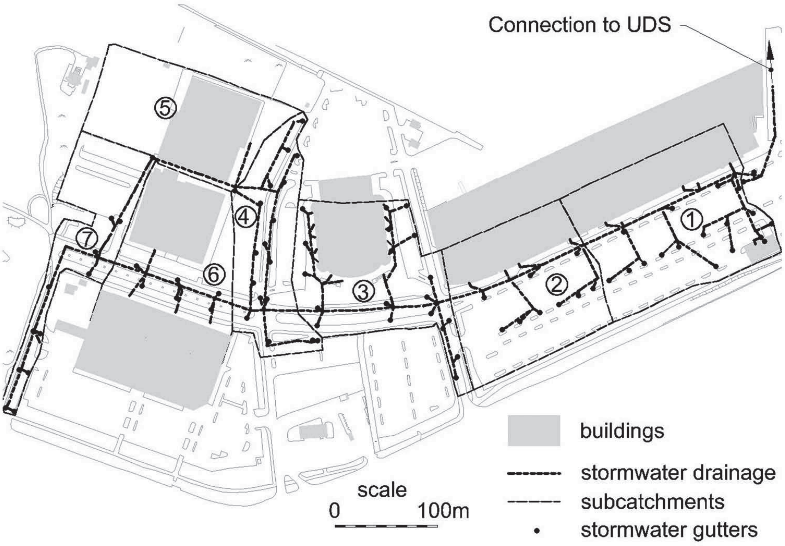

Figure 5. Stormwater drainage system of the case study area.

assumption that the design rainfall should not yield to node flooding was taken for the constraint, and different rainfall intensities were tested with the model. As a result, it was found that a rainfall of 25 mm/h in 20 min that corresponds to the return period of one year fits to the assumption.

Intense rainfall measured in Tallinn in July 2016 was used to test the concept of smart inlet under extreme weather conditions. It was estimated according to the methodology described in Estonian Design Standard EVS848:2013 that the return period of this rainfall event is ca 100 years. The comparison of the extreme rainfall with the design rainfall is presented in Figure 6.

It can be seen from the graph that the measured peak intensity is merely five times higher than the design figure. Therefore, an extreme rainfall poses significant stress on existing infrastructure. The extreme intensity results in a peak outflow of 1.0 m^3/s from the area, while the design rainfall yields only to 0.5 m^3/s.

As described before, two options were considered for runoff reduction – controlling inlets with smart stormwater gullies and secondly, installing underground detention tanks for temporary flow storage. The target was to reduce the peak outflow under extreme weather conditions to 0.5 m^3/s, which corresponds to the design storm presented in Figure 6.

In the first option, the control strategy was applied to the major stormwater inlets, by first determining the allowable ponded area per inlet. The maximum depth of ponded water was limited to 125 mm, as this is still a safe level for cars driving up to 26 km/h (Pregnolato et al. 2017). The total areas allowed to pond per catchment are listed in Table 3. As a result of the technical considerations described above, 57 smart inlets were determined with a total ponded area of 2 ha.

It is important to mention that only 17% of the total catchment is allowed to be ponded, which leaves sufficient space for raised pedestrian walkways and safe exit routes from the area. As described in the previous section, these areas have to be surrounded by a combination of speed bumps and street curbs in order to avoid spillages to the surrounding surfaces.

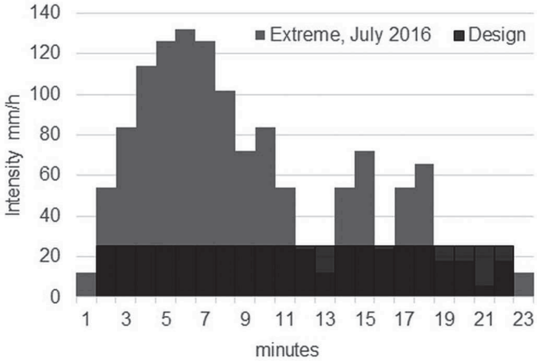

Figure 6. Comparison between the intensities of standard design and registered extreme rainfall event.

For the second option, peak flow reduction by utilising detention tanks needs an additional tank volume up to 1803 m^3. This volume is divided between seven subcatchments. Detention tanks are calculated on the basis of modelling results, setting the objective peak outflow to 0.5 m^3/s and calculating consequent volumes needed for excess flow storage. The volumes per catchment are presented in Table 3.

