University of Sheffield
Department of Civil and Structural Engineering

Optimal Positioning of RTC Actuators for Autonomous Control of Sewer Networks

Marco Eulogi

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

February 2022

Declaration

I, MARCO EULOGI, certify that all the material contained within this thesis titled "Optimal Positioning of RTC Actuators for Autonomous Control of Sewer Networks" is my own work except where it is clearly referenced to others, and confirm that this work was done wholly while in candidature for a research degree at The University of Sheffield.

Acknowledgements

I am deeply grateful to my academic supervisors, Dr Alma Schellart and Dr James Shucksmith, and my industrial supervisor, Dr Sonja Ostojin, for the incredible guidance, trust and support I have received throughout this 4-year journey. This research would not have been possible without your constant encouragement, invaluable advice and endless patience. I will always be thankful for that.

I gratefully acknowledge the funding received from the STREAM Industrial Doctorate Centre and Environmental Monitoring Solutions Ltd, which made this PhD possible.

I would like to express gratitude to the co-authors of my papers, Dr Pete Skipworth and Dr Stefan Kroll, for their encouragement, assistance and valuable suggestions. You made this research much easier.

My special thanks also go to Dr Will Shepherd. I often underappreciated your technical support with CENTAUR and optimisation algorithms. Your recommendations have been crucial in the planning and execution of this research.

I must also mention Dr Nuno Simões, who provided extensive documentation and valuable data on the field testing of CENTAUR in Portugal.

A big “thank you!” to my family, for their constant support, love and encouragement. Even with 1000 miles separating us, you were always with me.

And finally, my beloved Annalisa. Four years ago, we left home with just a few suitcases and a one-way flight ticket. Look what an incredible journey we have lived together. In my biggest successes and worse failures, days of joy and moments of despair, you never left my side. We both know that I would never have finished this PhD without your incredible support and constant encouragement. Thank you for believing in me, certainly more than I do.

This research has been supported by an Engineering and Physical Sciences Research Council research studentship (EP/LO15412/1) as part of the STREAM Industrial Doctorate Centre for the water sector.

Table of Contents

List of Figures

List of Tables

List of Symbols

N_s	Total number of possible FCD placements (-)
V_0	Minimum threshold volume (m^3)
Z_α	Normal distribution value (-)
n_r	Random sample size (-)
Δ	Safety margin (m)
RL	Reference level (m A.D.)
CI	Confidence interval (%)
p	Success probability (-)

List of Abbreviations

BMP	Best Management Practice
CPU	Central Processing Unit
CSO	Combined Sewer Overflow
EA	Evolutionary Algorithm
EPA	Environmental Protection Agency
FCD	Flow Control Device
GA	Genetic Algorithm
GI	Green Infrastructure
GIS	Geographic Information System
GPU	Graphic Processing Unit
HPC	High-Performance Computing
IDF	Intensity–Duration–Frequency
LID	Low Impact Development
MPC	Model Predictive Control
RTC	Real Time Control
SuDS	Sustainable Drainage System
SWMM	Storm Water Management Model
UDS	Urban Drainage System
VMM	Flanders Environment Agency
SA	Simulated Annealing
PSO	Particle Swarm Optimisation

Abstract

The enlargement of impervious areas, combined with the increase in the frequency of extreme precipitations due to climate change, pose increasing challenges for the management and operation of urban drainage systems (UDS). Local Real-Time Control (RTC) systems represent a potentially cost-effective alternative to concrete-based solutions (e.g. storage tanks) for enhancing the performance and resilience of UDS. Existing methods to locate Flow Control Devices (FCDs) commanded by RTC focus on identifying in-sewer storage capacity, without considering the hydraulic interactions occurring between the FCDs, their impact on the operation of existing UDS assets, and temporal variation of rainfall-runoff volumes within the catchment. In this study, a novel simulation-optimisation framework is developed to determine the optimal positioning of FCDs controlled by RTC in sewer networks. Optimal FCD locations are identified by a genetic algorithm (GA) solver coupled with hydraulic modelling software. The method is tested in two case study catchments with different characteristics, positioning FCDs commanded by a local and decentralised RTC system called CENTAUR. Results demonstrate how the proposed methodology provides a more robust evaluation of potential FCD placement schemes compared to storage-based design methods, facilitating the design and implementation of effective RTC systems in sewer networks. In the case studies evaluated, the local RTC was capable of efficiently reducing/preventing CSO spills discharged during high-frequency storm events, while mitigating CSO spills discharged during more severe storms. The simulation-optimisation framework is then further developed to optimise the spatial allocation of FCDs combined with simplified Sustainable Drainage Systems (SuDS), for CSO spill volume reduction. Optimal FCD-SuDS configurations are selected in two case study catchments to mitigate CSO spills over synthetic storm events. Implementation schemes are then validated over continuous rainfall series. Results show how the proposed method can successfully maximise the combined benefits of the two technologies when increasing the water storage capacity of UDS, highlighting the unexplored potential of FCD-SuDS intervention schemes as a flexible and decentralised solution for stormwater management.

Acknowledgement of collaborative work

The candidate confirms that the work submitted is entirely their own except where it has formed part of jointly authored publications. Appropriate credit to the work of others has been given within the thesis using references. Contribution of the candidate and other authors to this work is explicitly described below:

Chapter 1- Introduction: the candidate planned and wrote the original manuscript, supervisors James Shucksmith and Alma Schellart reviewed the manuscript over several iterations.

Chapter 2 - Background: the candidate planned and wrote the original manuscript, supervisors James Shucksmith and Alma Schellart reviewed the manuscript over several iterations.

Chapter 3 - Research questions and main objectives: the candidate planned and wrote the original manuscript, supervisors James Shucksmith and Alma Schellart reviewed the manuscript over several iterations.

Chapter 4 – Hydraulic optimisation of multiple flow control locations for the design of local real time control systems. Chapter adapted by corresponding journal article (published by the Urban Water Journal in 2021). Author: Marco Eulogi (candidate). Co-authors: Sonja Ostojin, Pete Skipworth, James Shucksmith and Alma Schellart.

The candidate formulated the overarching research goals and aims, designed the methodology and computer programs, performed the simulation study, visualised and interpreted the results, and wrote the original manuscript. Co-authors James Shucksmith and Alma Schellart supervised the research activity planning and execution, supported the interpretation of results and edited the manuscript. Co-author Sonja Ostojin supervised the development of the computer code and supporting algorithms, reviewed and edited the manuscript. Co-author Pete Skipworth reviewed and edited the manuscript.

Chapter 5 – Comparing methods to place adaptive local RTC actuators for spill volume reduction from multiple CSOs. Chapter adapted by corresponding journal article (published by the Journal of Hydroinformatics in 2022). Author: Marco Eulogi (candidate). Co-authors: Sonja Ostojin, Pete Skipworth, Stefan Kroll, James Shucksmith and Alma Schellart.

The candidate formulated the overarching research goals and aims, designed the methodology and computer programs, performed the simulation study, visualised and interpreted the results, and wrote the original manuscript. Co-authors James Shucksmith and Alma Schellart supervised the research activity planning and execution, supported the interpretation of results and edited the manuscript. Co-author Sonja Ostojin supervised the development of the computer code and supporting algorithms, reviewed and edited the manuscript. Co-author Stefan Kroll supported the formulation of the overarching research goals, supported the interpretation of results, reviewed and edited the manuscript. Co-author Pete Skipworth reviewed and edited the manuscript.

Chapter 6– Optimal positioning of RTC actuators and SUDS for sewer overflow mitigation in urban drainage systems. Chapter adapted by corresponding journal article in preparation. Author: Marco Eulogi (candidate). Co-authors: Sonja Ostojin, Pete Skipworth, Stefan Kroll, James Shucksmith and Alma Schellart.

The candidate formulated the overarching research goals and aims, designed the methodology and computer programs, performed the simulation study, visualised and interpreted the results, and wrote the original manuscript. Co-authors James Shucksmith and Alma Schellart supervised the research activity planning and execution, supported interpretation of the results and edited the manuscript. Co-author Stefan Kroll supported the interpretation of the results and edited the manuscript. Co-author Sonja Ostojin reviewed and edited the manuscript. Co-author Pete Skipworth reviewed the manuscript.

Chapter 7 - Discussion: the candidate planned and wrote the original manuscript, supervisors James Shucksmith and Alma Schellart reviewed the manuscript over several iterations.

Chapter 8 - Conclusion: the candidate planned and wrote the original manuscript, supervisors James Shucksmith and Alma Schellart reviewed the manuscript over several iterations.

1 Introduction

The enlargement of impervious areas, combined with the increase in the frequency of extreme precipitations under a future climate, pose increasing challenges for the management and operation of urban drainage systems (UDS) (Hosseinzadehtalaei et al., 2020; Madsen et al., 2014; McGrane, 2016; Miller and Hutchins, 2017; Zhou et al., 2019; Zittis et al., 2021). UDS are mostly composed of a sewer system (i.e. pipes, manholes) that collects stormwater drained from built-up areas and wastewater discharged from human activities. Sewer systems can be combined (stormwater and wastewater transported by the same pipe network) or separate. In Europe, urban drainage systems are mainly composed of combined sewer networks (Milieu, 2016). During heavy rainy periods or high-intensity storm events, run-off volumes can exceed the maximum water storage capacity of the drainage network, leading to urban flooding and/or discharges of untreated wastewater from combined sewer overflow (CSO) structures to receiving water bodies (i.e. channels, lakes, rivers). A study coordinated by the European Commission reported in 2016 more than 100,000 overflow structures in 19 Member States (number stated as “underestimated”), with 15,000 CSOs located in England and Wales (Milieu, 2016). CSO spills are recognised as a source of pollution for receiving water bodies, and CSO spill reduction is promoted and supervised by regulatory bodies (CEC, 1991; Environment Agency, 2018; Pistocchi et al., 2019). Despite the large number of CSOs reported, they are often positioned in remote or inaccessible areas, giving only a partial indication of the real occurrence and magnitude of overflows (Milieu, 2016).

Impacts from CSOs are likely to be more important in the future due to urban development and higher occurrence of extreme precipitation events, causing higher storm water loadings in combined networks (Fortier and Mailhot, 2015; Woods-Ballard and Cherrier, 2019). Conventional urban drainage solutions consider the enlargement of the existing sewer network, substituting existing pipes, separating stormwater from sewage water, or expanding the UDS with underground storage tanks. While concrete-based infrastructures are recognised as an efficient solution to increase the water capacity of drainage systems, they feature high up-front investment costs. Costs vary depending on size, catchment characteristics (e.g. property value, urban density) and the construction company. Dirckx et al. (2011) assessed the cost-efficiency of potential solutions for CSO spill mitigation in a typical medium-sized catchment in Flanders (~25,000 inhabitants, surface area of ~2,200 ha), estimating investment costs in the order of tens of millions of Euros for disconnection (building of a separate sewer system) and between 6 and 13 million Euros for storage tanks. Sriwastava et al. (2021) estimated the cost of storage tanks between £1,400 and £2,000/m^3 (urban areas outside London). Concrete-based infrastructures also feature long and difficult implementations in urban areas with limited available space (García et al., 2015), and potentially high embedded carbon and/or carbon emissions compared to green-based technologies (De Sousa et al., 2012; Liu et al., 2020).

There is increasing interest in the water sector in developing affordable, flexible and adaptive technologies to enhance the performance and resilience of existing UDS (EurEau, 2016; Gersonius et al., 2013; Guthrie, 2019). Current practices encourage the use of alternative non-pipe-based drainage infrastructure wherever possible (Butler et al., 2018), to offer greater adaptability in facing the effects of climate change and future urban development patterns (Altobelli et al., 2020; Miguez et al., 2015). Flexible and cost-effective alternatives to concrete-based solutions in UDS are Sustainable Drainage Systems (SuDS) and Real-Time Control (RTC) systems. SuDS are green-based distributed source controls aimed to remove and/or retain run-off volumes before they enter the drainage system, and include green roofs, bio-retention cells, permeable pavements among others. The deployment and management of such decentralised systems can be challenging due to space availability, especially in highly urbanised areas (Zhang and Chui, 2018) and spatially varied socio-economic constraints in urban catchments (e.g. lack of public interest and support, private and public lands owned by different parties) (Mandarano and Meenar, 2017; Montalto et al., 2013). RTC systems are instead designed to maximise the performance of UDS using real-time information (Schütze et al., 2004). Flow controllers (pumps, weirs, sluice gates…) are dynamically operated by a control algorithm based on monitoring data (e.g. water level, flow), regulating the flow conditions in real-time and bringing the system closer to the desired state. RTC systems can be configured to locally manage small portions of sewer networks (local RTC), or globally control the hydraulic conditions at the catchment scale (global RTC).

The selection of potential locations for flow control devices (FCDs) constitutes an essential step in the RTC design and deployment, with the choice of FCD placement strategy potentially leading to significant variations in system performance (Kroll et al., 2018). Current studies focus on the potential benefits of RTC, where the choice of optimal locations for flow controllers does not form an explicit research topic. Control locations are thus chosen by operators based on practical considerations (e.g. installation site accessibility, road and traffic management), static volume-based criterion (e.g. in-pipe volume mobilised by the FCDs) and previous knowledge of the system, potentially leading to sub-optimal performance. A more refined methodology for FCD location selection would enhance the performance achieved by the RTC, help operators in planning adaptable placement schemes to achieve specific operational targets (e.g. CSO spill volume reduction), and extend the range of applications of such flexible and adaptive technology in UDS. Moreover, limited research has been found aiming to understand how RTC and SuDS can be combined as a decentralised integrated system to enhance the efficiency and resilience of UDS, and how these technologies hydraulically interact and/or achieve additional benefits when combined.

1.1 Aim and structure of the thesis

This thesis will investigate the optimal spatial allocation of FCDs commanded by RTC for stormwater management in UDS. Emphasis will be given to designing effective FCD placement strategies for local RTC, deployed individually or combined with SuDS, for CSO spill mitigation in combined sewer networks.

A literature review of the main research topics is given in Chapter 2. Research questions and main objectives addressed in this dissertation are presented in Chapter 3. Chapters 4 to 6 are based on journal articles elaborated during this research, and address research questions outlined in Chapter 3. Key findings and suggestions for future research topics are discussed in Chapter 7. Outcomes and final considerations gathered from previous chapters are given in Chapter 8.

2 Background

An introduction to RTC in UDS is given in Section 2.1. CENTAUR, a low-cost and decentralised RTC developed to mitigate urban flooding and CSO spills, is reviewed in Section 2.1.1. Current methodologies to spatially allocate FCDs commanded by RTC in sewer networks are reviewed in Section 2.1.2. The implementation of RTC combined with SuDS is reviewed in Section 2.1.3. Optimisation-based approaches for RTC design and implementation in urban catchments are reviewed in Section 2.2.

2.1 Real-Time Control (RTC) systems

Hydraulic conditions within UDS are commonly regulated by assets and facilities (e.g. weirs, sluice gates, orifices, pumps) developed according to static design rules. RTC systems are instead designed to operate and manage existing UDS assets by monitoring the state of the system and regulating the flow conditions in real time. While stormwater volumes are generally regulated by static actuators (e.g. static weirs), RTC systems thus collect real-time data on the current state of the network and adjust it through active actuators to bring the system closer to the desired state (Figure 2.1).

RTC systems are recognised as a cost-effective technology to adapt existing UDS to future loading conditions (e.g. climate change) and urban development, with high flexibility to future system upgrades and investments (Dirckx et al., 2011; Erbe et al., 2007; Schütze et al., 2008). In some cases, initial investments can be reduced by integrating the RTC to infrastructure (e.g. flow control devices) already present in the catchment (Beeneken et al., 2013), or combining the RTC with conventional static solutions (Meneses et al., 2018).

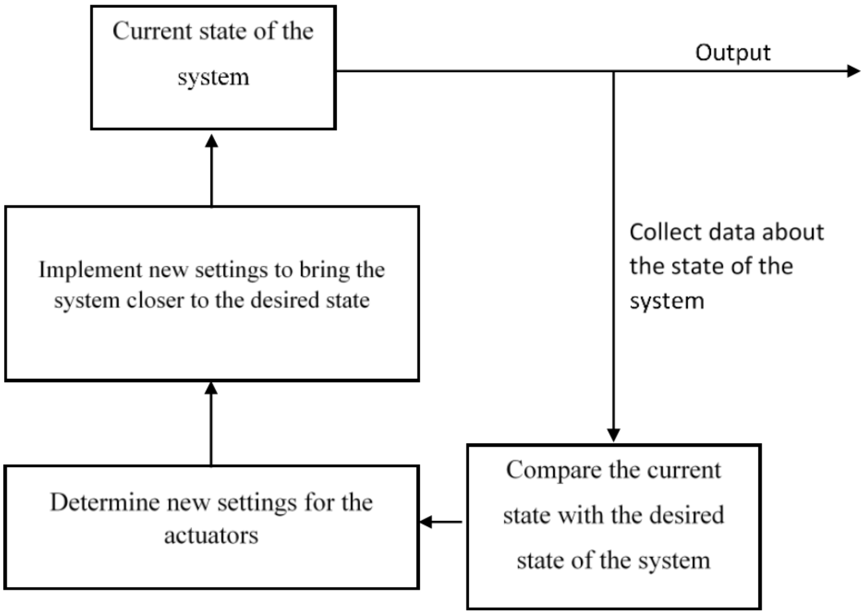


Figure 2.1: functions performed by an RTC system, based on Environmental Protection Agency [EPA] (2006).

The desired state of the network is a function of the RTC operational goals, which are site-specific. RTC can be implemented to mitigate CSO spills (Maeda et al., 2002; Schilling et al., 1996; Seggelke et al., 2013; Weyand, 2002) and urban flooding (Garofalo et al., 2016; Ostojin et al., 2017), improve water quality in receiving water bodies (Schütze et al., 2002), maximize treated sewage in wastewater treatment plants (Schilling et al., 1996), reduce pollution load (Rauch and Harremoës, 1999), optimise energy consumption (Kroll et al., 2018) among others. An introduction to RTC components can be found in EPA (2006) and Campisano et al. (2013), while guidelines on the implementation of RTC for stormwater management problems within UDS can be found in Erbe et al. (2007). An RTC is generally composed of hardware equipment (sensors, data communication systems, and actuators) and software programs (RTC control algorithm) (Figure 2.2). The current state of the drainage network is usually monitored in real-time by water level sensors (e.g. pressure transmitters, ultrasonic probes), rain gauges (e.g. tipping buckets). In more advanced RTC, future states are predicted through integrated radar rainfall forecast systems (e.g. Fuchs and Beeneken (2005)). Monitoring data is then transmitted, usually via SCADA (Supervisory Control And Data Acquisition) systems, to the RTC control algorithm that analyses the system performance and operates real-time decisions. Actuators (sluice gates, weirs, pumps, valves, flow splitters…) are controlled and coordinated by the RTC algorithm to control flows and levels within the drainage network. Different ways of classifying RTC systems are found in the literature (EPA, 2006; García et al., 2015; Schütze et al., 2003).

In this study, four classes of RTC are reviewed based on the control algorithm (heuristic algorithms versus optimization-based algorithms) and level of complexity (local RTC versus global RTC). "Hybrid" RTC designs can also be found in the literature. For example, Schütze and Alex (2008) describe a modular and distributed RTC that commands local control devices (i.e. throttle valves) based on local monitoring data (flows, levels) within sewer networks. The RTC is designed to ensure a uniform utilisation of available storage volume within sewage systems, and can be implemented as series of autonomous and independent control units (similarly to local RTC) as well as a global RTC based on a simple prediction model.

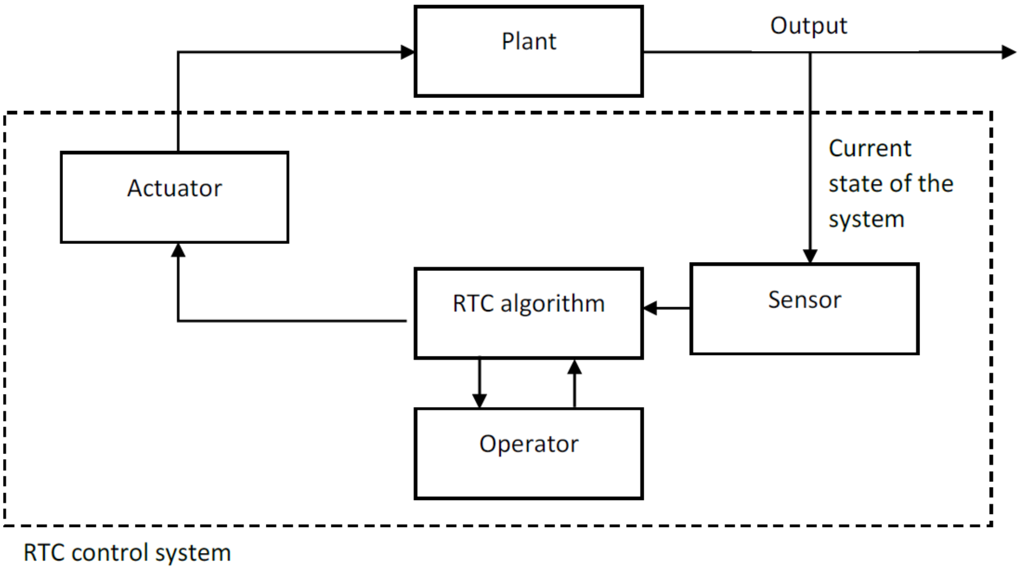


Figure 2.2: RTC flow chart.