The hydraulic performance and economic feasibility of these two options are presented in the following section.

Results

Hydraulic performance

Hydraulic response to the extreme rainfall presented in Figure 6 was analysed in three scenarios:

(1) system with no runoff control, i.e. present solution;
(2) applying smart inlets with RTC;
(3) installing traditional underground detention tanks.

The results of these three options are presented in Figure 7. It can be seen from the figure that the peak run-off in the case of no flow control will reach up to 1 m^3/s. The curve has a flat top section, which indicates a flood event. This occurs as the system's capacity is insufficient to convey all the extreme flow downstream. As neither control mechanisms nor dedicated ponded areas exist, this flooding is uncontrolled and thus may have negative consequences.

The other two options with control show the high efficiency of reducing the peak flow. In both cases, the flow is kept well under 0.5 m^3/s. Smart inlets regulate the flow gradually and this results in progressive flow changes. As a result, it takes 2.5 h to empty the system, which is two times longer than at no flow control. Detention tanks are capturing the rainfall and are emptied after the event; therefore, their flowrate decreases gradually. It takes ca 4 h to deplete the tanks.

Maximum ponded depth in the case of control by smart inlet gullies varies from 12 cm in catchment 1 to 5.7 cm in catchment 4.

Stormwater volume captured into tanks varies from 28% of the tank full capacity in catchment 7 to 53% in catchment 1. Tanks were not allowed to become full firstly, to reserve some volume for the possible follow-up rain event, considering that it takes 4 h to empty the tanks and secondly, to mitigate the negative impact of sedimentation.

Table 3. Ponded areas of smart inlets and volumes of the detention tanks for the reference option.

Sub-catchment	Area of the catchment, ha	Ponded area, m^2	Ponded area/ catchment area (%)	Volume of the detention tanks, m^3
1	2.3	2800	12	336
2	1.9	4093	21	340
3	1.8	2753	15	253
4	1.3	3247	25	185
5	1.7	1961	12	202
6	1.9	3928	21	322
7	1.1	1988	18	165
TOTAL	**12.1**	**20,770**	**17**	**1803**

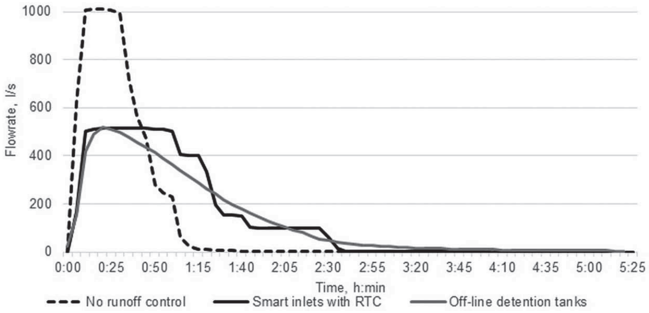

Figure 7. Results of controlling the stormwater run-off from the impermeable areas by using smart inlets and traditional detention tanks with pumping.

Economic feasibility

Based on the methodology described in the previous sections, the calculated investment cost of the smart inlet system would be 671,404 EUR, while the budget of the construction of the detention tanks would be 992,510 EUR. As discussed before, the difference in the investments stems from the scale of construction works. Also, the construction period of these two alternatives varies significantly from two weeks in the case of the smart inlet to eight weeks for detention tanks. Therefore, the indirect costs of smart systems are 100,000 EUR while the detention tanks reach 400,000 EUR. Consequently, the investment of a smart system is 1.8 times lower than in the case of the detention tank system. The results of our investment calculations are presented in Figure 8.

An interest rate of 2–5% proposed by Kei-Mu and Jing (2016) and established as a standard assumption in economics of long-term real yearly interest rate of investments was used for the NPV calculation. On the basis of these assumptions, the NPV of the detention tanks over a 50-year period is 1,094,608 EUR, while the value of the smart inlet system is 889,746 EUR (see Figure 8). This makes the smart system still ca 19% cheaper than that of detention tanks. Raising the interest rate up to 5% also increases the difference between the two options, thus improving the feasibility of the smart inlet system. The advantage of the smart system in NPV calculations stems from lower investment costs and lower yearly maintenance costs.