Heuristic algorithms

Heuristic algorithms combine expert knowledge of the system with pre-defined sets of rules. They are designed to have low complexity and be easy to comprehend by operators and regulators, with a lower computational burden compared to optimisation-based algorithms, and no need for predicted data or real-time optimisation routines to operate (García et al., 2015). The RTC performance is usually evaluated and improved offline with simulation-oriented models in a second stage. The two types of heuristic algorithms most used for RTC applications in UDS are the ruled-based control algorithms and the Fuzzy Logic (FL) control algorithms. In ruled-based control algorithms, flows and levels are regulated by the RTC based on pre-defined sets of if-then rules or decision matrices, while FL algorithms combine simple sets of rules with a linguistic description of the system (Figure 2.3). Rather than strictly binary cases of truth, in FL input values (e.g. water level, flow) are associated with fuzzy sets using simple terminology (e.g. low, medium, high) (fuzzification). Fuzzy output values are computed by a collection of logic rules in the form of if-then statements (a process called inference) and transformed into crisp output values (e.g. storage outflow, sluice gate opening degree) by a defuzzification process.

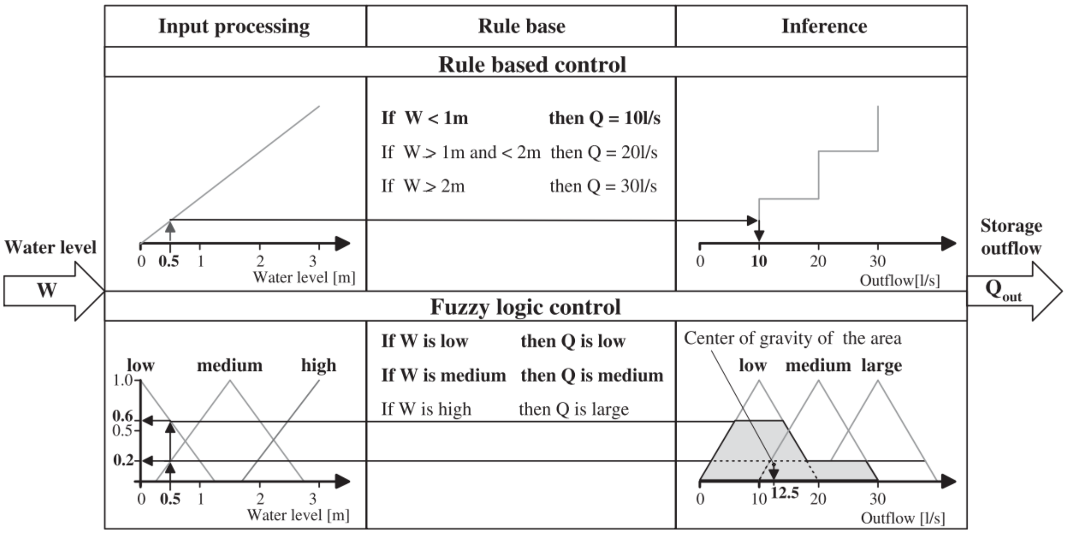


Figure 2.3: comparison between rule-based control and Fuzzy Logic control (Klepiszewski and Schmitt, 2002).

FL algorithms are known to efficiently handle monitoring data characterized by high variability or uncertainties (Ostojin et al., 2011). Input variables and fuzzification can be tuned after the RTC deployment without a change of the rule base set (Klepiszewski and Schmitt, 2002). Examples of FL algorithms with UDS applications include pumping optimization (Ostojin et al., 2011), CSO spill mitigation (Klepiszewski and Schmitt, 2002), state detection in anaerobic wastewater treatment (Murnleitner et al., 2002), rehabilitation of sewer networks (Tagherouit et al., 2011), and optimization of Integrated Wastewater Systems (Regneri et al., 2010).

While heuristic control strategies are known to be relatively easy to implement and operate, research studies have suggested that optimisation-based strategies are better suited to fulfil the RTC operational goals by optimising the objective functions in real-time (Mollerup et al., 2013; Vezzaro and Grum, 2014). However, it has been debated that the additional data collection and modelling systems, together with the number of water sensors and actuators required by more complex optimisation-based RTC to operate, might not be necessary for small sewer systems, where satisfactory results could be achieved by simpler control strategies (Mollerup et al., 2016).

Optimization-based algorithms

In optimization-based RTC, optimal sets of control actions are determined by the RTC control algorithm by minimizing a single or a group of objective functions. Objective functions can be solely based on quantity and/or quality monitoring data (e.g. peak-flow, total run-off, flood volume, pollution load), or can include other factors involved in the RTC deployment and operation (e.g., initial investment, operational costs) in a cost-benefit analysis.

Genetic algorithms (GAs) is a class of optimisation-based algorithms that replicates the mechanisms found in natural selection (reproduction, mutation, recombination, selection) to select the fittest individuals among populations of candidate solutions. Benefits of a high number of potential control actions are assessed through urban drainage modelling (e.g. rainfall-runoff models, water-quality models, pollution-load models) and the optimal solution identified through convergence to the global minimum, in a single (Cho et al., 2004) or multi-objective approach (Fu et al., 2008; Muschalla, 2008). GAs can be a suitable option to solve complex non-linear and mixed discrete/continuous optimization problems, since they can handle linear and nonlinear constraints and do not require continuity assumptions of the objective function. However, GAs feature higher computational effort compared to simpler heuristic algorithms, due to the high number of potential candidates assessed by the method. A refined tuning of GA parameters (number of generations, population size, crossover/mutation operators…) might also be needed to adapt the method to computationally demanding optimisation problems, to avoid redundant solutions and increase the efficiency of the method. Model predictive control (MPC) systems are a widely used type of optimization-based RTC that combines real-time monitoring data with rainfall radar images or rain forecast algorithms. Control actions are optimised recursively by the RTC algorithm based on current events as well as by predicting the system response to future events within a predefined time horizon. An extensive overview of MPC systems applied to UDS can be found in Lund et al. (2018). Uncertainties associated with rainfall predictions, and the conversion of predicted rainfall into inflows, are inherited by the RTC system, with the spatial and temporal resolution of rainfall data potentially affecting the outcomes (Ochoa-Rodriguez et al., 2015). This type of RTC is usually implemented as a system-wide control system in large and complex UDS (Copenhagen (Grum et al., 2011), Vienna (Fuchs and Beeneken, 2005), Quebec Urban Community (Schütze et al., 2004)), where the slow hydrological response to rainfall and the scale of the system call for a global analysis of the RTC operation based on current and future events. The implementation of MPC systems can be a challenging task in smaller urban areas, due to the faster runoff processes and shorter response times to rainfall inputs. While scale variations and uncertainties related to rainfall can be effectively filtered out when predicting future events in larger UDS (Rossa et al., 2011), high-resolution rainfall estimation is expected to be necessary when implementing MPC systems in smaller catchments, to improve the predictability of small-scale features (e.g. flow, water level) and reduce errors in the rainfall estimation (Schellart et al., 2014). Rainfall forecasting also adds significant complexity, computational demand and expense for maintenance to the system (EPA, 2006), making simpler control strategies a valid and cost-effective alternative when deploying RTC systems in smaller UDS (Mollerup et al., 2016).

Local RTC

In local RTC, flow controllers are handled independently based on water measurements taken within the area affected by the RTC system. Local RTC do not rely on online models, central server units or communication with other UDS assets and facilities to operate (EPA, 2006). Actuators can be added or relocated without the alteration of pre-existing RTC infrastructure or control strategies, in response to future network changes, urbanisation and climate trends (Mollerup et al., 2017). Local RTC can consist of a single flow controller, or a series of autonomous flow controllers implemented at different locations of the sewage system.

Despite being a flexible and relatively low-cost solution for stormwater management problems, there is a lack of research on strategy and implementation of such systems compared to global RTC, with few examples of local RTC applied to UDS found in the literature. In Carbone et al. (2014), a local RTC consisting of a series of 6 self-adjusting sluice gates is simulated to maximise the use of in-pipe storage capacity within a small urban watershed in the city of Cosenza (Italy). The RTC is then further evolved in Garofalo et al. (2016), where each movable gate is operated by a decentralized and distributed RTC system based on local monitoring data acquired in the neighbour areas. CENTAUR™ is a local and fuzzy logic-based RTC that combines local monitoring of water level with flow control devices (FCDs) inserted in pre-existing infrastructure (Mounce et al., 2020; Ostojin et al., 2017). The control system has been developed to offer a decentralised and modular technology to mitigate the effects of urban flooding and/or CSO spills in sewer networks. CENTAUR is reviewed in more detail in Section 2.1.1.

Global RTC

Global RTC systems are implemented to enhance the efficiency of UDS at a global level. Information on flows and levels can be shared amongst different actuators to coordinate their operation (distributed system), or actuators can be operated by a central control unit based on all measurement data collected within the catchment (hierarchical). The design and implementation of global RTC for CSO spill mitigation in combined sewer systems are widely documented in the literature (Dirckx et al., 2011; Kroll et al., 2018; Lund et al., 2018; Meneses et al., 2018). Global RTC systems are often deployed in large-scale and complex UDS in conjunction with model-based predictive control algorithms and optimisation techniques (Lund et al., 2018), with few examples of global RTC applied to smaller networks (Dirckx et al., 2014). Examples of full-scale global RTC include the cities of Tokyo (Maeda et al., 2002), Barcelona (Cembrano et al., 2004), Vienna (Fuchs and Beeneken, 2005), Seattle (Darsono and Labadie, 2007), Copenhagen (Grum et al., 2011), Wilhelmshaven (Seggelke et al., 2013) and Dresden (Beeneken et al., 2013), among others. Such RTC systems comprise rainfall forecast units, online modelling and central servers, as well as a high number of water sensors (flow meters, level sensors, rainfall gauges…) and remotely controlled flow controllers (pumps, weirs, sluice gates…).

Overall, global RTC, and MPC systems in particular, are regarded as the most successful control strategies applied to UDS so far (García et al., 2015). However, such systems can be costly and complex to install and operate, requiring extensive analysis and planning to determine the most efficient way to operate the RTC assets and facilities (EPA, 2006). Costs and equipment needed vary with the scale of the UDS. For example, the global RTC proposed by Seggelke et al. (2013) to reduce CSO spill volume and frequency in the Wilhelmshaven catchment (~100,000 inhabitants) includes a rainfall forecast unit, 5 rain gauges, 6 flow measurement units, 16 water level measurement units and 2 pumping stations, with approximately 1 million Euro invested for the RTC design and implementation. The multi-objective global RTC proposed by Fuchs and Beeneken (2005) for the city of Vienna (~1.8 million inhabitants) controls a total of 25 rainfall measurement stations, 40 flow measurement units, 20 water level measurement units and a not specified number of valves/weirs/pumps, covering a total drained area of 260 km^2 and 2,200 km of sewer pipes.

2.1.1 CENTAUR: local fuzzy logic-based RTC

CENTAUR[1] is a local RTC designed to maximise the use of existing in-pipe storage capacity for stormwater management within sewer networks. The RTC commands flow control devices (FCDs) inserted into existing infrastructure (i.e. gates installed in manholes), which consist of a movable sluice gate coupled with an emergency static overflow weir (Figure 2.4). The weir acts as a fail-safe in case of gate failure, preventing sewer flooding upstream of the FCD installation location. During storm events, the sluice gate is dynamically operated by the RTC to store stormwater volumes in the upstream in-sewer storage capacity, regulating water level at a pre-defined target location (e.g. CSO chamber, flooding manhole). The FCD operation is controlled by an autonomous FL-based algorithm. Water depths, locally measured by water sensors at the target location and immediately upstream to the FCD installation location, are transferred through local radio communication to a decentralised hub. In the hub, the sluice

---

[1] Details on CENTAUR project available at: https://www.sheffield.ac.uk/centaur/home/outputs.

gate opening degree is computed by the RTC control algorithm based on the real-time monitoring data (Figure 2.5).

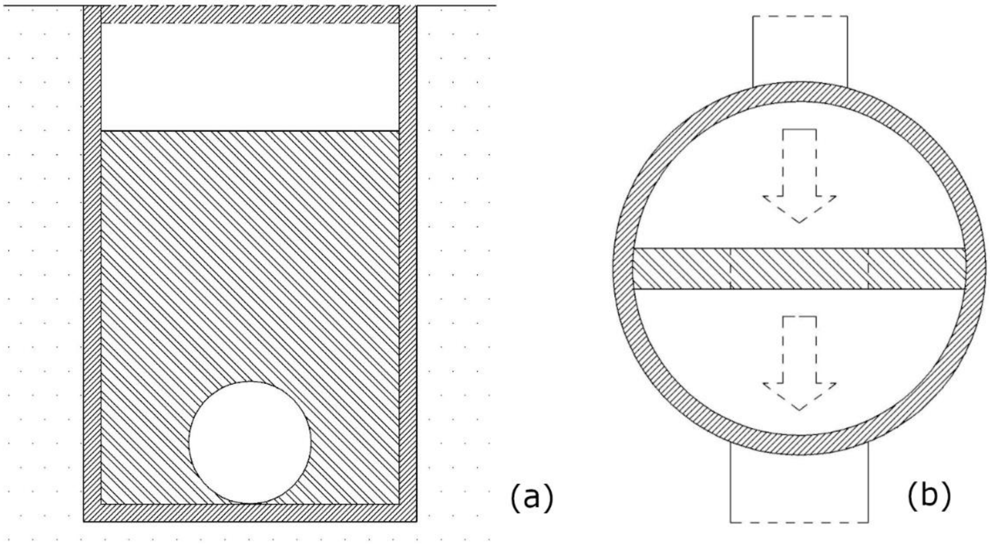


Figure 2.4: FCD side view (a) and plan view (b).

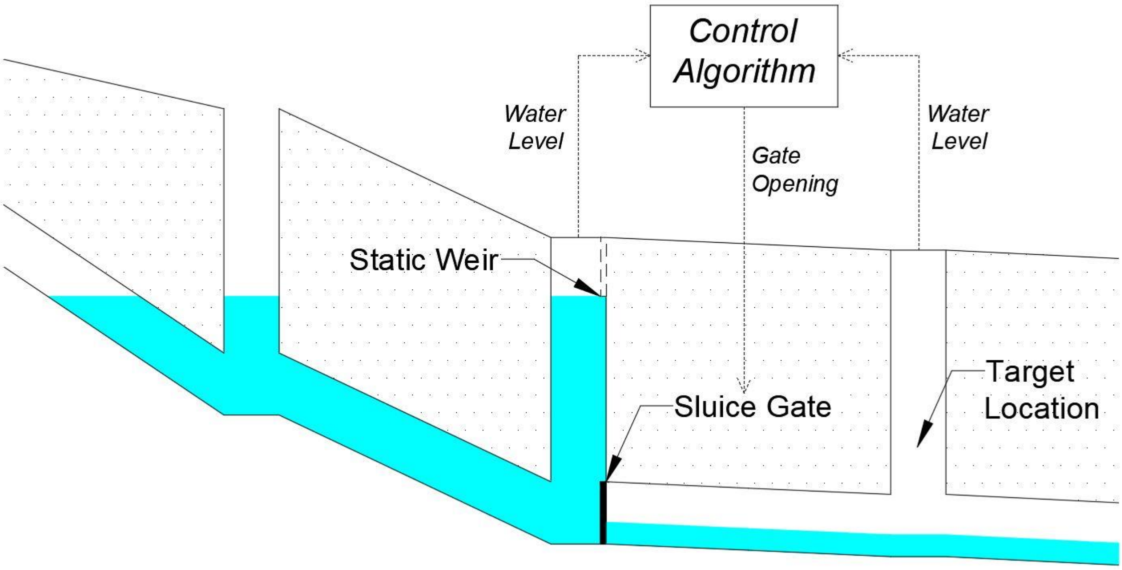


Figure 2.5: Scheme of the CENTAUR real-time control system.

Overall, CENTAUR has been developed to provide a local, low cost and easy-to-deploy alternative to more complex global RTC, with potential benefits equivalent to more capital-intensive solutions (Shepherd et al., 2016). The control system relies on a limited number of water sensors to operate, with limited civil works required to install and maintain the FCD and reduced initial investment compared to conventional solutions (e.g. storage units), offering a flexible and decentralised solution to stormwater problems within sewer network.

The design and implementation of CENTAUR as a single-gate system have been investigated in previous research through hydraulic modelling and field testing. In Shepherd et al. (2016) and Maluf et al. (2017), potential benefits in reducing flood volumes in wastewater networks are estimated by testing the performance of a single FCD within a benchmark and small scale model, respectively. The FL control strategy was then further developed by Mounce et al. (2020), which resulted in flood volumes further reduced by 25% compared to the performance obtained by simpler control rules manually defined based on expertise and knowledge of the system. Field testing of CENTAUR as a single-gate system (Figure 2.6) has been conducted in the combined sewer network of the city of Coimbra (Sá Marques et al., 2017). In Sá Marques et al. (2018), the performance of CENTAUR in regulating flows within the Coimbra sewer network has been assessed during 41 rainfall events registered over 5 months, demonstrating how the local RTC can successfully store stormwater volumes within the existing UDS without causing any problems to attached upstream properties. Several laboratory experiments were also run at the University of Sheffield, to better investigate the impact of a single FCD commanded by CENTAUR on flows and levels along pipe branches (Abdel-Aal et al., 2016) (Figure 2.7).

Figure 2.6: CENTAUR flow control device installed in the Coimbra combined sewer network (Portugal).

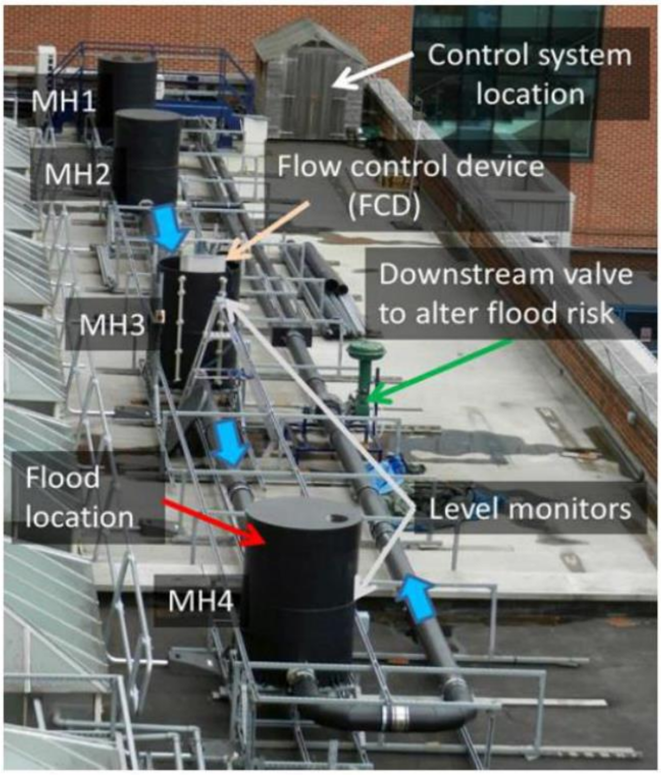


Figure 2.7: CENTAUR laboratory facility, University of Sheffield (Ostojin et al., 2017).

2.1.1.1 CENTAUR as a multi-gate RTC

Despite the extensive research on CENTAUR as a single-gate system, multiple FCDs will likely be needed in future implementations to meet required performance objectives in most UDS (e.g. defined reductions in CSO spill volume or frequency). To address that, CENTAUR could potentially be deployed as a series of autonomous and mechanically simple FCDs, without the need for real-time rainfall measurements, complex control strategies and infrastructure modifications. Single or groups of autonomous FCDs would locally handle small portions of the pipe network based on local monitoring of water level, mobilising “packages” of available in-pipe storage capacity at key points within existing sewer infrastructure. This could potentially deliver a flexible and affordable alternative to more complex global RTC, where FCDs can be easily relocated to address local changes in run-off volumes without alteration of pre-existing RTC infrastructure or control strategies.

An essential step in the design and implementation of RTC in UDS is the choice of installation sites for the flow controllers. An efficient placement of FCDs commanded by CENTAUR would maximise the impact of the local RTC in mobilising underutilised portions of the sewage system, and enhance the system performance. Assessing optimal locations of several FCDs manually is a complex and time-consuming process. This is mainly due to the number of possible configurations (number and location of FCDs) within the network and the computational effort demanded to assess the system performance through hydraulic analysis, especially in extended drainage systems. Such challenges make the deployment of multiple CENTAUR flow controllers difficult to optimize.

2.1.2 Spatial allocation of FCDs controlled by RTC

The selection of optimal locations for actuators is considered an essential step in designing RTC systems in sewer networks (Campisano et al., 2000; Leitão et al., 2017; Philippon et al., 2015). However, this has received far less attention than the study of control strategies and algorithms and constitutes an ongoing research topic (Kroll et al., 2018; Muñoz et al., 2019). Existing studies on FCD location selection usually focus on single case study catchments, offering only a partial overview on how the topography and hydraulic features of the catchment (i.e. shape, dimension, time of concentration, number, and position of UDS assets, distribution of in-pipe storage capacity, hydraulic response to precipitation) influence the optimal placement of FCDs. The choice of optimal control locations involves complex decisions due to the high number of possible implementation schemes, the complex nature of drainage networks, hydraulic interactions between RTC assets and spatial/temporal variability of rainfall and runoff volumes within the drainage network, potentially leading to significant variations in system performance (Kroll et al., 2018).

While practical (installation site accessibility, road and traffic management…) and economic factors can be considered when designing FCD placement schemes (Campisano et al., 2000; Sá Marques et al., 2018), the analysis of the in-sewer storage volume mobilised by the FCDs in the existing pipe network represents the main criteria in the literature. The storage volume activated by a flow controller can be defined as the sum of static storage and dynamic storage (Dirckx et al. (2011), see Figure 2.8). The static storage corresponds to pipe volume below a predefined horizontal reference plane (e.g. weir crest elevation, ground-level elevation). The dynamic storage corresponds to pipe volume between the reference plane previously defined and the hydraulic grade line, and it is due to flows within the network during rainfall events. This total in-sewer storage volume can be calculated neglecting the dynamic storage and assuming a flat energy line at the control location (Campisano et al., 2000; Dirckx et al., 2011;

Kroll et al., 2018; Philippon et al., 2015), or approximating the flow to steady-state condition (Leitão et al., 2017).

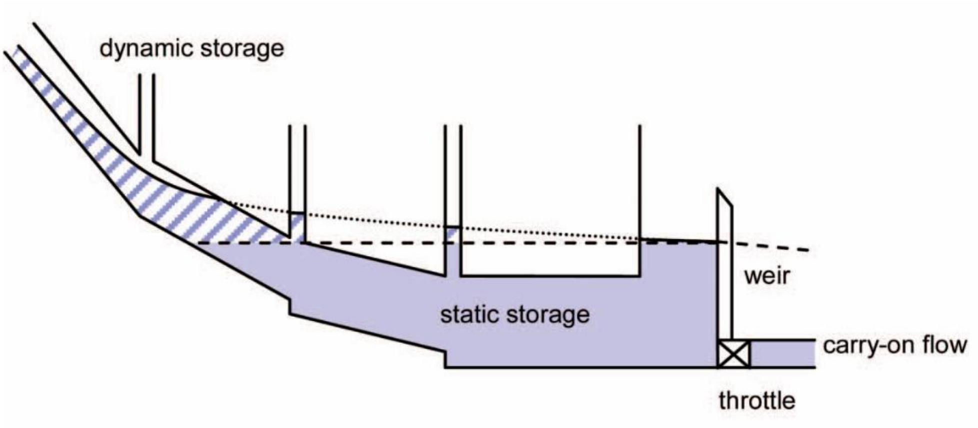


Figure 2.8: scheme of static and dynamic storage activated by a flow controller within sewer network, based on Dirckx et al. (2011).

In Campisano et al. (2000) and Philippon et al. (2015), placement schemes are designed solely based on the distribution of storage volume potential within the drainage network. Kroll et al. (2018) implemented 3 strategies for selecting control locations for a global RTC: 1) use existing sluice gates or pumping stations; 2) select control locations based on upstream and downstream flow capacity; 3) select control locations based on in-sewer storage potential. Leitão et al. (2017) proposed a method for FCD location selection based on five different reward functions, aimed to maximise the in-sewer storage potential and/or minimise the potential negative impact of a flow control device failure.

Overall, current approaches for RTC design consist of a trial-and-error process in which potential control locations are ranked (usually based on their upstream in-pipe volume potential) and subsequently evaluated through hydraulic simulations. Assessing placement strategies manually is a complex and time-consuming process due to the high number of possible configurations (number and location of FCDs), especially in large and complex UDS. This could potentially lead to sub-optimal placement strategies, diminishing the benefits of the RTC. A more refined performance assessment of placement schemes through hydraulic analysis could be used to determine the optimal trade-off between the number/position of FCDs and operational benefits of the RTC, the number of FCDs required to fulfil specific operational targets, and whether the locations of earlier placed FCDs should be adjusted to maintain an optimal spatial layout once additional resources are available for additional flow controllers. Moreover, a more refined assessment of the hydraulic interactions occurring between the flow controllers could deliver a better understanding of the benefits and limitations of RTC systems comprising of several FCDs.

2.1.3 RTC combined with SuDS

SuDS (Sustainable Drainage Systems), also known as LIDs (Low Impact Developments) or BMPs (Best Management Practices), are distributed source controls implemented to manage runoff volumes within urban catchments (Fletcher et al., 2015). These systems aim to enhance natural processes such as infiltration, percolation, evaporation, and attenuation with green infrastructures and may include green roofs, bio-retention cells, permeable pavement, vegetative swales, and infiltration trenches among others (Islam et al., 2021). SuDS are also known to provide water quality, biodiversity and amenity benefits (Woods Ballard et al., 2015). These green-based solutions are commonly used as an alternative to RTC systems, or coupled with concrete-based solutions (Duan et al., 2016), to reduce/attenuate run-off volumes before they enter the sewage system. The widespread implementation and management of distributed LID-BMPs-SuDS practices can be challenging due to space availability, especially in highly urbanised areas (Zhang and Chui, 2018), and spatially varied socio-economic constraints (e.g. lack of public interest and support, private and public lands owned by different parties)

(Mandarano and Meenar, 2017; Montalto et al., 2013). The performance of SuDS for stormwater management can be maximised by optimising their spatial distribution, type, and size. However, due to the high number of possible implementation schemes, as well as a large number of constraints (e.g. physical, socio-economic) potentially involved in the selection, traditional trial-and-error approaches often deliver sub-optimal designs and optimisation-based methodologies are preferred (Zhang and Chui, 2018).

Similarly to the selection of FCD locations controlled by RTC, numerous studies have considered the optimal design and spatial distribution of SuDS in urban watersheds. This is commonly achieved by coupling hydraulic models with optimisation-based methods in a simulation-optimization framework (Arabi et al., 2006; Giacomoni and Joseph, 2017; Shen et al., 2013; Srivastava et al., 2002; Wu et al., 2019), or by coupling a geographic information systems (GIS) feasibility analysis with an optimisation model in cases where hydraulic models are not available (Muñoz et al. 2017; Muñoz et al., 2020). A comprehensive overview of spatial allocation of green-based practices for stormwater management can be found in Zhang and Chui (2018), while a bibliometric review on design optimization (allocation, type, dimensioning) and performance evaluation of SuDS in UDS can be found in Islam et al. (2021). In these simulation-optimization frameworks, placement schemes are selected comparing the performance of specific types of SuDS (Damodaram and Zechman, 2013), aggregated SuDS configurations (Mao et al., 2017) or simplified infiltration-based SuDS (Perez-Pedini et al., 2005), using single objective (Harrell and Ranjithan, 2003) or multi-objective optimisation approaches (Yang and Best, 2015).

Experimental and modelling studies reviewed by Brasil et al. (2021) demonstrate how potential benefits achieved by nature-based solutions (i.e. detention basins, bioretention cells, green roofs) can be enhanced by coupling the system with an RTC. For example, in Gaborit et al. (2013) the performance of stormwater detention basins is improved through dynamic control of regulators (i.e. outlet valves) using rainfall forecasts, while Shen et al. (2020) conducted an experimental study on the real-time control of stormwater biofilters for rainfall harvesting and reuse. Altobelli et al. (2020) found that the impact of an RTC in reducing CSO spill volumes, consisting of FCDs installed at different locations within the sewer network, can be further enhanced by coupling the control system with SuDS implemented in the catchment level. Jean et al. (2022) investigated the optimal locations of SuDS (bioretention swales, planters, flat roof disconnections) combined with different types of RTC (ruled-based, MPC) commanding FCDs at fixed locations within the sewer network, showing how higher CSO spill volume reduction can be achieved for specific RTC+SuDS configurations. The implementation of RTC combined with SuDS could offer an integrated approach to enhance the water storage capacity of urban watersheds, reducing and/or attenuating surface run-off volumes before they enter the sewage system while maximising the use of available in-pipe storage capacity within the existing sewer infrastructure. Moreover, similar or equivalent performance could potentially be achieved by different FCD-SuDS configuration schemes, offering different alternatives to fulfil operational targets, and extending the range of applications of such schemes as a flexible and decentralised solution for stormwater management problems. However, currently, there is a lack of consideration on how the relative placement and design of RTC and SuDS systems affect the performance of the UDS at the urban catchment level, and how these technologies hydraulically interact. To date, no robust and efficient methodology to optimise implementation strategies for RTC combined with SuDS systems, or design such decentralised systems to achieve a given level of performance, can be found in the literature. Furthermore, most existing spatial optimization studies focus on single case study catchments, with little consideration of how the type and nature of the catchment influence the effectiveness of the solution. Current challenges include the time-consuming nature of optimisation in large UDS and the need to accurately simulate the hydraulics within the UDS to fully capture the interaction between different systems (e.g. green infrastructure plus FCDs).

2.2 Optimisation of RTC in urban drainage systems

A common approach in UDS optimisation problems is to combine an optimisation algorithm, to test different alternatives and search the near-optimal solutions, with a simulation model, to describe hydrologic and hydraulic processes within the catchment. A review on optimisation techniques in stormwater management problems can be found in Shishegar, Duchesne and Pelletier (2018). Optimisation methods applied to engineering problems can be divided in deterministic and heuristic approaches (Lin, Tsai and Yu, 2012). Deterministic methods generate sequences of points that converge to the global optimal solution, where the convergence is guaranteed by theoretical assumptions and analytical properties of the problem (e.g. linear programming, quadratic programming, and nonlinear programming). Optimisation of UDS is typically a nonconvex nonlinear problem, where the hydraulic behaviour of the system (e.g. levels, flows) is represented in simulation models by nonlinear equations (Saint-Venant equations). For this class of optimisation problems, deterministic methods may not be easy to derive an optimal solution and other methods are generally preferred. There is a small body of literature regarding the application of classic optimisation techniques (e.g. linear programming) to stormwater management problems (Limbrunner et al., 2013). A review of deterministic methods applied to engineering problems can be found in Lin, Tsai and Yu (2012). The study concludes that, for solving nonconvex or large-scale optimisation problems, heuristic approaches are more flexible and efficient than deterministic approaches. Heuristic methods can handle large space of candidate solutions with few or no assumptions in the objective function and are based on trial-and-error processes.

As highlighted by Maier et al. (2015), in water resource problems little understanding has been made to determine why an optimisation algorithm performs better with certain case studies than others, with no consistency in the algorithm implementation, performance criteria and case studies. Moreover, the choice of solution methodology usually relies on the type of problem (e.g. linear/non-linear, convex/nonconvex), level of expertise and familiarity with the optimisation algorithm, with little evidence why a methodology has been selected over another (Mala-Jetmarova, Sultanova and Savic, 2017). This limits the development of general guidelines for the application of such algorithms in the wider research field, with a large number of papers relying on theoretical or simplistic case studies. In the following paragraphs, three popular heuristic optimisation algorithms applied to water and wastewater management problems are briefly discussed: simulated annealing, particle swarm optimisation and genetic algorithms (GAs).

Simulated annealing (SA) simulates the controlled annealing of a cooling metal, where the temperature is slowly decreased and the system energy minimized. The energy of a system in thermal equilibrium E is controlled by the temperature T according to the Boltzmann probability distribution: $P(E) = e^{\frac{-E}{kT}}$, where k is the Boltzmann's constant. The SA method is an iterative process in which a new point (solution) is randomly generated at each generation, with the distance between consecutive points function of the temperature. The algorithm allows large gaps in the search space during the initial cycles (high temperature), while gaps become more limited with lower temperatures. Temperature is gradually decreased until convergence conditions are satisfied. Several examples of SA applications in water and wastewater management are found in the literature. In Cunha et al. (2016), a novel SA algorithm is proposed to size and locate storage units for flooding mitigation within sewer networks. In Zeferino, Antunes and Cunha (2009) a SA algorithm is applied to determine the minimum-cost configuration for regional wastewater system planning, where SA parameters are calibrated using a particle swarm algorithm. Sebti et al. (2016) applies three optimisation methods, linear programming, GA and simulated annealing, to optimize the implementation of best management practices (e.g. retention ponds, infiltration trenches, and roofs) in a combined sewer system. In the latter study, linear programming, while providing a lower total intervention capital cost compared to GA and SA, is found to be limited by the linear equations used by the rational hydrograph method to estimate peak flow in sewer pipes.

Particle Swarm Optimisation (PSO) is a population-based evolutionary algorithm that replicates the behaviour of living colonies, such as insects or birds. At the beginning of a PSO simulation, a set of particles are generated at random points in the design space. Each particle, characterized by a certain position and velocity, moves in the design space and communicates the path followed in the simulation to the other particles. Position and velocity of each particle are adjusted following the general direction of convergence. PSO is based on the following criteria:

- When a particle locates minimum/maximum in the objective function, transmit information to other particles.
- Each particle minimises/maximises the objective function by following different paths.
- Each particle path is a combination of individual paths and the general direction of convergence.

While PSO and GAs are both evolutionary algorithms, PSO does not generate new solutions through genetic operators such as crossover and mutation, but instead converges to minimum updating velocity and memory of the best solution reached by each particle during the simulation. While in the last decades, hundreds of papers have reported successful implementation of PSO in water resources (Cyriac and Rastogi, 2013), other heuristic methods such as genetic algorithms are usually preferred for optimisation problems in UDS (Nicklow et al., 2010).

Genetic algorithms (GAs) are one of the most popular and successful optimisation methods in urban drainage and sewer system applications (Nicklow et al., 2010). GAs is a class of evolutionary algorithms particularly adapted to solve nonlinear, nonconvex, and discrete problems since it does not require continuity assumption of the objective function and can handle linear and nonlinear constraints. GAs replicate the process of natural selection, where the fittest candidates are identified amongst populations of potential candidates through the mechanisms of reproduction, mutation and recombination. The generalized framework of a genetic algorithm is shown in Figure 2.9. The main features of GAs are (Rao, 2009):

- Population of solutions are used as starting points, instead of a single design point.
- The search procedure requires only the value of the objective function, and not derivatives.
- Variables are represented as binary strings, replicating chromosomes in natural genetics.
- In each new generation performed by GA, new sets of binary strings are produced from the old generation through randomized selection and crossover.

Examples of GA-based approaches applied to UDS problems include optimisation of water quality and water treatment costs in a river basin (Cho et al., 2004), allocation of best management practices (Arabi et al., 2006; Perez-Pedini et al., 2005), positioning and sizing of detention tanks in UDS (Cimorelli et al., 2015) and stormwater detention systems in watersheds (Yeh and Labadie, 1997). Vezzaro and Grum (2014) utilise a GA to minimize the cost function of an RTC implemented within a UDS, while Rauch and Harremoës (1999) combine a GA with a model-predictive RTC to minimize pollution from an urban wastewater network.

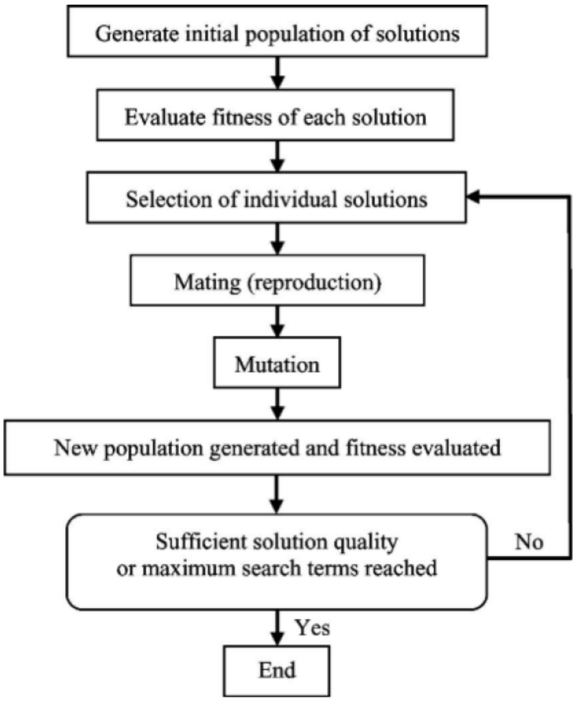


Figure 2.9: generalized framework of a genetic algorithm (Nicklow et al., 2010).

GAs are usually combined with urban drainage models, to reproduce the real behaviour of the RTC during rainfall events and provide a hydrological-hydraulic description of the watershed. They are generally composed of a hydrology model (drainage basin characteristics) coupled with a hydraulic model (characteristics of network). Urban drainage models can be used to compare different RTC control strategies, investigate the impacts of the controlled elements on the hydraulics of the network, and perform simulations of short-term as well as long-term operational scenarios (EPA, 2006) (Figure 2.10). Several commercial software packages such as MIKE, SewerCAD, MicroDrainage, and Infoworks ICM (commonly used in the UK industrial water sector) can be used for performance analysis of RTC systems in urban catchments. However, these software programs are considered “closed packages” since they do not allow the modification of the source code, offering limited customisation of RTC designs and control strategies with third-party add-ons developed for research purposes (Riaño-Briceño et al., 2016).

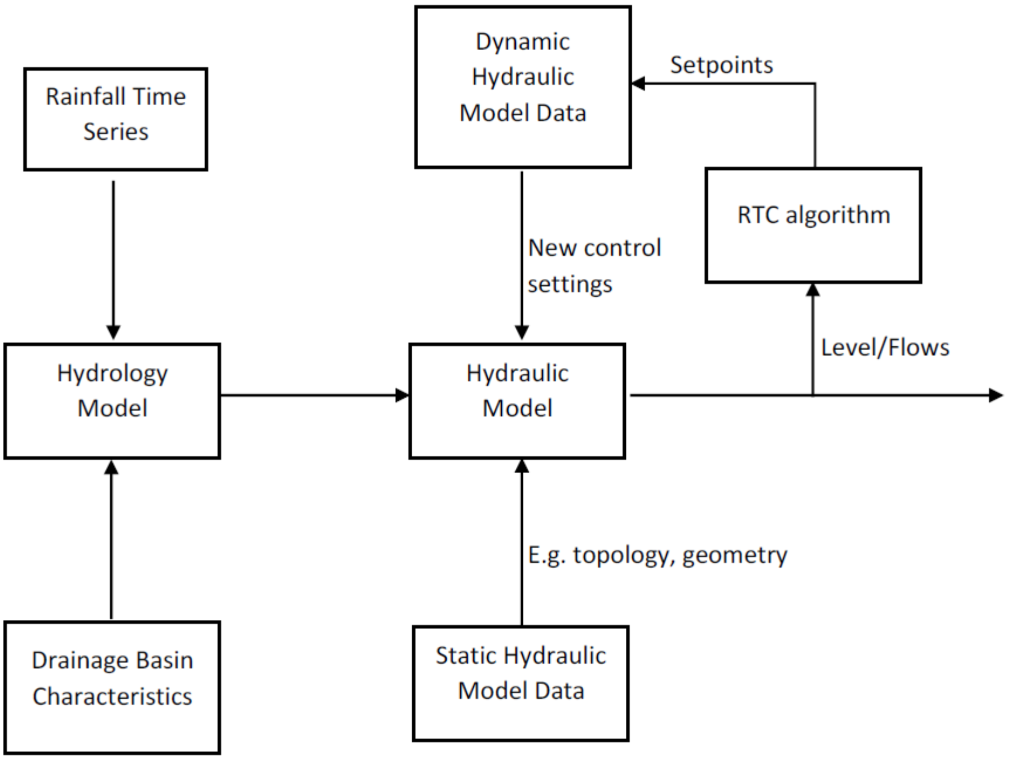


Figure 2.10: off-line simulation of an RTC system within urban drainage model, based on EPA (2006).