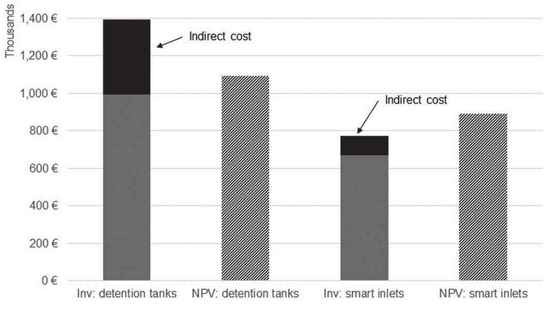

Figure 8. Comparison of investment costs and NPV of two alternatives.

As the life-span of a smart inlet system is shorter than that of detention tanks, which are more robust and versatile, in the long term, the difference between these two alternatives is reducing. Nevertheless, the smart solution still sustains the economic advantage over a 50-year period. In our study, the cost of a smart lid has been taken relatively conservative, assuming a high cost for new product development. As the quantity of the orders increases, the unit price is expected to decrease. On the other hand, the costs of concrete detention tanks remain relatively stable.

Discussion

A conceptual approach for the reduction of stormwater peak run-off by using smart inlet control in small catchments with dense urban development was created. The solution uses a two-level control algorithm with RBC and MPC layers capable of predicting the system status and adjusting the inlet openings according to the weather situation. To implement the solution, minimum construction works are required as the inlets are operating as off-grid elements. The inlet lids are standardised; they can be installed without any modification of the manholes themselves. Typical LID detention tanks were chosen for comparison to determine the feasibility of the smart inlet solution.

The concept was tested in a 12 ha catchment in Tallinn, Estonia. The smart inlet system showed high hydraulic performance, capable of reducing the peak flow up to 50% using only 17% of the catchment area for temporarily ponding. This was achieved with 57 smart inlets at the threshold level of the ponded water of 0.125 m.

To reach the same effect with detention tanks, ca 1803 m^3 of underground storage is needed. As a result, the cost of the tanks overtopped the smart solution merely 1.8 times. Although the lifetime of the electronics and sensors is substantially shorter than that of the concrete tanks (5–15 years compared to 50 years) or pumps (15 years), the net present value over a 50-year period of the smart systems was still 19% lower. This is merely because of lower investment and lower yearly maintenance costs. As a result, the small-scale real-time control strategy with smart inlets seems a promising and feasible solution to be implemented in existing parking areas for peak flow reduction.

Additionally, we draw attention to the fact that also above ground structures, like existing permeable surfaces are part of UDS. This aspect is often neglected due to different ownerships and interests. Typically, in such areas, the water utility maintains the underground UDS while a landowner is responsible for operating the parking lot. This division poses challenges and might even hinder the implementation of novel stormwater management solutions. We clearly demonstrated that the co-operation between these two operators can yield a positive impact on urban run-off management.

Further research and development activities are needed to create a prototype of the adjustable manhole gully required to implement the solution and test the communication solution in real life situations. Also, optimisation and control algorithms need improvement to be ready for field testing. In addition, residents' mindset needs a shift from fighting against water to living with it.

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Disclosure statement

In accordance with Taylor & Francis policy and my ethical obligation as a researcher, I am reporting that I have no financial and/or business interests in nor am I a consultant in or receiving funding from a company that may be affected by the research reported in the enclosed paper.

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Appendix 4

Publication IV

Malik, H.; Kändler, N.; Alam, M. M.; Annus, I.; Le Moullec, Y.; Kuusik, A. (2018). **Evaluation of Low Power Wide Area Network Technologies for Smart Urban Drainage Systems**. Proceedings of 2018 IEEE International Conference on Environmental Engineering (EE).: 2018 IEEE International Conference on Environmental Engineering (EE), Milan, 2018, pp. 1–5. Milan, Italy: IEEE, 1−5. DOI: 10.1109/EE1.2018.8385262.