Storm Water Management Model (SWMM) is instead a free and open-source package developed by the U.S. Environmental Protection Agency (Rossman, 2015). SWMM is a distributed and discrete-time model for hydrologic, hydraulic and water quality simulations, where state variables (e.g. water level, flow) within a UDS are computed over a sequence of time steps. The software is designed to simulate hydrologic processes (e.g. rainfall interception, infiltration and percolation) and hydraulic routing within the catchment (Figure 2.11). The catchment area is divided into a series of homogeneous sub-catchments to consider the spatial variability of the hydrologic processes within the water drainage area, collecting the precipitation and generating runoff and pollutant loads. Hydraulic routing of external inflows and runoff volumes is performed by a network of pipes, channels, storage units, orifices, weirs, and other diversion structures. SWMM is widely used in wastewater and stormwater management research studies, including design and sizing of flood control devices, design of detention facilities, flood plain mapping, and reduction of CSO spills among others (Rossman, 2015). Examples of optimization techniques for stormwater management developed using SWMM as the hydraulic model can be found in (Baek et al., 2015; Cunha et al., 2016; Duan et al., 2016; Eckart et al., 2018; Karamouz and Nazif, 2013; Newton et al., 2014; Oraei Zare et al., 2012; Tao et al., 2014; Wang et al., 2017).

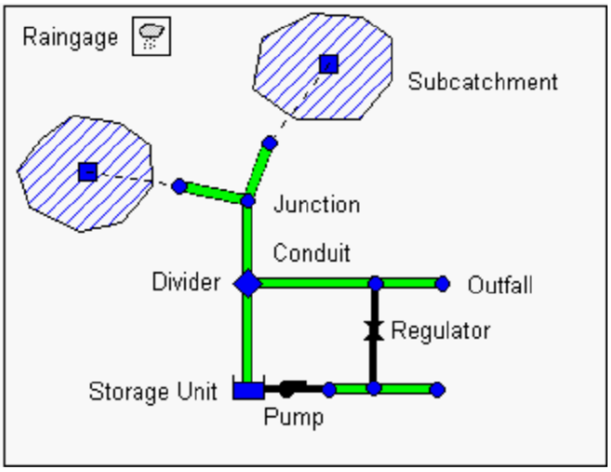


Figure 2.11: SWMM conceptual model (Rossman, 2015).

In SWMM, the RTC default functionalities can be modified or extended thanks to the open-source nature of the software. The software package thus allows an FCD to be operated by the CENTAUR fuzzy logic control algorithm (see Section 2.1.1), with a methodology described by Shepherd et al. (2016). Therefore, an optimisation-based solver such as GA could potentially be combined with an SWMM model to identify the optimal deployment strategy for multiple FCDs controlled by CENTAUR, maximising the performance of the local RTC for overflow spill mitigation. However, there are still significant research challenges and questions involved with the design of an optimisation-simulation framework for FCD location selection. The simulation runtime required by drainage models to run hydraulic analysis is by far the most time-consuming element (Butler et al., 2018), potentially limiting the capability of the framework in identifying optimal FCD placement schemes in a reasonable timeframe. As such, it could be unsuitable for larger UDS, multiple CSOs, adaptation studies/scenario analysis and many more potential FCD configurations.

3 Research questions and main objectives

Based on the literature review and knowledge gaps identified in Chapter 2, the key research questions to be tackled by this dissertation are:

1. Can a local RTC be implemented as a multi-gate system with decentralised control, as a valid alternative to more complex global RTC to manage CSO spills?

2. To what extent should the analysis of the hydraulic interaction between multiple FCDs be part of the decision-making process when designing placement schemes?

3. Can the optimal locations for FCDs controlled by local RTC be determined in a reasonable timeframe using standard computational resources, using an optimisation-simulation framework and/or general rules or indicators?

4. How can the optimal trade-off between the number and position of FCDs and the operational benefits of the system be determined when reducing CSO spill volumes within UDS?

5. How do the catchment characteristics influence the optimal spatial allocation of FCDs?

6. When combining multiple FCDs controlled by local RTC with SuDS implemented in the catchment level, how does the relative placement and design of the two systems affect the performance of the UDS, and how do these technologies hydraulically interact?

To summarise, the main objectives of the proposed research are:

1. Develop a novel optimisation-simulation framework to determine the optimal spatial allocation of multiple FCDs controlled by local RTC for CSO spill volume reduction, evaluating the system performance through hydraulic analysis (Chapter 4). The framework will be tested on a case study network, comparing a high number of possible FCD location arrangements, and evaluating the RTC effectiveness in reducing CSO spills over a range of design storm events. Objective 1 will address research questions 1, 2, 3 and 4.

2. Further develop the framework to design FCD placement schemes in larger UDS mitigating sewer overflow spills discharged at single as well as multiple CSOs, and compare results obtained by the optimisation-based method with existing volume-based approaches for FCD placement solely based on static storage volume potential (Chapter 5). Objective 2 will address research questions 1, 2, 3, 4 and 5.

3. Further develop the framework to optimise the spatial allocation of FCDs combined with infiltration-based SuDS implemented in the sewage and catchment level respectively, for CSO spill volume reduction within UDS (Chapter 6). Objective 3 will address research questions 5 and 6.

4 Hydraulic optimisation of multiple flow control locations for the design of local real time control systems

In this chapter, a novel optimisation-simulation framework is developed to determine the optimal spatial allocation of multiple FCDs controlled by local RTC, for overflow spill volume reduction within urban drainage systems. The chapter is based on the following publication: Eulogi, M., Ostojin, S., Skipworth, P., Shucksmith, J.D., Schellart, A., 2021. Hydraulic optimisation of multiple flow control locations for the design of local real time control systems. Urban Water J. 18, 91–100. https://doi.org/10.1080/1573062x.2020.1860238

4.1 Abstract

Local real-time control (RTC) represents a potentially cost-effective solution for stormwater management in urban drainage systems. Existing methodologies to select the location of flow control devices (FCDs) are limited to single gate systems and are based on analysis of activated storage volume capacity, without considering hydrodynamic processes or rainfall characteristics. In this paper, a new genetic algorithm (GA) based methodology is developed to determine the optimal location of multiple FCDs in urban drainage networks, when assessing RTC performance through hydraulic analysis. The methodology is tested on a case study network, where a high number of possible FCD location arrangements are tested and compared, and the RTC effectiveness in reducing combined sewer overflows has been evaluated over a range of design storm events. Results demonstrate the capability of the proposed method in selecting robust FCD placement strategies, for example when designing local RTC systems to meet specific performance criteria.

4.2 Introduction

Urbanisation, rapid population growth and more intense rainfall events are placing urban drainage systems (UDS) under significant operational pressure (Berggren et al., 2012; Butler et al., 2007; Miller and Hutchins, 2017; Todeschini, 2012). RTC systems in drainage networks are designed to operate and manage existing assets by monitoring the state of the system and regulating flow conditions in real time. They are usually implemented to mitigate urban flooding, regulate flows to wastewater treatment plants, reduce pollution for receiving water bodies while minimizing capital and operational investments (Schütze et al., 2008). RTC systems are considered alternatives to construction-focused solutions (Dirckx et al., 2011), since their operational objectives are reached through dynamic control of operations mostly within the existing system. RTC systems can be classified either as local control systems or system-wide control systems, based on their complexity level and control scope (EPA, 2006; García et al., 2015; Schütze et al., 2003).

In local control systems, the control strategy usually relies on a limited number of actuators, and the operation is managed by direct measurement (e.g. level, flow) collected within the area affected by the RTC system. In system-wide control systems, the operational objectives are reached using a global control strategy and asset control may rely on data collected in other locations within the drainage network, often in conjunction with hydrodynamic models and optimisation techniques. Local control has the advantage of lesser effort and expense for data transfer than a complex RTC system (Schütze et al., 2003), making such a solution more economically viable for smaller UDS. Moreover, the operation of local RTC does not depend on the communication with other UDS assets and facilities, central RTC servers, or on-line models (EPA, 2006), enhancing the resilience to failure of the system.

Despite being an affordable and low-cost solution for stormwater management problems, there is a lack of research on strategy and implementation of decentralized and local RTC (Carbone et al., 2014; Garofalo et al., 2016) compared to studies of global control systems (Dirckx et al., 2011; Fuchs and Beeneken, 2005; Grum et al., 2011; Kroll et al., 2018; Lund et al., 2018; Meneses et al., 2018; Seggelke et al., 2013). CENTAUR is a local RTC system that utilizes the existing in-sewer capacity to control stormwater volumes in sewer networks (Mounce et al., 2020; Ostojin et al., 2017). CENTAUR commands FCDs inserted into existing infrastructure (i.e. gates installed in manholes), which consists of a movable sluice gate coupled with an emergency overflow weir. Sluice gate operation is based on an autonomous Fuzzy Logic-based control algorithm, and monitoring of water levels close to the FCD installation location. This technology has been developed to provide a local, low cost and easy to deploy solution for stormwater management, with potential benefits equivalent to capital intensive solutions (Shepherd et al., 2016). Whilst design and implementation of a single FCD operated by CENTAUR has been investigated in previous research (Abdel-Aal et al., 2016; Leitão et al., 2017; Sá Marques et al., 2018; Shepherd et al., 2017, 2016; Simões et al., 2018), there are still significant research challenges and questions involved with the optimal positioning and interaction of multiple FCDs within a UDS. Selection of optimal control locations for urban flooding and CSO spills reduction is considered an essential step in designing RTC systems in sewer networks (Campisano et al., 2000; Leitão et al., 2017; Philippon et al., 2015), and constitutes an ongoing research topic (Kroll et al., 2018; Muñoz et al., 2019). While a single FCD controlled by CENTAUR has been implemented as a pilot test in a sewer network (Sá Marques et al., 2018), multiple flow controllers will likely be needed in future implementations to meet required performance objectives (e.g. defined reductions in flood or CSO spill frequency).

Assessing optimal combinations of several FCD locations manually is a complex and time-consuming process, due to the high number of possible configurations (number and location of FCDs), hydraulic interactions between RTC assets, and spatial and temporal variation of rainfall and runoff volumes within the drainage system. One methodology to rapidly assess FCDs placement is to consider the in-sewer volume mobilised by the actuator in the existing pipe network (Campisano et al., 2000; Dirckx et al., 2011; Kroll et al., 2018; Philippon et al., 2015). Leitão et al. (2017) proposed a method to identify locations to install FCDs based on the in-pipe volume activated by the actuator, without the need for hydraulic simulations, by approximating the flow using a steady-state assumption. Their case study results showed that manholes with good storage potential can be located close together, however, under steady-state assumptions it is not possible to evaluate how such actuators hydraulically interact, and thus the effectiveness of using installation locations that utilise the same storage volume. When considering optimum combinations of FCDs within the local control RTC system, Kroll et al. (2018) discarded all potential locations directly upstream/within the steady-state energy line of another FCD location. Therefore, to better understand the benefits and limitations of local RTC systems comprising of several flow control locations, a robust assessment of the hydraulic interaction of different combinations of several FCDs would be beneficial.

A common approach in UDS optimisation problems is to combine a simulation model, to describe hydrologic and hydraulic processes within the catchment, with an optimisation algorithm, to test different alternatives and search the near-optimal solutions. Optimisation in stormwater management problems is typically a nonlinear and nonconvex problem (Shishegar et al., 2018), and a limited number of applications of classic optimisation techniques (e.g. linear programming, dynamic programming) can be found in the literature (Limbrunner et al., 2013a). For solving nonconvex or large-scale optimisation problems, heuristic approaches are considered more flexible and efficient than deterministic approaches (Lin et al., 2012). Genetic Algorithms (GAs) are a popular and well-established heuristic optimisation method, capable to solve both constrained and unconstrained problems with discontinuous and non-differentiable objective functions (Kokash, 2005). A literature review of the state-of-the-art of

GAs in water resources planning and management can be found in Nicklow et al. (2010) within which evolutionary algorithms (EAs), and GAs in particular, are found to be the most popular and successful optimisation method in urban drainage and sewer system applications. Examples include: optimisation of water quality and water treatment costs in a river basin (Cho et al., 2004), allocation of best management practices (Arabi et al., 2006; Perez-Pedini et al., 2005), positioning and sizing of detention tanks in UDS (Cimorelli et al., 2015) and stormwater detention systems in watersheds (Yeh and Labadie, 1997). Vezzaro and Grum (2014) utilized a GA to minimize the cost function of an RTC implemented in an urban drainage system, while Rauch and Harremoës (1999) combined a GA with a model-predictive control system to minimize pollution from an urban wastewater network.

In such optimisation-based methods, the simulation runtime required by drainage models to run hydraulic analysis is by far the most time-consuming element, and can limit the ability of a GA to find near-optimal solutions in a feasible time frame (Butler et al., 2018). Wang et al. (2019) proposed an alternative approach when assessing a large number of potential solutions, resulting in a significant reduction of computational time compared to optimisation methods. In the framework outlined by Wang et al. (2019), the best combination and placement of sustainable drainage systems (SuDS) devices in UDS are determined by random sampling of potential candidate locations. This approach can be potentially used to determine the best combination and location of FCDs within sewer networks and offers an alternative approach if computational time limits the implementation of optimisation algorithms. However, the efficiency and reliability of this method have not been directly tested against more conventional optimisation methods.

The main aim and novelty of this study is therefore to test a GA optimisation as well as a random sampling method, in combination with full hydrologic and hydraulic urban drainage network simulations, to find optimum combinations of FCD locations within a UDS. As far as the authors are aware, to date no existing methodologies to robustly optimise the deployment strategy for multiple FCD placement within a local RTC approach are to be found in the literature. A case study in the sewer network of Coimbra (Portugal) where locations of between 1 and 10 FCDs operated by the CENTAUR system were optimised. The single objective function to assess the different combinations of FCD locations in the case study is CSO spill volume reduction, and the procedure is repeated for different design storm events. Performance and computational demand of GA solutions are also compared to those found using the random sampling method proposed by Wang et al. (2019).

4.3 Methodology

4.3.1 Case study network

The sewer network selected for this study is a subcatchment of the *Zona Central Catchment* (Coimbra, Portugal). It consists mostly of a combined sewer system, with a catchment area of 0.89 km^2. The sewer network is simulated using an EPA Storm Water Management Model (SWMM) (Rossman 2015), and comprises 434 subcatchments, 536 manholes, 538 conduits and a single combined sewer overflow. Pipe diameters vary between 0.2m and 1.7m, and pipe slopes vary between -0.51m/m and 2.26m/m with 90% of the pipes between -0.08 m/m and 0.22 m/m. SWMM is a dynamic rainfall-runoff and network hydraulics simulation model widely used in sewerage and stormwater management studies. Surface run-off routing is calculated by a nonlinear reservoir model, in which precipitation excess is converted into overland flow. The unsteady and non-uniform flow within the drainage system is computed solving the Saint-Venant equations (conservation of mass and momentum equations) via the dynamic wave approach (Rossman, 2006). Several examples of optimisation problems in UDS performed with SWMM models can be found in the literature. They include flood mitigation (Newton et al., 2014), CSO spill volume reduction (Kroll et al., 2018), detention tanks (Cunha et al., 2016; Duan et al., 2016; Tao et al., 2014; Wang et al., 2017), low impact development (LID) practices (Baek et al., 2015; Eckart et al., 2018), best management practices (Karamouz and Nazif, 2013; Oraei Zare et al., 2012) and water quality (Fu et al., 2008).

SWMM default functionalities (e.g. data analysis, RTC modelling) can be modified or extended by third party add-ons, thanks to the open-source nature of the software. In this work SWMM simulations are carried out by the interface *MatSWMM* (Riaño-Briceño et al., 2016) in the Matlab environment. MatSWMM is an open-source Matlab, Python, and LabVIEW-based software package. It can be used for designing and testing RTC systems in urban drainage networks, and allows a flow control device to be operated by the CENTAUR control algorithm. Shepherd et al. (2016) describes the methodology used to link a SWMM sewer network model with a Fuzzy Logic control algorithm through the MatSWMM interface in Matlab.

4.3.2 Identifying FCD locations

Flow control devices are designed as actuators comprised of a controlled sluice gate coupled with an overflow weir, and can be installed in pre-existing manholes within an UDS. In this study, the emergency overflow weir is designed to prevent flooding upstream of the FCD location during a 50-year return period storm, when the sluice gate is fully or partially closed. It also guarantees safety in case of failure of the system. More details of the system are described by Mounce et al. (2020). The FCD operation is autonomous and locally handled by the CENTAUR control algorithm, measuring water level in the CSO chamber and immediately upstream of the FCD location. Sluice gates can work independently but hydraulically interact within the sewer network. FCD dimensions and properties are adapted for each location (manhole) and automatically added to the SWMM sewer network model by a Matlab tool developed for the current study. FCDs have a sluice gate diameter set equal to the downstream pipe diameter, to avoid restrictions in cross-section. The sluice gate opening degree ranges between 0 (fully close) and 1 (fully open). The emergency overflow overtop weir is modelled as a rectangular opening at the top of the FCD.

A Matlab programme converts the sewer network model into tabular form. The network is thus represented as a collection of nodes (i.e. manholes) connected by links (i.e. pipes), and the potential FCD locations are determined by applying constraints to each node of the network. A manhole is considered a potential location for installation of the FCD if located upstream of the target location (CSO chamber), with one upstream entering pipe and one downstream exiting pipe. In the case study catchment, a total of 389 potential FCD locations are identified.

4.3.3 In-sewer storage capacity

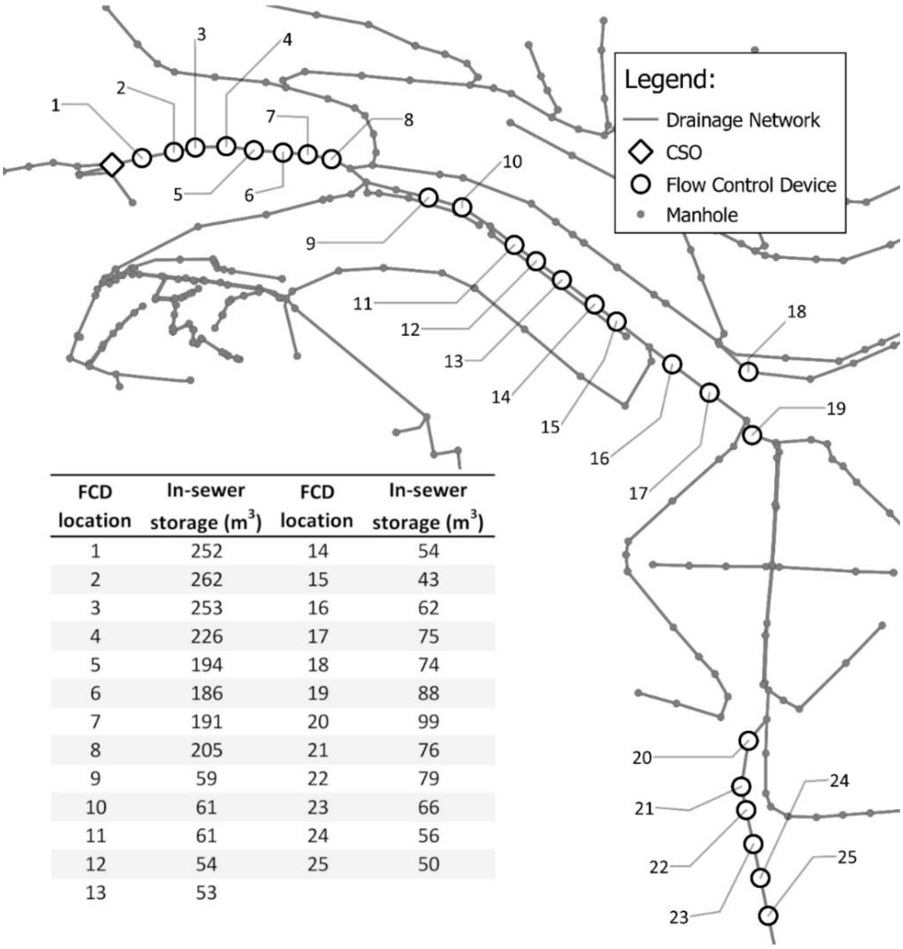
To reduce the computational run time of optimisation, potential FCD locations are initially screened based on the assessment of available storage capacity. The in-sewer storage capacity activated by an FCD corresponds to the maximum stormwater volume that can be stored upstream of the actuator. Calculations are carried out for the 389 potential locations previously identified, with a procedure based on Leitão et al. (2017). The in-sewer storage capacity mobilised by an FCD is approximated to the pipe volume upstream of the actuator location, under a reference level RL (m A.D.):

$$RL = GL - \Delta \tag{1}$$

where GL is the ground level elevation at the FCD location (m A.D.) and Δ is a safety margin (set equal to 0.1 m). Reference level RL matches the maximum static water level of the stormwater stored upstream to the FCD.

The computation starts at the FCD location, advances upstream identifying links connecting the nodes, and continues until the node invert is higher than reference level RL, or the node has no upstream links. If upstream bifurcations are identified, the computation is carried out along each bifurcation branch until one of the previous conditions occurs, as suggested by Kroll et al. (2018). A control location is excluded if the computation identifies nodes connected to pumps.

The analysis shows that the 389 potential control locations previously identified have static storage capacities ranging from 0.1m^3 to 262m^3. A total of 8 locations present storage volume between 186 and 262m^3 (all located along the same sewer branch immediately upstream to the CSO chamber), while 17 locations show in-sewer storage volume between 50 and 100m^3. Potential FCD locations which mobilise less than 50m^3 are judged highly unlikely to be optimal locations for FCDs and are hence removed from subsequent analysis. The number of control locations considered is thus reduced to 25 (see Figure 4.1).



FCD location	In-sewer storage (m^3)	FCD location	In-sewer storage (m^3)
1	252	14	54
2	262	15	43
3	253	16	62
4	226	17	75
5	194	18	74
6	186	19	88
7	191	20	99
8	205	21	76
9	59	22	79
10	61	23	66
11	61	24	56
12	54	25	50
13	53		

Figure 4.1: In-sewer storage capacity at potential control locations.

4.3.4 Genetic Algorithm for optimising FCD placement schemes

In this study, a GA is used to minimize spill volumes discharged in the receiving water body during synthetic storm events based on different FCDs placement schemes. Spill volume reduction performed by FCDs is evaluated by linking the hydraulic analysis, carried out using SWMM, with a Matlab GA. The number of variables optimized by the GA is equal to the number of potential FCD locations considered within the sewer network. The implementation of a FCD in a given potential location (i.e. manhole) is represented by a binary 0/1 integer variable (0 = actuator not implemented, 1 = actuator implemented). A GA solution is therefore a sequence of 0/1 integer values, and corresponds to a unique set of control locations within the network. Each FCD placement scheme is thus represented by the one-dimensional binary array: $[x_1, x_2, \dots, x_i, \dots, x_N]$, where x_i represents the implementation of a FCD at the i-th potential location within the sewer network (0/1 integer variable), and N the total number of potential FCD locations considered. The GA solver is implemented using the Global Optimization Toolbox available in Matlab 2018a (Matlab, 2018) to solve the mixed-integer constrained optimization problem. GA options are shown in Table 4.1. The population size is set equal to 100 per GA generation, and the actual number of FCDs implemented in each hydraulic simulation is forced by the linear equality constraint $\sum_{i=1}^{N} x_i =$ number of FCDs implemented. Examples of 0/1 programming in GA, successfully implemented in stormwater and watershed management problems, can be found in Arabi et al. (2006), Damodaram and Zechman (2013), Limbrunner et al. (2013b), Perez-Pedini et al. (2005), Shen et al. (2013) and Srivastava et al. (2002).

Table 4.1: Genetic algorithm parameter settings.

PopulationType	doubleVector
EliteCount	0.05*PopulationSize
FitnessScalingFcn	@fitscalingrank
MaxStallTime	Inf
NonlinearConstraintAlgorithm	‘auglang’
SelectionFcn	@selectionstochunif
CreationFcn	@gacreationuniform
CrossoverFcn	@crossoverscattered
CrossoverFraction	0.9
MaxGenerations	100
MaxStallGenerations	20
MaxTime	Inf

Optimisation is carried out for different design storm events and a given number of installed FCDs. Three synthetic design storms obtained by the alternating block method (Chow et al., 1988) are selected to assess the capability of the local RTC system to minimize spill volumes. Storms are based on Portuguese IDF curves (RGSPPDADAR, 1995), with return period equal to 1 year and duration of 15, 30 and 60 minutes respectively (time of aggregation 5 minutes). SWMM’s hydraulic computations are solved using the dynamic wave routing model, accounting for backwater effects, flow reversal and pressurised flow generated by flow controllers within the sewer network (routing step set to 15 s, minimum variable time step set to 0.5 s). For each FCD implemented in the sewer network model, the opening degree is computed at a predefined time-step of 30 seconds to properly capture the fast runoff processes and quick response time of the small urban catchment. After preliminary analysis of in-sewer storage capacity within sewer network, design events longer than 60-minute duration generate runoff volumes considerably higher than the overall in-sewer capacity mobilised by any combination of the 25 potential FCD locations previously selected (Figure 4.1). For storms with longer duration, as well as larger return period events, additional storage volume would need to be constructed for a local RTC system of this type to be effective. Time of concentration is calculated using synthetic storms with constant rainfall intensities (RGSPPDADAR, 1995); it corresponds to the time interval between beginning of the rainfall event, and moment of constant discharge at the most downstream outlet within the network. The resulting time of concentration of the sewer network is approximated to 15 minutes for the 15-minutes storm, and 25 minutes for the 60-minutes storm. Spill volume reduction achieved by the local RTC system is quantified by comparing modelled stormwater volume discharged at CSO in the original network with no intervention (Table 4.2), with the stormwater volume discharged at the same location with FCDs implemented within the network. Placement of FCDs is optimised for the number of installed flow controllers ranging between 1 and 10, and for each storm event examined. Due to the limited number of possible FCD placement schemes in the case study site, all possible combinations of FCD locations are tested for schemes where the number of implemented FCDs is less than 3. When the number of FCDs ranges from 3 to 10, the placement is optimised by the GA.

Table 4.2: Design storm parameters (test storm events) and resulting modelled uncontrolled spill volume.

Design Storm (1 Year Return Period)		**Spill Volume at CSO (m^3)**
Duration (min)	**Rainfall Depth (mm)**	
15	9	1632
30	12	2287
60	15	3034

4.3.5 Comparison of GA method with randomly sampled FCD placement schemes

Spill volume reductions achieved as well as computational time of GA solutions are compared with those obtained using the random sampling approach proposed by Wang et al. (2019). Random sampling of FCD placement schemes is based on degree of confidence, where every possible combination of FCD placement has the same probability of being selected. This method is used to test a large number of combinations with lower computational burden compared to the GA. For each number of FCDs tested in this study, n_r combinations of control locations are randomly generated, and the performance (spill volume reduction) calculated through hydraulic analysis. The random sample size n_r is calculated as (Brase and Brase 2012):

$$n_r = \frac{N_s * p * (1-p)}{(N_s - 1) * (\frac{CI}{Z_\alpha})^2 + p * (1-p)} \tag{2}$$

where N_s is the total number of possible FCDs placements in each sampling round, p is the success probability (0.5), CI is the confidence interval ($\pm 5\%$) and Z_α is the normal distribution value (1.960 for confidence interval 5%).

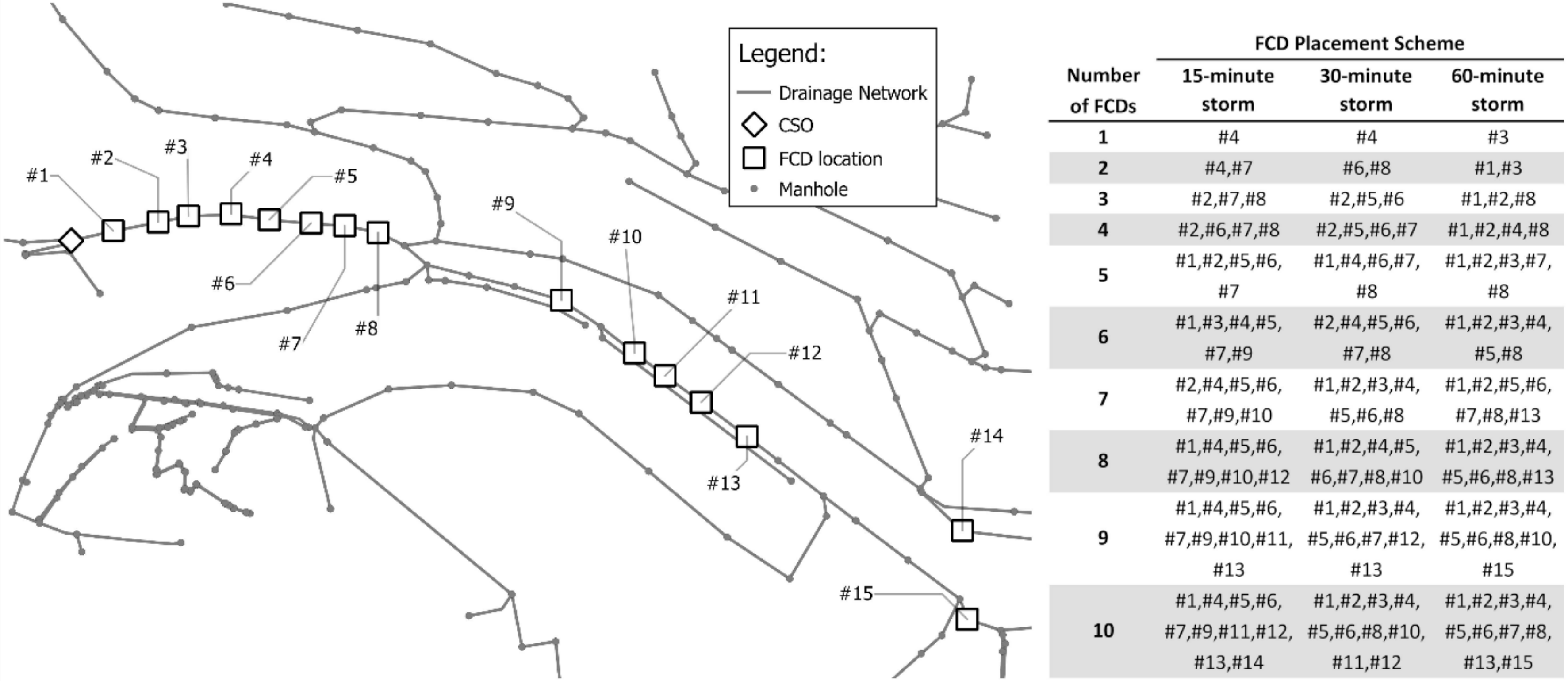
A random sampling of control locations is carried out for different numbers of flow control devices. For each number of FCDs evaluated, 384 random FCD placement schemes are generated and tested (see Equation 2). In cases where the total number of schemes is less than 384, all possible schemes are considered and tested. A total of 3397 combinations between the number and location of FCDs are thus generated and tested with this approach.

4.4 Results and discussion

4.4.1 Solutions found by GA

4.4.1.1 FCD locations within sewer network

Figure 4.2 shows the installation locations of the FCDs as determined by the GA methodology for different numbers of FCDs within the sewer network. Optimal FCD placement schemes are found to be dependent on the storm event and the number of installed flow controllers. Results show that the GA generally favours manholes located near the target location (CSO). In case of 1 to 5 FCDs, GA solutions correspond to locations along the pipe-line immediately upstream of the target location for all storms considered, where devices mobilise a larger storage capacity compared to other potential FCD locations within the network. At these locations, flow control devices are capable of reacting quickly to changes in water depth at the target location and to reduce peak flows during storm events. When additional devices are deployed, FCDs are placed along one of the upstream pipes contributing to the target location. This results in a local RTC system composed of independent FCDs implemented in series, capable of quickly reacting to changes in water level at the target location and storing stormwater in different areas within the network. Control locations from #1 to #8 are selected more often than others in the optimised FCD placement schemes, while locations from #9 to #15 are only selected when the number of FCDs is between 6 and 10. Potential FCD locations in the most upstream area of the sewer network are never selected by GA (see Figure 4.1). While control locations in this area show storage capacity comparable to locations further downstream, the distance between CSO and FCDs affects the capability of the gates to quickly reduce flow at the target location before CSO spills occur. Results on FCD locations obtained by the GA are in agreement with recommendations outlined by Sá Marques et al. (2018), based on the implementation of a single FCD controlled by CENTAUR in a sewer network. In both studies, the dynamic control of water depth achieved by a flow control device is found more efficient when the target site is located close to the FCD location, and it decreases if additional flows are conveyed by other branches that contribute to the target location.



Number of FCDs	FCD Placement Scheme 15-minute storm	30-minute storm	60-minute storm
1	#4	#4	#3
2	#4,#7	#6,#8	#1,#3
3	#2,#7,#8	#2,#5,#6	#1,#2,#8
4	#2,#6,#7,#8	#2,#5,#6,#7	#1,#2,#4,#8
5	#1,#2,#5,#6, #7	#1,#4,#6,#7, #8	#1,#2,#3,#7, #8
6	#1,#3,#4,#5, #7,#9	#2,#4,#5,#6, #7,#8	#1,#2,#3,#4, #5,#8
7	#2,#4,#5,#6, #7,#9,#10	#1,#2,#3,#4, #5,#6,#8	#1,#2,#5,#6, #7,#8,#13
8	#1,#4,#5,#6, #7,#9,#10,#12	#1,#2,#4,#5, #6,#7,#8,#10	#1,#2,#3,#4, #5,#6,#8,#13
9	#1,#4,#5,#6, #7,#9,#10,#11, #13	#1,#2,#3,#4, #5,#6,#7,#12, #13	#1,#2,#3,#4, #5,#6,#8,#10, #15
10	#1,#4,#5,#6, #7,#9,#11,#12, #13,#14	#1,#2,#3,#4, #5,#6,#8,#10, #11,#12	#1,#2,#3,#4, #5,#6,#7,#8, #13,#15

Figure 4.2: FCD locations selected by the GA within the sewer network model.

4.4.1.2 CSO spill volume reduction

Figure 4.3 shows spill volumes relative to the baseline system with no FCDs (Table 4.2), for the three design storms tested. The overall spill volume reduction is progressively increased by implementing additional FCDs. Each point in Figure 4.3 represents the performance achieved by the RTC system, for the optimised FCD placement scheme for a given storm event. While a higher number of installed flow controllers corresponds to increasing spill volume reduction, the reduction associated with the implementation of additional FCDs declines with the numbers of devices implemented. Moreover, the effectiveness of the RTC system in controlling stormwater volumes depends heavily on the storm duration. The RTC system’s impact in reducing CSO spills decreases with increasing duration (and hence storm volume) entering the UDS. The RTC system is observed to have the highest efficiency for the 15-minute storm, in which more than 90% of the original spill volume can be reduced by the use of 5 FCDs. During the 30-minute storm, the same 90% efficiency is reached when deploying 7 FCDs. In the case of the 60 minute storm duration, a spill volume reduction of 70% is obtained by the RTC system using 10 flow controllers.

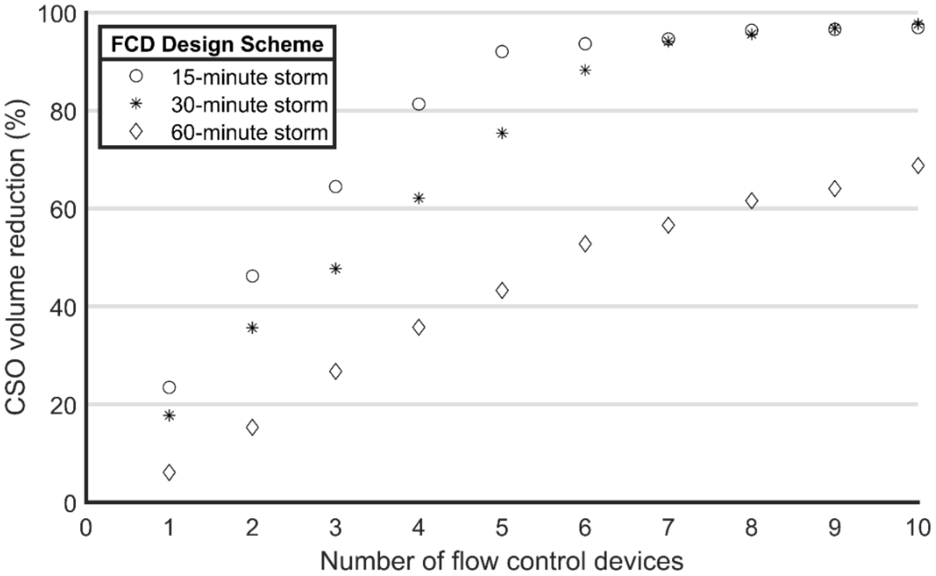


Figure 4.3: Performance of solutions found by GA, for different storm events and number of flow control devices.

Solutions found by the GA were also tested under storm durations other than those used within the original optimisation. The purpose of this is to investigate the capability of a selected set of FCD locations to control stormwater volumes for a range of rainfall events, other than which this set was originally optimised for. Each set of FCD locations was originally optimised for either only the 15-, 30- or 60-minute design event (Figure 4.2). These optimised location arrangements are then tested against all three design storms in order to assess the impact of the type of event. The resulting performance is compared in Figure 4.4, for when the number of FCDs is 1, 5 and 10. For example, the scheme optimised for the 30-minute duration storm with 5 FCD locations can reduce the original spill volume by 75%, while the scheme with 5 FCD locations that was optimised for the 60-minute or 15-minute storm results in a spill volume reduction of 70% for the 30-minute storm. As expected, the GA solution performs best for the storm duration the scheme was optimised for, although the differences are relatively small, especially when only 1 FCD is implemented. The performance during other duration events is reduced by around 3-8% if 5 FCDs are implemented, and by around 3-18% if 10 FCDs are implemented. Results show that, for a given number of FCDs, similar overflow volume reduction is achieved by different optimised FCD placement schemes, giving alternate options in the choice of definitive placement of flow controllers. The selection of definitive placement of FCDs is expected to be function of operational targets (e.g. required spill volume or spill frequency reduction), efficiency (i.e. identifying the number of FCDs above which placement of additional FCDs does not activate considerable additional spare storage capacity), and other factors not considered in this study such as installation site accessibility, initial investment and operational costs.

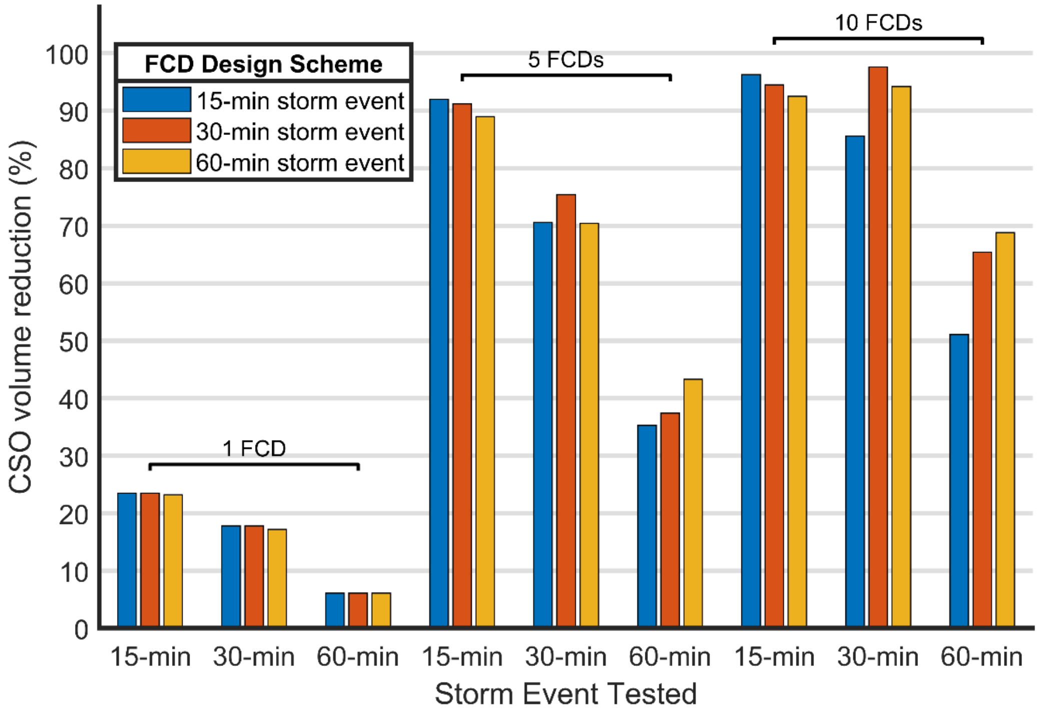


Figure 4.4: Spill volume reduction achieved by FCD schemes optimised for a given design rainfall duration (FCD Design Scheme, denoted by different colours), when tested for other storm event durations (indicated on x-axis).

4.4.2 Comparison between optimisation-based and random sampling approaches

4.4.2.1 Performance of FCD placement schemes

For each number of installed FCDs and all storm events considered, maximum spill volume reduction obtained by the GA based optimisation method is compared with performance of solutions found by the randomly sampled approach. Figure 4.5 shows the additional CSO volume reduction achieved by the GA method relative to the random sampling approach for each placement scheme. As shown in Figure 4.5, optimised FCD locations found by the GA based meth result in equal or higher spill volume reduction compared to those obtained from the randomly sampled methodology in all cases (systems limited to 1 or 2 FCDs not shown, as here all possible options were compared). FCD placement schemes found by the GA result in performance improvements between 1% and 29% compared to those found by the random sampling approach, with the largest performance improvements found for 30 & 60 minute storms with 4 to 7 FCDs placed.