Evaluation of Low Power Wide Area Network Technologies for Smart Urban Drainage Systems

Hassan Malik, Nils Kändler*, Muhammad Mahtab Alam, Ivar Annus*, Yannick Le Moullec, Alar Kuusik
Thomas Johann Seebeck Department of Electronics
*School of Engineering
Tallinn University of Technology, Estonia
Email: {hassan.malik, nils.kandler, muhammad.alam, ivar.annus, yannick.lemoullec, alar.kuusik}@ttu.ee

***Abstract*—Smart urban drainage systems (SUDS) with real-time control are considered to be one of the prominent approaches to tackle the impact of climate change which results in heavy rainfall and floods in urban areas. However, the lack of reliable and efficient communication with sensors buried underground is considered as one of the main deficiencies preventing ubiquitous application of SUDS. With the recent developments of new noise insensitive technologies for ultra-narrow band (UNB) and chirp spread spectrum (CSS) communication, introducing new low-power long-range communication technologies (e.g. NB-IoT, LoRa), implementation of such drainage systems is becoming feasible. This paper presents a comparative study of NB-IoT and LoRa and evaluate the potential of these technologies to be used for SUDS. The study is conducted in different underground scenarios such as dry and damp conditions to highlight the potential benefits offered by LoRa and NB-IoT in terms of coverage, information rate, and energy consumption. It has been shown through the simulation results that NB-IoT offers capillary coverage with a high level of scalability as compared to LoRa. Furthermore, NB-IoT also provide high information rate and low energy consumption and is best suited for underground scenarios.**

***Index Terms*—Narrowband Internet of Things (NB-IoT), LoRa, smart drainage system, information rate, coverage, energy consumption.**

I. INTRODUCTION

Climate change will have considerable impact on urban areas. One of the effects of this process, especially in Northern Europe, is the increase of storm water peak intensities and extreme rainfall events and it is expected that the frequency of rainfall events will increase more than 3 times by the year 2030 [1]. Currently, urban drainage systems (UDS) are typically designed to operate on ca. 2/3 water elevation rate in the conduits as this is hydraulically the most efficient stage. In addition to that, free space between the pipe obvert and the water level allows ventilation of the UDS and avoids thus trapping the air in the conduits. Trapped air may lead to disturbances and impair the operation of pumping stations and treatment plants. If the design threshold for the water height is exceeded, the system becomes surcharged, i.e. losing the free capacity, which will eventually lead to the situation where water is flowing backwards from the manholes to the ground. This is the common reason of urban floods caused by the extreme rainfall events, posing risk on buildings, structures and disturbing life in cities. In case of combined sewer systems where stormwater and wastewater is conveyed through the same system, this type of flood brings a threat on the surface water quality and human health as untreated wastewater may reach to surrounding water bodies.

There are several options available to tackle the surcharge problem of UDS. As the UDS infrastructure is deep underground, situated in dense urban environment, rebuilding the system is the most expensive and effort demanding approach. Replacing drainage collectors with new and larger pipelines in such environments may cost thousands of euros per meter and will have substantial indirect costs related to the closure of the streets and ensuring constant operation of other communication lines. In addition, over-dimensioning the pipes will decrease the critical flow velocities needed to self-clean the system. Therefore, other less interruptive methods to reduce the risk of UDS surcharge and consequent flood have been largely investigated during the past decades [2]. These options comprise structural approaches, were the system is supplied with additional storage tanks capable to temporarily accumulate the excess water and non-structural solutions focusing on operational possibilities, i.e. better management of pumping stations in the system [3]. The efficiency of these solutions is relatively moderate (10-25% cut from of the peak flow) [4]. The reason for that is the lack of free space in urban environments to construct massive storage tanks and scarcity of network actuators, i.e. pumps to lead possibilities to adjust the operation of UDS.

Smart urban drainage systems (SUDS) with real-time control has been seen as a most efficient way to reduce the water level overload and thus tackle the impacts of climate change and surface sealing [5]. For that, different actuators, i.e. gates, weirwalls, closable inlets and curbs are installed into the system to control the flow at the upstream. These are usually easy to install and need therefore no extensive construction projects. In addition to that, the control system will be fed with data from weather radar to turn real-time control (RTC) proactive. This means that water levels are decreased in the system prior the rainfall event and thus lowering the risk of flood. It has been found that these type of RTC systems are able to cut the peak flow in the system by up to 50% [6]. This is significantly higher result than in the case of conventional options. Therefore, smart urban drainage systems are seen as economically feasible. Until today the development of SUDS has been impeded inter alia by limitations of the communication options between the sensors in the network and the control unit. This paper contributes filling this gap and thus accelerating the development of efficient and affordable SUDS.