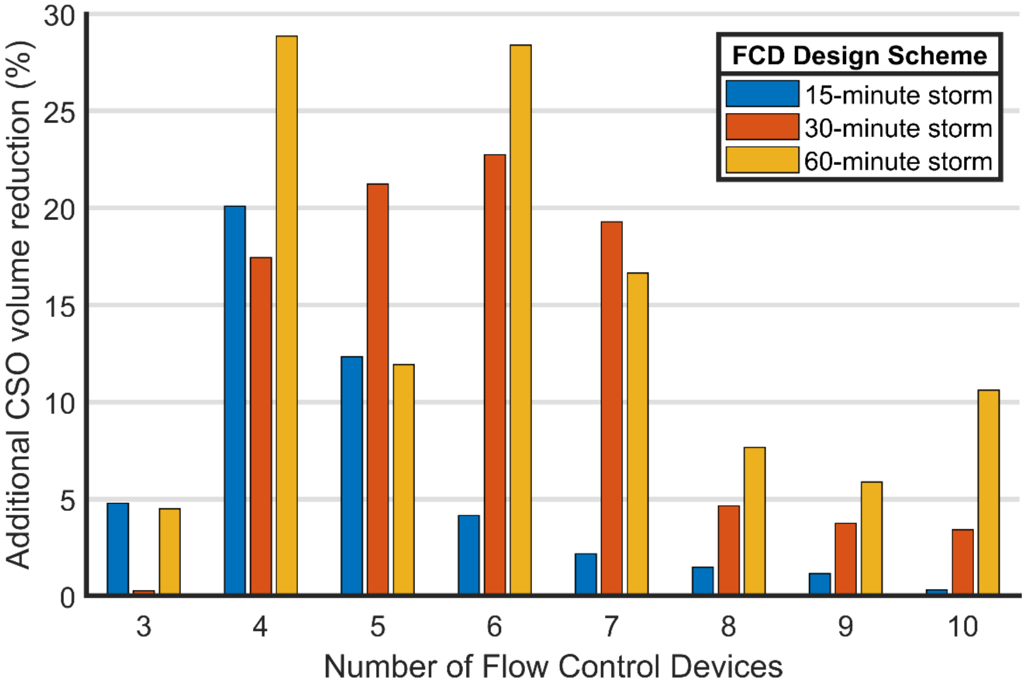


Figure 4.5: Percentage additional CSO spill volume reduction achieved by FCD placement schemes optimised using GA relative to schemes selected by random sampling method.

4.4.2.2 Computational times for hydraulic FCDs location optimisation using GA or random sampling

Hydraulic simulations of the site resulted in run times between 20 and 60 seconds depending on the number of FCDs and storm event tested, allowing the analysis of a wide range of spill volume mitigation scenarios. The GA optimisation and SWMM simulations were run in parallel on two Windows10 computers with Intel E5-2637 processor and 32GB of RAM, and one Windows10 computer with Intel i5-7200 processor and 8GB of RAM. The computational time required by the GA to identify solutions ranged between 14 hours and 3 days in each scenario considered. Hydraulic analysis of randomly sampled FCDs schemes during three storms was carried out on a single machine, with total computational time of 4 days (Windows10 computer with Intel i5-7200 processor and 8GB of RAM).

The number of candidates tested by the GA is significantly higher than the 3397 randomly sampled FCD placement schemes. With a population of 100 solutions per generation, the optimisation-based framework resulted in a total of 80,200 SWMM hydraulic simulations. Computational time is a function of the number of potential FCD locations considered, number and level of complexity of hydraulic elements within the sewer network, and the machine's computational power used to perform hydraulic analysis. If computational time might constitute a limiting factor, the number of hydraulic simulations may be reduced by limiting the number of storm events tested as in this case the optimum FCD locations showed fairly similar performance independent of the design event used during optimisation. However, this would warrant further testing for different case studies. A reduced number of potential FCD locations can significantly lower the total population of candidate solutions evaluated in the optimisation process. In this regard, a static or steady-state analysis of available in-sewer storage capacity suggested in the literature (Campisano et al., 2000; Kroll et al., 2018; Leitão et al., 2017; Philippon et al., 2015) provides an efficient methodology to discard potential FCD locations which only have a small potential storage volume.

4.5 Conclusions

A novel GA-based optimisation framework has been developed to identify optimal location of FCDs in urban drainage networks to reduce CSO spill volume based on an established local RTC system. Optimal FCD locations are obtained through hydraulic analysis rather than assessing the static storage volume potential within the network. This ensures that hydraulic interaction between FCDs and their impacts on flows and levels within the network are considered in the process.

In the case study, the flow controllers are all individually operated by the CENTAUR fuzzy logic algorithms. Results show that GA optimisation favours FCD locations close to the CSO, where flow controllers can mobilise large in-pipe volumes compared to other potential FCD locations further upstream. Moreover, the limited distance allows the devices to quickly react to changes of water level at the CSO location, and reduce the flow before the spill occurs. When selecting multiple FCD locations, the approach also favours locations quite close together, which in a location selection method based only on potential storage volume comparisons, would likely be discounted.

A better performance is achieved by the GA based optimisation compared to a simpler random sampling optimisation approach. However, the computational time required to run hydraulic simulations is found to potentially limit the number of scenarios evaluated by the GA solver. In the case of large urban drainage systems, particular attention is needed when establishing the number of potential FCD locations and storm events evaluated in the optimisation, so that optimal FCD placement schemes can be found in a reasonable timeframe. For this, a simple static volume based screening approach would be useful to discount locations with very limited storage volumes.

For the case study, optimal placement of FCDs proved robust and not overly sensitive to design storm duration used in the optimisation, although sensitivity of the location selection for the design event does increase as more FCDs are added and solutions become more bespoke. The case study results show how the local RTC system has the potential of preventing CSO spills for short and intense storms, and diminish total overflow discharged volumes during rainfall events with longer duration.

The proposed methodology can be used to select optimal installation strategies to fulfil different specific operational targets, such as spill volume or spill frequency reduction, and design flexible local RTC systems capable of controlling stormwater volumes under a wide range of storm events. It needs to be acknowledged that in practical applications, the final choice of FCD number and locations is expected to also be based on cost-benefit analysis carried out during preliminary design of the RTC system. Factors such as initial investment and operational costs, installation site accessibility, road and traffic management, might hinder or impede the installation of FCDs at locations identified as effective through hydraulic analysis. These issues could be identified prior to analysis in order to reduce the number of examined potential FCD locations and, thus, diminish the computational time required by the optimization procedure. This information, while not available in this study, may be included in future work to further enhance the applicability of the proposed methodology to other scenarios. In cases of scarce feasible installation sites, or inadequate reduction of overflow discharge volumes due to rainfall events of long duration or consecutive events, the overall performance could be increased by coupling the RTC system with other solutions to control run-off volumes, such as SuDS systems or storm tanks.

5 Comparing methods to place adaptive local RTC actuators for spill volume reduction from multiple CSOs

In this Chapter, the framework proposed in Chapter 4 is further developed to design FCD placement schemes in larger UDS, mitigating sewer overflow spills discharged at single as well as multiple CSOs. Results obtained by the optimisation-based method are also compared with existing approaches for FCD placement solely based on static storage volume potential. The chapter is based on the following publication: Eulogi, M., Ostojin, S., Skipworth, P., Kroll, S., Shucksmith, J.D., Schellart, A., 2022. Comparing methods to place adaptive local RTC actuators for spill volume reduction from multiple CSOs. J. Hydroinformatics 24, 78–92. https://doi.org/10.2166/hydro.2021.085

5.1 Abstract

The selection of flow control device (FCD) location is an essential step for designing real-time control (RTC) systems in sewer networks. In this paper, existing storage volume-based approaches for location selection are compared with hydraulic optimisation-based methods using a genetic algorithm (GA). A new site pre-screening methodology is introduced, enabling the deployment of optimisation-based techniques in large systems using standard computational resources. Methods are evaluated for CSO volume reduction using the CENTAUR autonomous local RTC system in a case study catchment, considering overflows under both design and selected historic rainfall events as well as a continuous three-year rainfall time series. Performance of the RTC system was sensitive to the placement methodology, with CSO volume reductions ranging between -6% and 100% for design and lower intensity storm events, and between 15% and 36% under continuous time series. The new methodology provides considerable improvement relative to storage-based design methods, with hydraulic

optimisation proving essential in relatively flat systems. In the case study, deploying additional FCDs did not change the optimum locations of earlier FCDs, suggesting that FCDs can be added in stages. Thus, this new method may be useful for the design of adaptive solutions to mitigate the consequences of climate change and/or urbanisation.

5.2 Introduction

Urban drainage systems (UDS) are being placed under significant operational pressure due to the effects of urbanisation and the increasing occurrence of intense rainfall events due to climate change (Berggren et al., 2012; Butler et al., 2007; Miller and Hutchins, 2017; Todeschini, 2012). Uncertainties related to the extent of future rainfall patterns as well as large investment costs associated with extending UDS to maintain or improve performance levels, call for flexible and adaptable solutions to improve the operation of existing drainage infrastructure (Gersonius et al., 2013; Guthrie, 2019).

Real Time Control (RTC) systems are designed to improve operation and management of existing urban drainage assets by monitoring the state of the system and regulating flow conditions in real time (Dirckx et al., 2011; Schütze et al., 2008). RTC systems can be classified as local control systems, or system-wide control systems, based on their complexity level and control scope (EPA, 2006; García et al., 2015; Schütze et al., 2003). In local RTC systems, the control strategy usually relies on a limited number of actuators acting independently, and the operation is managed following direct measurement (e.g. level, flow) collected within the area affected by the RTC system. Local control can have the advantage of reduced effort and expense for data transfer compared to a complex RTC system (Beeneken et al., 2013). The operation of local RTC does not depend on the communication with other UDS assets and facilities, central RTC servers, or on-line models (EPA, 2006), enhancing the resilience to failure of the system. Local RTC is an adaptable approach, as it can be modified/extended by the addition or relocation of actuators without the alteration of pre-existing RTC infrastructure or control strategies, in response to network changes or possible future changes in climate (Mollerup et al., 2017). Gersonius et al. (2013) used a case study in urban flood risk reduction to illustrate that if there is the possibility to incrementally adjust a solution considering future learning, the overall cost of climate change adaptation can be reduced.

There is a current lack of research on strategy and implementation of local RTC (Altobelli et al., 2020; Carbone et al., 2014; Garofalo et al., 2016), compared to studies of global control systems (Dirckx et al., 2011; Fuchs and Beeneken, 2005; Grum et al., 2011; Kroll et al., 2018; Lund et al., 2018; Meneses et al., 2018; Seggelke et al., 2013). CENTAUR is a local RTC system that utilizes the existing in-sewer capacity to control stormwater volumes in sewer networks (Mounce et al., 2020; Ostojin et al., 2017). CENTAUR consists of autonomous flow control devices (FCDs), inserted into existing manholes and locally handled by the CENTAUR control algorithm. The design and implementation of a single FCD operated by CENTAUR has been investigated in previous research (Abdel-Aal et al., 2016; Leitão et al., 2017; Sá Marques et al., 2018; Shepherd et al., 2017, 2016; Simões et al., 2018). Field deployment of the CENTAUR system has been tested in Coimbra (Portugal), this prototype CENTAUR system consisted of a movable flow control gate, which is regulated through a fuzzy logic algorithm informed by local flow depth monitoring system through local radio communication (Ostojin et al., 2017; Sá Marques et al., 2018). As fail-safe, the flow control gate has an emergency overflow weir. The CENTAUR system can be simulated in SWMM & MatSWMM (Riaño-Briceño et al., 2016), whereby the FCD is modelled as a circular orifice (gate diameter set equal to the downstream pipe diameter to avoid restrictions in cross-section), with a sluice gate opening degree ranging between 0 (fully closed) and 1 (fully open). The overflow weir is modelled as a rectangular opening positioned at the top of the FCD (Eulogi et al., 2021).

Selection of optimal control locations for the reduction of urban flooding and combined sewer overflow (CSO) spill is considered an essential step in designing RTC systems in sewer networks. However, this has received far less attention than the study of control strategies and algorithms (Kroll et al., 2018; Muñoz et al., 2019). Assessing optimal combinations of several FCD locations manually is a complex and time-consuming process due to the high number of possible configurations, hydraulic interactions between RTC assets, and spatial and temporal variation of rainfall and runoff volumes within the catchment. Several methodologies to rapidly assess FCDs placement locations without the need for detailed hydraulic network simulations can be found in the literature (Campisano et al., 2000; Dirckx et al., 2011; Kroll et al., 2018; Philippon et al., 2015), considering the static in-sewer volume potential mobilised by the flow controllers in the existing pipe network when placing FCDs in sewer networks. When considering the best combinations of FCD locations within the global control RTC system, Kroll et al. (2018) discarded all potential locations directly upstream/within the steady-state energy line of another FCD location. Leitão et al. (2017) identified locations based on the in-pipe volume activated by the actuator through approximating the flow using a steady-state rather than a static assumption. However, under such static or steady-state flow assumptions the hydraulic interactions between flow controllers and impacts of the RTC system in-flows and levels within the sewer network cannot be evaluated.

Eulogi et al. (2021) developed a Genetic Algorithm based method to optimise the location of flow controllers controlled by a local RTC system, which can be utilised in combination with a full hydraulic network model and therefore account for dynamic flow conditions within the design procedure. Using a case study looking at the reduction of spill volume from a single CSO under a design rainfall event, Eulogi et al. (2021) showed that optimal strategies may include designs in which FCDs partially mobilise the same storage volume, which would normally be discounted in a location selection method solely based on the potential storage volume. However, the optimisation methodology proposed by Eulogi et al. (2021) is relatively computationally demanding, due to the time required to repeatedly run drainage models in MatSWMM. As such, it is potentially unsuitable for commercial deployment for larger UDS, multiple CSOs, adaptation studies/scenario analysis and many more potential FCD configurations, limiting the capability of the optimisation-based approach in identifying optimal FCD placement schemes in a reasonable timeframe. To demonstrate the potential benefits of adaptive local RTC approaches requires regular quantification of performance and regular running of the optimisation method when more information on the future climate has become available, or when changes in the built-up environment have occurred (e.g. new housing developments).

The aims of this paper are thus to 1. Develop a GA / hydraulic modelling methodology for designing local RTC systems which is applicable to larger UDS featuring multiple CSOs using standard computational resources (Windows10 computer, Intel E5-2637 processor and 32GB of RAM). 2. Compare the approach to existing approaches for FCD placement based on static storage volume as well as the technique presented in Eulogi et al. (2021), in a case study catchment using both a standard design rainfall event and verified using independent historical rainfall events as well as long-term rainfall series, such that the relative performance of the design techniques can be directly compared.

5.3 Methodology

5.3.1 Case study network and flow control devices

The case study network selected for this study is the Arendonk sewage system, located in the River Nete basin in Flanders (Belgium). The sewer network model has been provided by the Flemish wastewater operator Aquafin. The system has a total population equivalent of 15100, total contributing area of 479 ha, and consists of 1513 nodes, 16 CSOs, and a total pipe length of 69.8 km (Kroll et al., 2018). Pipe slopes vary between -0.044 m/m and 0.88 m/m (90% between 0m/m and 0.006 m/m), while pipe diameters range between 0.11 m and 2 m. The sewer network is simulated with a calibrated EPA SWMM model (Rossman, 2015). SWMM hydraulic simulations are run in the Matlab environment using MatSWMM (Riaño-Briceño et al., 2016), an open-source interface that allows advanced design and simulation of real-time control systems in UDS. The FCD operation through the CENTAUR control algorithm is linked with the SWMM sewer network model as described by Shepherd et al. (2016). FCD opening degree is calculated by the Fuzzy Logic control algorithm through MatSWMM, based on water level in the CSO chamber and immediately upstream of the FCD location. Sluice gate opening and closing is locally handled by the CENTAUR control algorithm to prevent spills at the downstream CSO (Shepherd et al., 2016).

For each CSO controlled by the RTC within the case study network, upstream manholes are considered potential locations for FCDs if connected to one entering conduit and one exiting conduit. FCDs are modelled as a circular sluice gate coupled with an internal overflow weir, which acts as a safety measure in case of gate failure. The overflow weir prevents sewer flooding upstream of the FCD when the sluice gate is partially or fully closed. The overflow weir height is calculated using a historical rainfall event recorded in the year 2004, with a return period equal to 14 years and rainfall duration of 27 minutes.

5.3.2 Selection of optimal FCD locations

Three methods for selecting FCD locations are compared: a method exclusively based on static storage capacity (*Static Storage Method*), and two methods based on Genetic Algorithm optimisation (*GA Method A*, *GA Method B*). The FCDs positioning methods are implemented to both reduce spill volumes discharged at a single CSO, and the total spill volume discharged at all 16 CSOs within the sewer network. A range of RTC designs are produced for each case, based on differing numbers of installed FCDs. Spill volume reduction in each case is calculated by comparing modelled overflow spill volumes both with and without the FCDs implemented within the sewer network model, using both design storm. RTC designs are then validated for a series of historical rainfall events and a long-term rainfall series.

In each method, FCDs are placed such that spill volumes are not increased at any of the individual CSOs within the sewer network, so that overall overflow spill volumes are only reduced by maximizing the use of storage within existing drainage infrastructure. When selecting FCDs locations using the Static Storage Method, this constraint has to be verified with a trial-and-error process, since no hydraulic simulations are carried out in the method. In GA Method A and B, the constraint is verified by comparing the spill volume discharged at each CSO with and without the FCDs implemented within the sewer network, and discarding solutions that result in an increasing spill volume.

5.3.2.1 FCD locations selected using the Static Storage Method

In the Static Storage Method, installation sites for flow controllers are selected so that the in-sewer storage volume mobilised by the FCDs is maximised for each number of devices implemented within the sewer network. In-sewer storage capacity is calculated with a procedure based on Leitão et al. (2017) under the assumption of a horizontal energy line (i.e. static assumption, velocity of flow equal to 0 m/s), and is equal to the total in-pipe volume upstream of the FCD location under a reference level *RL* (m A.D.). In this study the reference level *RL* is set equal to the ground level decreased by a safety margin of 0.1 m. The in-sewer storage capacity, calculated under the static assumption, is considered a reasonable approximation of the maximum in-pipe volume that can be mobilised by a fully close actuator within the case study network evaluated. This is due to the limited pipe slopes (90% of pipe slopes vary between 0m/m and 0.006 m/m) and corresponding quasi-horizontal hydraulic energy line upstream of the FCDs. In case of steeper networks, the impact of a non-horizontal hydraulic energy line due to the flow velocity within the drainage system may be considered in the storage volume calculation.

This FCDs positioning method, found in several research studies for the design of RTC systems in sewer networks (Eulogi et al., 2021; Kroll et al., 2018; Philippon et al., 2015), allows the rapid assessment of a high number of potential FCD installation sites without the need for hydraulic simulations.

5.3.2.2 FCD locations optimisation using Genetic Algorithm (Methods A and B)

Within this approach the performance of numerous potential FCD locations is evaluated through hydraulic analysis, with near-optimal placement schemes identified by GA. In the methodology proposed by Eulogi et al. (2021), in order to reduce the computational time, the number of potential FCD locations evaluated by the optimisation tool is reduced by discarding installation sites with in-sewer storage volume capacity less than a minimum threshold V_0 (in this study V_0 set equal to 100 m^3). The threshold screening allows the exclusion of potential FCD locations with limited in-pipe storage volume, decreasing the computational time required by the GA to converge to a near-optimal solution. The GA optimisation is carried out by linking the MatSWMM hydraulic simulation tool with a GA solver in the Matlab environment. The GA solver is implemented using the Global Optimization Toolbox available in Matlab 2018a (Matlab, 2018) to solve the mixed-integer constrained optimization problem. GA options are shown in Table 4.1. The implementation of a flow controller within the sewer network is represented by a binary integer variable 0/1 (0: FCD not implemented, 1: FCD implemented), and the number of variables optimised by GA corresponds to the total number of potential FCD locations evaluated. The GA input population size is set to 100, as found through initial trials to provide an efficient balance between area of search, computational load, rate of convergence and improvement of the objective function values. The number of FCDs in each hydraulic simulation is constrained by the linear equality $\sum_{i=1}^{N} x_i =$ number of FCDs implemented. GA run is considered to have converged and stops if the average relative change in spill volume at CSOs regulated by the RTC system over 20 generations is less than or equal to 1 m^3. More details about GA optimisation (here termed GA method A) of FCD locations in sewer networks can be found in Eulogi et al. (2021).