As mentioned, the lack of reliable and efficient communication with sensors buried underground is considered as one of the main deficiencies preventing ubiquitous application of SUDS. The attenuation of electromagnetic (EM) waves in (wet) soil is so significant that communication through soil has been considered not feasible for decades, especially for low transmission power battery-powered devices and decent communication ranges of at least hundreds to tens of meters. Furthermore, another major challenge is the connectivity issue, due to the difficult location, particularly non-line of sight (NLOS) in which underground sensors are deployed. Legacy (2G, 3G) mobile M2M networks would enable establishing wireless link at short distances but as far as such wireless devices consume significant amount of energy, the battery-powered operation time would be limited [7]. Better energy efficiency would be achievable with sub-gigahertz short range wireless communication technologies like IEEE802.15.4g based WiSUN and WMBus operating at 433 MHz or 169 MHz ranges [8]. Still, the maximum achievable radio link budget would be around 135-140 dB with short distances. That may be still insufficient for decent communication ranges between underground sensors and wireless access points above the ground.

However, due to recent developments of new noise insensitive technologies for ultra-narrow band (UNB) and chirp spread spectrum (CSS) communication, introducing new low power long range communication technologies (e.g. NB-IoT, LoRa), implementation of energy efficient wireless sensor networks for drainage systems is becoming feasible. NB-IoT is a cellular technology based on licensed spectrum, whereas LoRa is a CSS modulation based radio technology that is usually deployed at 868 MHz in Europe and 902-927 MHZ in North-America, respectively. NB-IoT provides better coverage with a high level of scalability due to high maximum coupling loss (MCL) as compared to LoRa. LoRa is prominent because of it possibility to operate in sub-GHz ISM bands and transfer short messages efficiently, as required by SUDS systems.

However, to deploy these technologies for practical applications, achievable information rate, coverage and energy consumption are the key performance measures that need to be evaluated. In the literature, few efforts has been made to investigate the coverage and device capacity of both NB-IoT [9] and LoRa [10]. In [11], the author presents the general overview of LoRa and investigated the scalability and capacity of LoRa in an outdoor environment in terms of throughput and number of devices that can be served by cell. Similarly, in [12], the coverage measurement has been presented for outdoor scenario along with the channel characterization aspect of LoRa. The effect of mobility and doppler effect on LoRa have been presented in [13]. In addition, the evaluation of NB-IoT in smart-grid application has been presented in [14]. Furthermore, capacity evaluation of NB-IoT has been presented [15] and it is shown that NB-IoT is able to achieve the expected capacity of 52K devices per cell. To the best of the authors knowledge, there are no studies investigating the impact of environment on the performance of these technologies, particularly in underground scenarios. It is, therefore, necessary to answer the following:

- Whether it is sufficiently reliable to use these technologies for SUDS systems?
- Which technology is able to provide high spectrum and energy efficiency while maintaining quality of service (QoS)?

To address these question, this paper presents an extensive study on the feasibility of LoRa and NB-IoT in a star-like network used for SUDS systems. The focus of evaluation is on the impact of underground environment on the radio transmission characteristics of LoRa and NB-IoT. The performance of LoRa and NB-IoT is presented in terms of coverage, effective information rate and energy efficiency.

The remainder of paper is organized as follows. In Section II, the system model under consideration is presented along with the underground drainage system architecture and factors influencing the signal strengths. Furthermore, the simulation parameters and traffic model considered as per the 3GPP and LoRa standards are also presented. In Section III, the detailed evaluation on the performance of NB-IoT and loRa systems in term of effective cell coverage, information rate and energy consumption is provided, followed by a conclusion in Section IV.

II. SYSTEM MODEL

For this study, we have considered the most common UDS structure as presented in Figure 1. UDS are mostly underground and are therefore accessible through the manholes usually covered with an iron lid. It is not possible for EM waves to pass through the lid. Therefore, the signals has to travel through the combination of materials i.e. concrete, compacted sand, gravel or soil. However, EM waves has to suffer much more attenuation in such underground environment as compared to air which significantly degrade the communication quality. Furthermore, multi-path fading due to

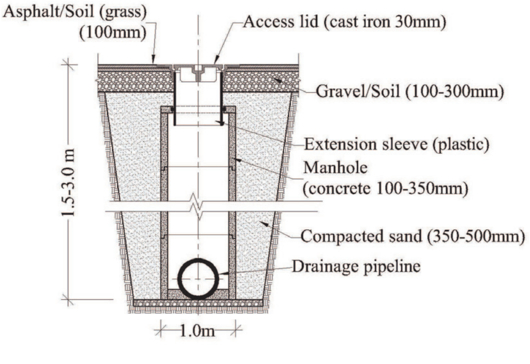

Fig. 1: Urban drainage system architecture

the small particle such as rock or tree roots in soil results in refraction and scattering of EM waves. This further degrades the performance of communication link.