In optimisation-based methods such as those using GAs the computational runtime required to run a hydraulic simulation of a drainage model and assess potential candidates is by far the most time-consuming element (Butler et al., 2018). When optimising FCD locations within the sewer network, the computational time is found to be highly influenced by the number of flow controllers implemented and the number of potential FCD locations evaluated by the optimisation tool. A novel approach (termed GA method B) is therefore proposed for the implementation of an optimisation-based framework in cases where the computational time is a limiting factor (i.e. most mid to large size UDS with multiple CSOs). To reduce the initial population of candidate solutions and computational time, the approach implements an additional rule applied when selecting potential FCD locations before GA optimisation. Only the most downstream manholes of each individual tributary branch of the sewer system are selected as the potential FCD locations, and along individual tributary branches if different in-sewer storage volume is mobilised by the flow controllers (Figure 5.1). In-sewer storage capacity is calculated under the static flow assumption. The additional rules based on the FCDs' position within the sewer network enable to evaluate the performance of a high number of potential FCD placement schemes capable of activating large portions of in-sewer storage potential, while significantly reducing the number of nodes considered and hence the GA computational burden.

To summarise: 1. In GA Method A potential FCD locations are selected if capable of mobilising in-sewer storage volume greater than a minimum threshold V_0. 2. In GA Method B potential FCD locations, featuring in-sewer storage volume greater than V_0, are selected along individual tributary branches only if positioned at the most downstream manholes, or positioned further upstream along the branches such that different in-sewer storage capacity can be mobilised.

All GA optimisation and hydraulic simulations were run on a Windows10 computer with Intel E5-2637 processor and 32GB of RAM. SWMM's hydraulic computations were solved using the dynamic wave routing model, which can account for backwater effects, flow reversal and pressurised flow generated by flow controllers within the sewer network (routing step set to 15 s, minimum variable time step set to 0.5 s). During rainfall events, FCD opening degrees were computed by the RTC control algorithm at a predefined time-step of 30 seconds.

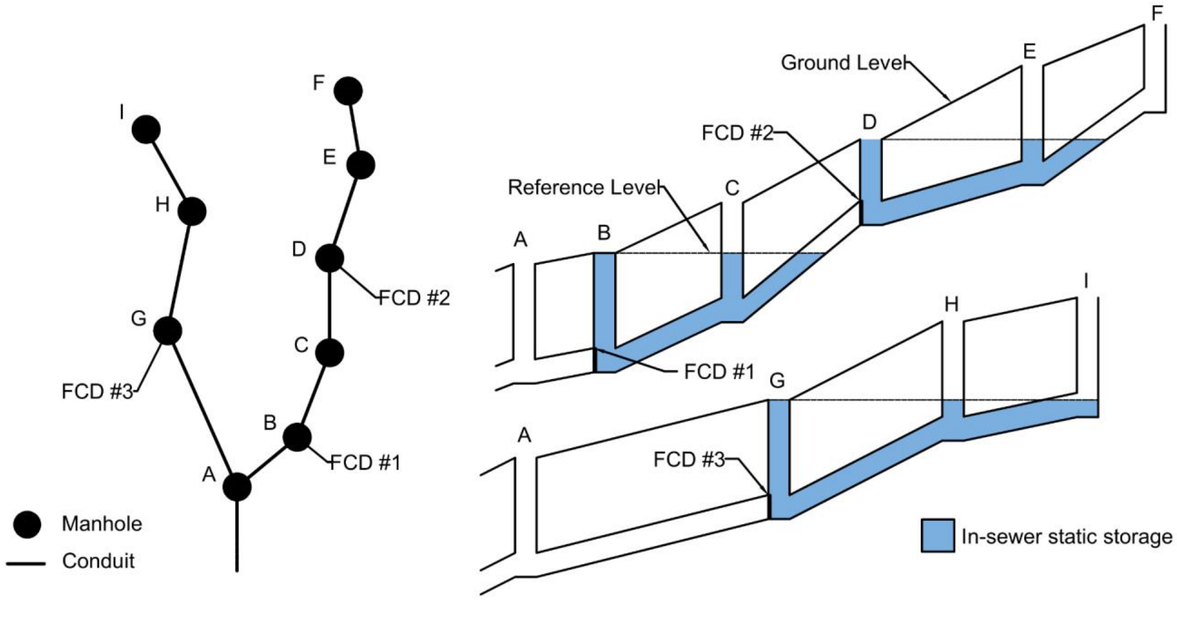


Figure 5.1: Selection of potential FCD locations under GA method B, based on mobilised in-sewer storage capacity and FCD's position within sewer network.

5.3.2.3 Rainfall events

FCD placement schemes are obtained by the Static Storage Method and GA optimisation using a composite design storm event *f7* with a total duration of 48 hours (storm event with a return frequency 7 times per year, time of aggregation 5 minutes), following the Flanders Environment Agency (VMM) design guidelines for sewer systems (Coördinatiecommissie Integraal Waterbeleid, 2012a). The composite storm is part of the official code of good practice for the design of urban drainage systems used in Flanders (Coördinatiecommissie Integraal Waterbeleid, 2012b).

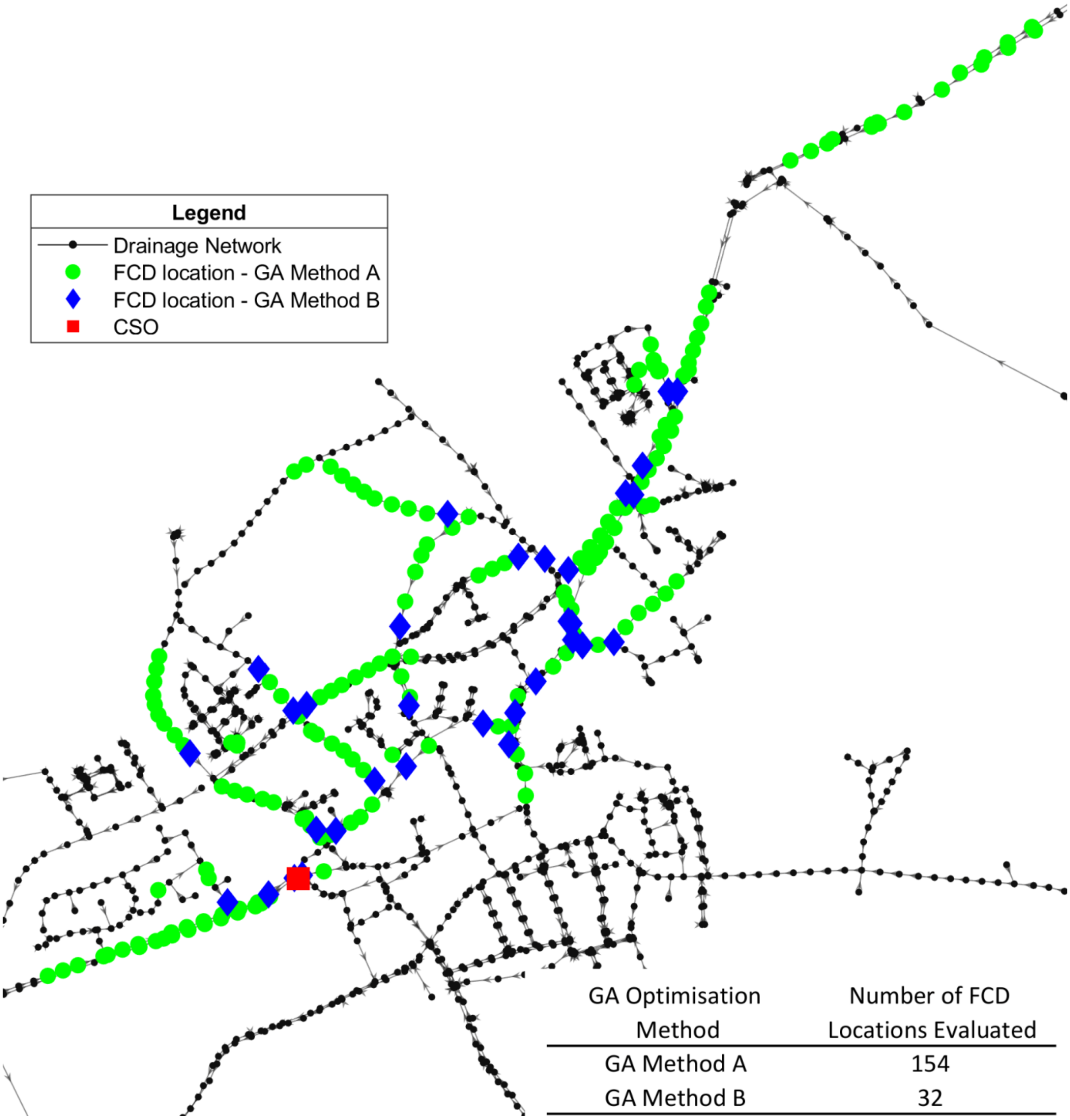
The RTC effectiveness in reducing spill volumes within the sewer network is then validated for a series of independent storm events, representative of different return periods, and for a full 3-year continuous rainfall series (Kroll et al., 2018). Hydraulic simulations were carried out using regional rainfall data available at Waterinfo.be. (n.d.) (station 'Herentals'). A total of 24 independent storms with duration between 100 min and 1268 min were selected from regional historical rainfall series recorded in the period 2004-2017 (rainfall temporal resolution 1 minute), and 3 classes comprising of 8 rainfall events are thus examined: storms with a return frequency of 10 times per year; storms with a return frequency of 7 times per year; set of storms with return period between 1 and 3 years. FCD placement schemes are also validated using a regional long-term rainfall series recorded between January 2006 and December 2008 (temporal resolution of 1 minute). The rainfall temporal resolution and the RTC resolution (frequency of water level reading) are found suitable to properly capture the fast runoff processes and response time of the sewage system during storm events.

5.4 Results

5.4.1 Spill volume reduction at a single CSO

The methodologies are utilised to define locations for installation of FCD with an objective to minimise the spill volume at a single CSO with one, two and three FCDs installed in the network. Within the unregulated network, a total predicted spill volume of 731 m^3 is discharged at the regulated CSO under an *f7* design storm event.

The potential FCD locations analysed by GA methods following pre-screening are shown in Figure 5.2. Pre-screening reduces the total number of potential FCD locations from 533 to 154 for GA Method A, and from 533 to 32 for GA Method B (V_0 equal to 100 m^3). The minimum threshold V_0 value is selected prior to the optimisation process based on analysis of the overall distribution of in-pipe storage capacity within the sewer network, so that nodes judged highly unlikely to be optimal locations for flow controllers are discarded.

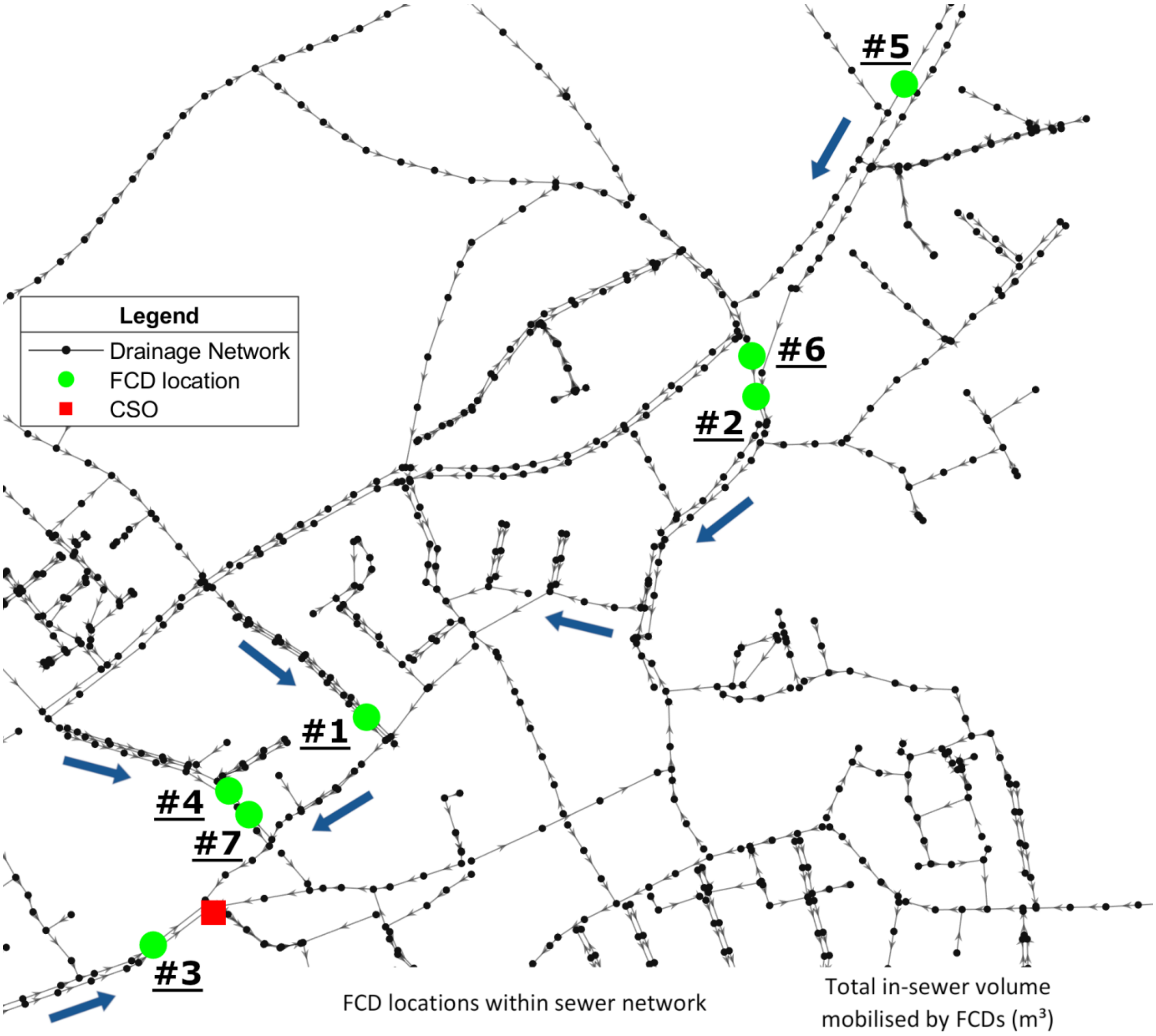


GA Optimisation Method	Number of FCD Locations Evaluated
GA Method A	154
GA Method B	32

Figure 5.2: potential FCD locations evaluated using GA Method A and GA Method B for the composite design storm event f7 (spill volume reduction at single CSO).

The resulting FCD locations and corresponding mobilised storage volumes selected by the Static Storage Method, GA Method A, and GA Method B are shown in Figure 5.3. Overall, FCDs placement schemes are found to be inclusive sets of solutions for each FCD positioning method considered in this study for all strategies tested. For example, the location proposed for a single FCD system are also included within the 2-FCDs and 3-FCDs solutions. This would suggest that an optimal scheme for a higher number of FCDs can be accomplished in stages, without adjusting locations of earlier placed FCDs.

Installation sites selected by the Static Storage Method mostly differ from solutions found by the GA, while FCD locations selected by both GA methods coincide or show little difference. For example, FCD locations #1 and #3, while selected by the Static Storage Method and capable of mobilising significant storage volume potential within the sewer network, do not appear in any GA solution. Location #2 is instead selected both as an installation site for the second gate in the Static Storage Method, and as a third installation site for the GA pre-screening Method B. Figure 5.3 also shows how the GA does not necessarily favour installation sites with higher storage potential or located near the CSO regulated by the RTC system. For example, in the case of a single gate system, FCD location #5 is preferred over FCD location #1 in both GA Methods while mobilising only 51% of the storage volume activated by the latter and positioned further upstream within the sewer network. The distance between control locations found by the GA and regulated CSO is mainly due to the maximum hydraulic capacity being exceeded in the downstream portion of the subcatchment, in which FCDs are not able to activate additional storage and collect stormwater during the peak storm event.



	FCD locations within sewer network			Total in-sewer volume mobilised by FCDs (m³)		
Number of FCDs	Static Storage Method	GA Method A	GA Method B	Static Storage Method	GA Method A	GA Method B
1	#1	#4	#5	980	463	502
2	#1,#2	#4,#5	#5,#7	1781	965	917
3	#1,#2,#3	#4,#5,#6	#5,#7,#2	2347	1740	1718

Figure 5.3: FCD locations selected by Static Storage Method, GA method A and GA method B for the composite design storm event f7 (spill volume reduction at single CSO).

For each FCD positioning method, the simulated spill volume reduction resulting from the implemented CENTAUR control system is shown in Figure 5.4. FCD placement schemes optimised by the GA provide higher CSO spill volume reduction compared to those obtained by the Static Storage Method in all cases. Under the static storage approach, spill volumes are higher when implementing a single FCD compared to the baseline system with no intervention, and when implementing the third flow controller compared to the 2-FCDs solution. Analysis showed that this increase is due to flow direction reversal along the pipe branches where the gates are implemented, which cannot be predicted by the Static Storage Method prior to hydraulic analysis. Therefore, the selection of optimal FCD locations with the static approach consists of a trial-and-error process, in which FCD installation sites are selected solely based on storage volume potential and subsequently evaluated through hydraulic simulations. While solutions found by the Static Storage Method could be manually modified and the flow controllers relocated along pipe branches without flow reversal, this result demonstrates the incapability of the Static Storage Method in efficiently identifying optimal locations for flow control devices. The manual relocation of FCDs is also found to be a time-consuming process, due to the high number of possible combinations between the number and location of FCDs within the case study network.

The positive overflow reduction achieved by the GA based design approach is therefore due to the ability of the method to consider hydraulic interactions between RTC assets as well as the temporal variation of rainfall and runoff volumes within the drainage system. The CSO spill volume reduction achieved by the RTC system by placing FCDs using GA Method A is approximately 7 to 10% higher than solutions found by GA Method B. No CSO spills occur for the design storm event under a 3 FCDs scheme placed using GA Method A. However, since the computational time required by the GA to identify solutions is highly influenced by the number of potential FCD locations evaluated by the solver, GA Method B results in lower computational times compared to GA Method A. The computational time needed by the GA to identify near-optimal solutions is reduced from 5h to 4h with 2 FCDs implemented, and from 9h to 6h with 3 FCDs implemented (Windows10 computer with Intel E5-2637 processor and 32GB of RAM).

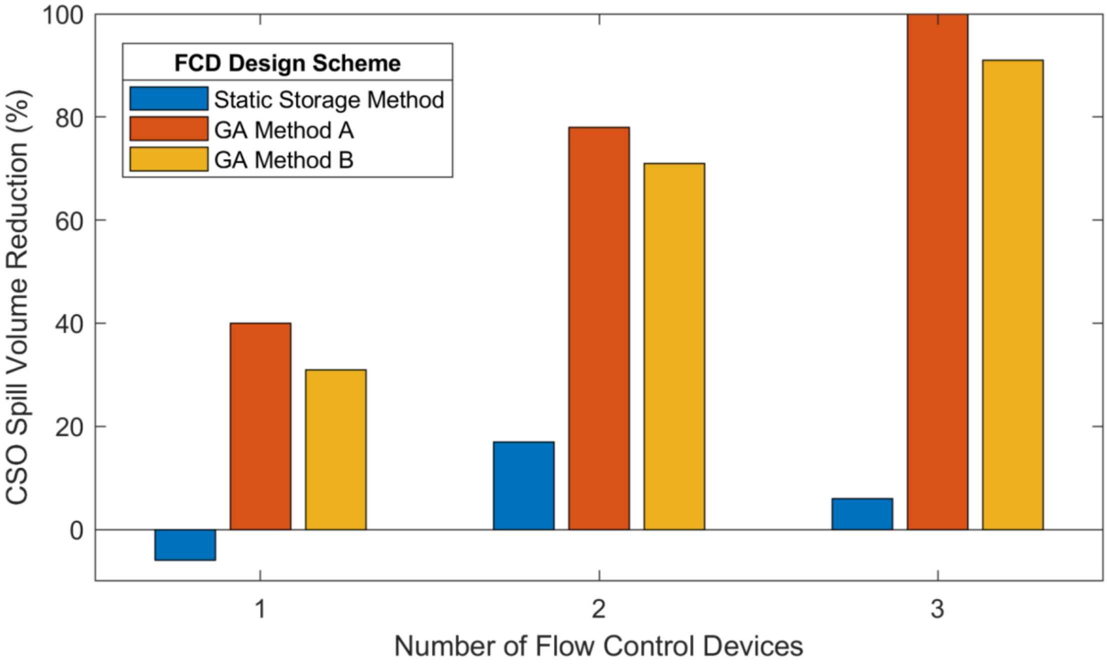


Figure 5.4: spill volume reduction at single CSO for composite design storm event f7, obtained by placing FCDs using Static Storage Method, GA Method A and GA Method B.