As presented in Figure 1, we have taken into account the loss in signal strength due to **concrete, sand and soil or gravels**. Furthermore, as the UDSs are deployed either under roads, pathways or greenery, with different groundwater level. We have evaluated the performance of NB-IoT and LoRa in both dry and damp environments to observe the impact of water content on the signal in these surfaces as well. As, each of these surfaces will impact the propagation of signals differently, therefore, we have considered soil (greenery) with a thickness of 100 mm for this analysis. The sensor communication process in remote sensing of SUDs is governed by the target geometry and dielectric properties relative to the sensor parameters. At microwave frequencies, i.e. 800 MHz, the dielectric properties of sand and soils are particularly important as they are very susceptible to moisture content and at incidence angles. The signal attenuation that can be caused from the above-mentioned materials are presented in Table I. The values in Table I have been taken from the already existing work on the effect of dielectric properties of soil, sand and concrete on EM waves [16], [17].

TABLE I: Different medium and signal losses in 800 MHz band

Concrete	16 dB/ 35 cm
Dry Soil	21 dB/m
Damp Soil	44 dB/m
Dry Sand	6 dB/m
Damp Sand	15 dB/m

A. Simulation Setup

In this study, the performance analysis has been conducted in a single-cell scenario with an inter-site distance of 500 m. All the sensors are uniformly random distributed. For NB-IoT, the deployment is in standalone mode with a bandwidth of 180 kHz consisting of 12 subcarriers (multi-tone) at 15 kHz subcarrier spacing. The performance of multi-tone is considered to be worse than single-tone e.g. 3.75 kHz or 15 kHz. The performance achieved in this study can be regarded as lower bound as compared to single-tone NB-IoT system. Thus, for NB-IoT investigation, it is a more realistic assumption to consider. For LoRa, the bandwidth is assumed to be 125 kHz with 8 symbols of preambles and header enabled. The other simulation assumptions that closely follows NB-IoT and LoRa standards are presented in Table II.

TABLE II: Simulation Assumption

Parameters	Assumptions
Cell layout	Hexagonal grid
Frequency band	800 MHz
Cell Radius	1 km
User distribution	Users dropped uniformly in entire cell
Sensor Transmit power	23 dBm (NB-IoT), 14 dBm (LoRa)
Pathloss Model	L=120.9 + 37.6 log10(R), R in km
Shadowing standard deviation	8 dB
SC between cell sectors	1.0
Noise figure at base station	5 dB
Noise figure at UE	3 dB
Noise power spectral density	-174 dBm/Hz

Furthermore, the maximum achievable information rate can be calculated using the Shannons formula for Gaussian channel, if signal-to-interference-plus-noise (SINR) is known. Thus, the information rate R_i for a node i is given by:

$$R_i = B\log_2(1 + SINR_i) \tag{1}$$

where B is the bandwidth assigned for transmission and $SINR_i$ for node i and is given as:

$$SINR_i = \frac{P_i h_i}{N_o} \tag{2}$$

where P_i is the transmit power of the node and h_i is the channel gain between node i and the base station. N_o is the noise power spectral density. Based on the SINR, the corresponding MCL is computed. The relationship between SINR and MCL is given as [14]:

$$\begin{aligned}\text{Target SINR} = \text{Tx power} + 174 - \text{Noise figure} \\ - 10\log_{10}(\text{Bandwidth}) - \text{MCL}\end{aligned} \tag{3}$$

For this study, chase combining is used based on MCL, such that the same information is repeated N times in case of NB-IoT or different spreading factors are used for LoRa. The number of repetitions and spreading factors assumed with different MCL values are presented in Table III.

B. Traffic Model

For this study, we have considered the Mobile Autonomous Reporting (MAR) periodic traffic model as presented in annex E of 3GPP standard [18]. Based on the model, the application payload size is Pareto distributed with alpha = 2.5, minimum (beta) = 20 bytes, cutoff = 200 bytes. However, for simplicity, we have assumed an average 25 bytes of uplink packet size. On top of that, a header of 32 bytes including CRC field is applied to NB-IoT and 13 bytes with CRC to LoRa as specified in the standards. Furthermore, all sensors apply the QPSK and 4/5 coding scheme.

III. PERFORMANCE EVALUATION

In this section, the system-level performance of the NB-IoT and LoRa is evaluated through Monte Carlo simulations in terms of coverage, effective information rate and energy consumption. With the settings presented in Table II and subsection II-B, the simulation is run for over 5000 random samples.

TABLE III: Coverage classes with repetition factor (RF) for NB-IoT and spread factors (SF) for LoRa

MCL-dB	RF (NB-IoT)
Below 145	1
145 to 147	2
147 to 150	4
150 to 153	8
153 to 156	16
156 to 159	32
159 to 162	64
162 to 164	128

MCL-dB	SF (LoRa)
Below 138	6
139 to 142	7
142 to 146	8
146 to 149	9
149 to 152	10
152 to 155	11
155 to 157	12

First, we evaluate the minimum link loss that can be achieved by the sensors deployed in SUDS with both NB-IoT and LoRa. It will help to evaluate how many sensors can be in outage due to poor signal strength. The minimum link loss between the base station and sensor in terms of cumulative distribution function (CDF) is presented in Figure 2. The sensors are uniformly distributed in a cell with radius of 1 km. The MCL of LoRa (157 dB) and NB-IoT (164 dB) is presented by doted and dash vertical lines, respectively as defined in the technical specifications. The part of the CDF to the left of a dashed line indicate the sensors which are in outage. This means that these device cannot be served by these technologies as the link loss exceeding the MCL. The results show that with an MCL of 164 dB, NB-IoT provides the best coverage. The NB-IoT has an outage of 5.4% sensors for locations with damp environment experiencing high penetration loss in addition to the outdoor path loss. LoRa cannot provide coverage for 11.2% of those sensors. The results also show that the performance slightly degrade further when multi-path fading effect will be considered.

Figure 3 shows the CDF of the average information rate in both dry and damp scenarios with an information packet size of 25 bytes in uplink. The information rate is defined as the number of information bits transmitted per second. This includes the overhead information such as control information of NB-IoT and header and preamble required for LoRa transmission. The result reveals that the maximum information rate that can be achieved with NB-IoT and LoRa are 65 Kbps and 5 Kbps, respectively. It can be noted that LoRa throughput is significantly lower than that of NB-IoT. In addition, in case of damp environment, the information rate reduces significantly by up to 49.5% in NB-IoT (i.e.   30 Kbps) and 60.1% in LoRa (i.e.   1 Kbps). The impact of damp environment on LoRa is much more than NB-IoT, this is due to the use of higher spreading factor in LoRa. As the signal quality decrease due to damp environment, higher spreading factors in case of LoRa and more repetition in NB-IoT are required to overcome the MCL, resulting in performance degradation.

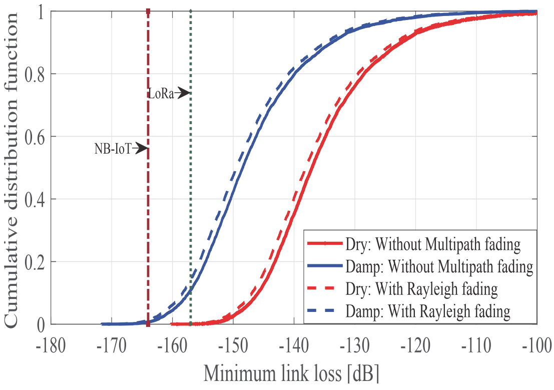

Fig. 2: MCL CDF for sensor deployed underground with 35 cm thick concrete and 50 cm compact sand and 30 cm soil layer in an urban area

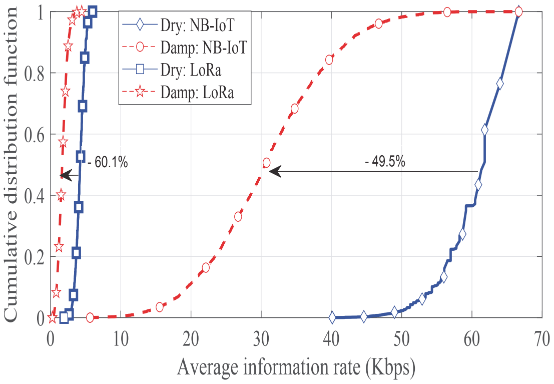

Fig. 3: Effective information rate (Kbps) per sector for sensor deployed underground in an urban area with rayleigh fading for both dry and damp scenario

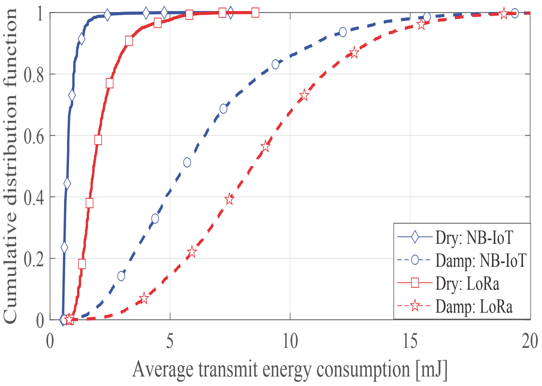

Fig. 4: Average transmit energy consumption (mJ) per sector for sensor deployed underground in an urban area with rayleigh fading for both dry and damp scenario

Figure 4 shows the CDF of the average transmit energy consumption per sector in both dry and damp scenarios with an information packet size of 25 bytes in uplink. It can be observed that the energy consumption of NB-IoT is much less than that of LoRa. This is because the time required to transmit the packet over-the-air in LoRa is significantly higher than in NB-IoT. Furthermore, the energy consumption is significantly higher in damp environment due to increased number of repetitions and spreading factor in NB-IoT and LoRa, respectively.

IV. CONCLUSION

In this paper, we have presented a detailed performance analysis of NB-IoT and LoRa for underground drainage systems in an urban area. From the conducted analysis, it is observed that the performance of these technologies highly depend on the moisture content in the underground environment. However, these technologies are still able to provide the required reliability of communication for SUDS at the feasible density of gateway network. Furthermore, it is also observed that NB-IoT outperforms LoRa in all aspects i.e., coverage, information rate and energy consumption. Therefore, to provide a suitable solution for SUDS, NB-IoT can be regarded as a prominent technology.

As future work, based on the results presented in this study, we will be able to evaluate different strategies for resource management in NB-IoT and LoRa systems for specific SUDS use-cases in urban areas.

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Curriculum vitae

Personal data

Name:	Nils Kändler
Date of birth:	18.07.1976
Place of birth:	Tallinn
Citizenship:	Estonian

Contact data

E-mail:	nils.kandler@taltech.ee

Education

2016 – …	Tallinn University of Technology, School of Engineering, Course Environmental and coastal engineering, PhD
2000 – 2002	Tallinn University of Technology, Institute of Civil Engineering, Course Environmental engineering, MSc
1994 – 1999	Tallinn University of Technology, Institute of Civil Engineering, Course Environmental engineering, BSc

Language competence

Estonian	native
English	fluent
Russian	basic level
Finnish	basic level

Professional employment

2016 – …	Tallinn University of Technology, researcher
2010 – 2016	AS Infragate Eesti, civil engineer and project manager
2007 – 2010	AS Infragate Eesti, head of consulting department
2003 – 2007	AS Eesti Veevärk Konsultatisoon, consultant
1998 – 2002	Tallinn University of Technology, senior researcher

Elulookirjeldus

Isikuandmed

Nimi:	Nils Kändler
Sünniaeg:	18.07.1976
Sünnikoht:	Tallinn
Kodakondsus:	eestlane

Kontaktandmed

E-post:	nils.kandler@taltech.ee

Hariduskäik

2016 – …	Tallinna Tehnikaülikool, Inseneriteaduskond, Keskkonna ja rannikutehnika õppekava, doktoriõpe
2000 – 2002	Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika õppekava, magistriõpe
1994 – 1999	Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika õppekava, bakalaureuse õpe

Keelteoskus

Eesti	emakeel
Inglise	kõrgtase
Vene	baastase
Soome	baastase

Teenistuskäik

2016 – …	Tallinna Tehnikaülikool, teadur
2010 – 2016	AS Infragate Eesti, insener ja projektijuht
2007 – 2010	AS Infragate Eesti, konsultatsiooniüksuse juht
2003 – 2007	AS Eesti Veevärk Konsultatisoon, konsultant
1998 – 2002	Tallinn University of Technology, vanemteadur

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