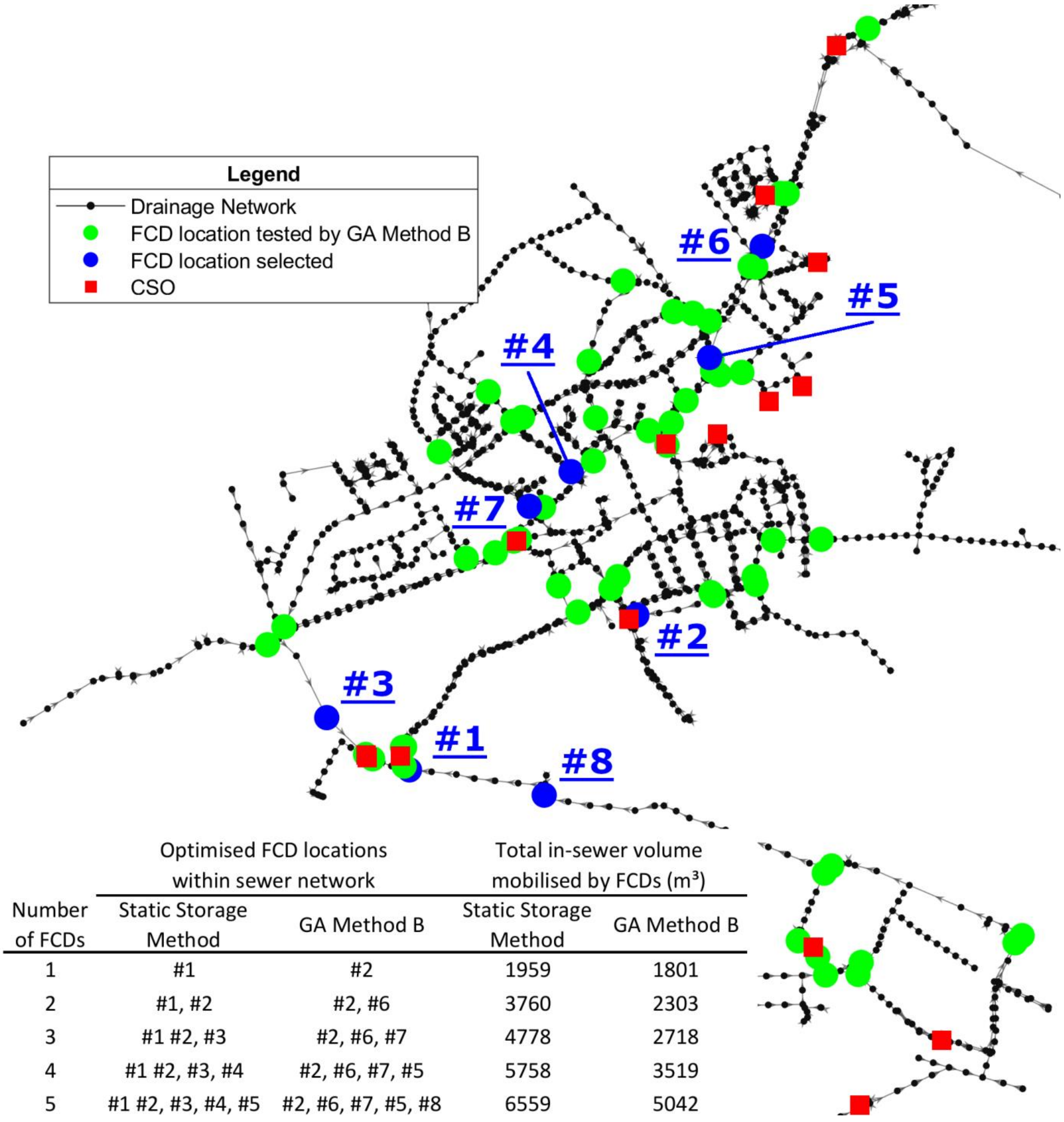
5.4.2 Spill volume reduction at all CSOs

The Static Storage Method and GA Method B are implemented to select FCD locations and reduce total overflow spill volume discharged at all 16 CSOs during the composite design storm event *f7*, for a number of FCDs between 1 and 5. Within the unregulated network, a total predicted spill volume of 1955 m^3 is discharged at the 16 CSOs under the *f7* design storm event. In this case, the implementation of GA Method A for overflow volume reduction is neglected due to the computational burden required for simulating spill at 16 CSOs. The capability of the

GA solver in selecting near-optimal solutions in a feasible time frame is found to be limited by the simulation runtime required to run hydraulic analysis, and number of combinations between potential FCD locations and number of FCDs tested in the case study network. In this regard, the additional constraints implemented in GA Method B based on FCDs' position within the sewer network, coupled with the minimum storage volume requirement, allows the reduction in the number of potential installation sites evaluated from 1002 to 63 (V_0 equal to 100 m^3), and this resulted in a computational time between 9h (2 FCDs) and 16h (5 FCDs).

As shown in Figure 5.5, 2 FCD locations obtained by the Static Storage Method (#2, #5) coincide with solutions found by GA Method B, while the remaining installation sites are located in different areas of the catchment. FCDs activate a large number of pipe branches within the catchment due to the low sewer pipe slope of the case study site, with storage volume capacity mobilised by each actuator ranging between 800 m^3 and 1960 m^3 for the Static Storage Method, and between 500 m^3 and 1800 m^3 for GA Method B. As expected, installation sites identified by the Static Storage Method are capable of mobilising higher in-pipe volumes compared with GA solutions, with an increase of total storage volume activated ranging between 9% (1 FCD implemented) and 76% (3 FCDs implemented). Overall, inclusive sets of FCDs placement schemes are obtained by both FCD positioning methods, in which FCDs can be gradually added at different stages within the sewer network while maintaining optimal FCDs layout in the entire sewer network.

Total spill volume reduction obtained at all CSOs by the Static Storage Method and GA Method B solutions are compared in Figure 5.6. GA based installation sites always result in larger CSO volume reduction, with a total CSO spill volume reduction of 37% when implementing 1 FCD, and 90% when implementing 5 FCDs. A negative or marginal further reduction in overflow volumes is obtained if the number of FCDs placed using the Static Storage Method exceeds two. This is again due to the flow reversals taking place in the sewer network, which cannot be predicted by the static approach prior to hydraulic analysis of the results.



Number of FCDs	Optimised FCD locations within sewer network Static Storage Method	 GA Method B	Total in-sewer volume mobilised by FCDs (m³) Static Storage Method	 GA Method B
1	#1	#2	1959	1801
2	#1, #2	#2, #6	3760	2303
3	#1 #2, #3	#2, #6, #7	4778	2718
4	#1 #2, #3, #4	#2, #6, #7, #5	5758	3519
5	#1 #2, #3, #4, #5	#2, #6, #7, #5, #8	6559	5042

Figure 5.5: FCD locations selected by Static Storage Method and GA method B for the composite design storm f7 (spill volume reduction at 16 CSOs).

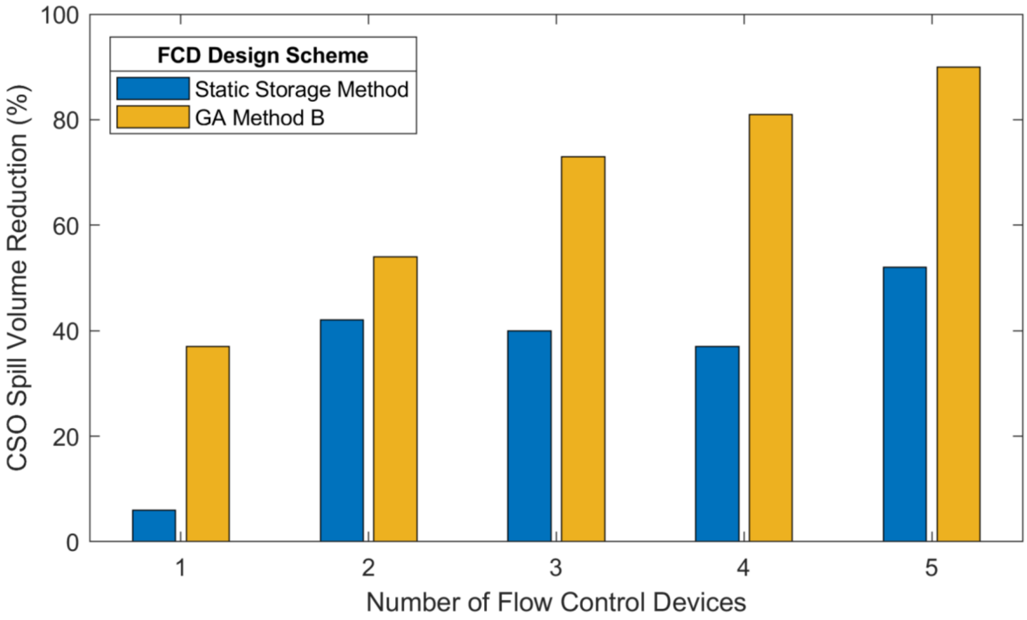


Figure 5.6: total spill volume reduction at all CSOs within the sewer network for the composite design storm f7, obtained by placing FCDs using the Static Storage Method and GA Method B.

5.4.3 Validation with historical storm events

FCD locations obtained by the GA optimisation and Static Storage Method for the *f7* design storm event are tested to regulate stormwater volumes during a series of 24 independent storm events, capable of triggering overflow spills at multiple CSOs within the sewer network, and during a full 3-year continuous rainfall series (see Kroll et al. (2018)).

5.4.3.1 Series of independent storm events

All 24 storms belong to a 13-year record of historical rainfall events recorded near the catchment area and are classified based on their return period. Three classes of storms are thus identified (8 storms per class): storms with a return frequency of 10 times per year, storms with a return frequency of 7 times per year, and storms with return period between 1 and 3 years. The FCD location selection procedure is repeated to reduce spill volumes at a single CSO (3

FCDs implemented) and reduce the total overflow volume spilled at all 16 CSOs within the network (5 FCDs implemented). Table 5.1 shows total overflow spill volume reduction for the series of 24 historical rainfall events, based on the number of CSOs regulated by the RTC system and FCD placement strategy tested.

In the case of a single CSO where control locations were selected by GA Method A, the FCDs are capable of preventing all overflow spills for storms with a return frequency of 10 times per year, while reducing the total CSO spill volume by 80% and 19% for storms occurring 7 times per year and storms with return period between 1 and 3 years, respectively. Similar results are achieved by GA Method B solutions, with respectively 100%, 73% and 17% total CSO spill volume reduction for the 3 classes of storms tested. FCDs locations selected by the Static Storage Method result in total CSO spill volumes increasing by 3% compared with the baseline system for storms occurring 10 times per year, and total CSO spill volume reduction of 25% and 15% for storms occurring 7 times per year and storms with longer return periods respectively. Overall, GA-based FCD placement schemes ensure considerably higher reduction of CSO spill volumes compared with storage based method solutions for storms occurring multiple times per year, with GA Method A performing slightly better compared with GA Method B. The capability of the RTC system in reducing overflow spills becomes insensitive to the choice of control locations for storms with return period greater than 1 year. In these cases, the stormwater volumes significantly exceed the maximum hydraulic capacity of the UDS in large portions of the catchment, causing a limited or negligible impact of flow controllers in regulating drained stormwater in the sewer network irrespective of location.

Table 5.1: Overflow spill volume reduction achieved by RTC system for the series of 24 historical rainfall events, based on the number of CSOs regulated and FCD placement strategy tested.

			Storm events return period (yr)			Storm events return period (yr)			
			1/10	1/7	1-3	1/10	1/7	1-3	
Number of CSOs	Number of FCDs	FCD Positioning Method	Spill volume baseline network (m^3)			Spill volume reduction compared with baseline network (%)			Total spill volume reduction compared with baseline network over all rainfall events (%)
1	3	Static Storage	1658	5607	26370	-3	25	15	16
		GA Method A				100	80	19	33
		GA Method B				100	73	17	30
16	5	Static Storage	3365	11846	78946	41	45	20	24
		GA Method B				80	68	21	29

In the case of 16 CSOs regulated by the RTC system, a higher spill volume reduction is obtained by placing FCDs using GA Method B compared with installation sites selected solely based on static storage capacity. Compared with control locations obtained by Static Storage Method, GA solutions provide a further increase in CSO spill volume reduction (relative to the baseline system with no intervention) of 39% for storms occurring 10 times per year, and 23% for storms occurring 7 times per year. Comparable CSO volume reduction is achieved during storms with return period between 1 and 3 years (20% for Static Storage Method solution, 21% for GA Method B solution).

5.4.3.2 Long-term rainfall series

The RTC effectiveness in mitigating overflow spills is also evaluated during a continuous historical rainfall series recorded between January 2006 and December 2008. Total CSO spill volume reduction achieved during the long-term simulation is shown in Table 5.2, based on the number of CSOs regulated by the RTC system and FCD placement strategy tested.

Table 5.2: Overflow spill volume reduction achieved by RTC system for the 3-year rainfall series, based on the number of CSOs regulated and FCD placement strategy tested.

Number of CSOs	Number of FCDs	FCD Positioning Method	Spill volume baseline network (m^3)	Spill volume reduction compared with baseline network (%)
1	3	Static Storage	86230	15
		GA Method A		36
		GA Method B		33
16	5	Static Storage	242070	26
		GA Method B		33

In case of single CSO regulated by the RTC system, overflow volumes discharged during the continuous rainfall series are reduced by 15% when placing the FCDs using the Static Storage Method, while higher CSO spill volume reduction is achieved optimising the control locations with GA: 36% by placing FCDs using GA Method A and 33% using GA Method B. When 5 FCDs are implemented to reduce overflow volumes at all 16 CSOs, 26% and 33% CSO spill volume reduction is achieved by the RTC system by placing the flow controllers using the Static Storage and GA Method B respectively.

Overall, similar results are obtained testing the FCD placement strategies for the 3-year rainfall series compared to the RTC performance obtained during the 24 independent storm events. GA-based FCD placement schemes always correspond to higher reduction of CSO spill volumes compared with storage-based solutions, demonstrating how the GA methods can be efficiently used to identify optimal FCD placement schemes and significantly reduce overflow volumes at single as well as multiple CSOs within sewer networks.

5.5 Discussion

In this study three different FCD placement strategies for local RTC systems have been implemented with the aim of reducing combined sewer overflow spills in sewer networks: a FCD position selection method solely based on static storage volume mobilised by flow controllers (Static Storage Method), and two methods based on GA optimisation (GA Method A, GA Method B – Method A being more exhaustive and computationally demanding than Method B). The RTC performance evaluation with a composite design storm ensured a robust implementation of flow controllers in the sewer network, capable of controlling stormwater volumes for a wide range of rainfall events with a return frequency of multiple times per year. Comparable results have also been achieved for the series of historical rainfall events and long-term rainfall series used for validation, giving confidence in the choice of design storm applied in the methodology.

GA optimisation methods always result in FCD locations capable of achieving higher spill volume reduction at the CSOs compared with installation sites identified solely based on static storage capacity, with GA Method A giving lower spill volume at the expense of higher computational time. While the Static Storage Method allows rapid assessment of potential FCD placement schemes, the performance of the RTC system is likely to be limited compared with hydraulic optimisation. This is due to the capability of the hydraulic optimisation-based method in testing the impacts of the potential FCD placement schemes on flows and levels within the sewer network during storm events, so that the mobilisation of unused hydraulic capacity within the UDS is optimised. The advantage of selecting FCD locations based on GA methods is also likely more evident when placing devices in sewer networks in flat areas, where low pipe slopes can lead to flow reversals, and hydraulic interaction between gates are likely more significant and difficult to predict without detailed hydraulic analysis.

When testing FCD placement schemes during historical rainfall events, CSO spill volumes are found to be very sensitive to the choice of FCD locations for more frequent events, while limited difference in overflow volume reduction is observed for larger events as the in-sewer storage potential of the sewer network was observed to be completely utilised in all cases. The performance of the RTC system is therefore significantly increased when positioning FCDs with GA methods when controlling low intensity storms, while limited impact on the choice of FCD placement scheme is observed for less frequent and severe storm events. The reduction of overflow spills for high intensity storms could be further enhanced by coupling the RTC system with other solutions such as storage tanks.

The slightly more efficient control of stormwater volumes achieved by placing flow controllers using GA Method A, when compared to GA Method B, is mainly due to the higher number of potential FCD locations and FCD placement schemes tested, resulting in a more tailored positioning of devices in the sewer network. However, the higher computational demand of GA Method A has been found to constitute a limiting factor in the implementation of the GA-based method in more complex case study networks involving multiple CSOs. In the case of a CSO regulated by the RTC system, the overflow spill volume reduction achieved by GA Method B solutions is diminished between 9% (3 FCDs implemented) and 23% (1 FCD implemented) compared with results obtained by GA Method A.

Overall, GA Method B enables a good trade-off between total number of potential FCD locations evaluated, computational time required by the GA solver to converge to a near-optimal solution, and spill volume reduction achieved by the RTC system especially for high number of devices implemented. The computational effectiveness of GA Method B is also expected to be higher in large sewer networks characterised by low gradient and homogeneous distribution of in-sewer storage capacity within the catchment. In these cases, the minimum upstream storage volume threshold applied by GA Method A when selecting potential FCD locations has limited influence in effectively reducing the total number of FCD placement schemes tested in the process. However, GA Method A remains recommended in all potential applications where the computational demand does not limit the implementation of the optimisation-based method.

In the scenarios investigated, flow controllers are placed such that spill volumes are not increased at any CSO within the sewer network during the storm event investigated. This optional constraint ensures that the CSO spill volume reduction achieved by the RTC system is solely due to optimal use of existing drainage infrastructure, rather than increase of individual CSO spill volumes in the system. The methodology can also be applied to design FCD placement schemes where the total CSO spill volume is reduced by allowing less critical CSOs to spill more compared with the baseline system with no intervention, although this would require a more detailed receiving water assessment. In this regard, optimisation-based methods are particularly effective by having the constraint automatically verified through hydraulic analysis. The advantage of using GAs over storage-based methods can therefore be crucial in complex case study networks with multiple CSOs, where hydraulic impacts of the flow controllers on the overflow volumes discharged by the system might be difficult to predict.

The optimised FCD placement schemes found for both GA methods suggest that an optimal scheme for a higher number of FCDs can be accomplished when a scheme optimised for a lower number of devices is first implemented. Such inclusive sets of FCDs locations are advantageous during the adaptive design of an RTC system, as then FCDs could be gradually added and a design implemented in stages as and when more knowledge about the future climate and land-use becomes available. The achievement of inclusive set of solutions is expected to be influenced by the sewer system evaluated, and non-inclusive solutions might be obtained by GA in systems featuring different slope or distribution of available in-sewer storage capacity within the catchment.

5.6 Conclusion

This paper evaluates the performance of different design tools used to identify FCD locations for local RTC systems, and the performance of the CENTAUR real-time control system in reducing CSO spill volume. A novel GA pre-screening method was developed that allows optimisation of FCD locations in large sewer networks using a full hydraulic network model. This new FCD positioning method gave only slightly less favourable results when compared with full GA optimisation, but a considerable reduction in computational effort. Location selection based only on static storage volume (rather than a full hydraulic method) gave a considerably worse performance in CSO spill reduction, due to this method not being able to account for system hydrodynamics, including flow reversals. Hence especially in flat catchments, an optimisation technique that utilises a full hydraulic network model is recommended. FCD placement schemes found by GA optimisation were also validated by comparing performance relative to the uncontrolled network during 24 independent storm events as well as a 3-year rainfall series, showing how the optimised FCD locations result in a RTC system are capable of mitigating spill volumes over a wide range of rainfall inputs, and preventing CSO spills during frequent storms. In the case study evaluated, FCDs placement schemes were found to be inclusive sets of solutions for each FCD positioning method, which suggests that FCDs could be deployed in stages. This means the method can be used for the adaptive design of local RTC placement schemes in complex case study networks, which is expected to deliver further options for flexible adaptation of urban drainage systems, to cope with future challenges and fulfil environmental targets set by regulatory bodies. With adjustments to the pre-screening rules, the method may be extended to be applicable for adaptive design of the placement of other distributed local solutions for CSO mitigation, such as SuDS and nature-based solutions.

6 Optimal positioning of RTC actuators and SUDS for sewer overflow mitigation in urban drainage systems

In this Chapter, the framework proposed in Chapter 5 is further developed to optimise the spatial allocation of FCDs combined with infiltration-based SuDS implemented in the sewage and catchment level respectively, for CSO spill volume reduction within UDS. The chapter is based on the following manuscript in preparation: M. Eulogi, S. Ostojin, P. Skipworth, S. Kroll, J. D. Shucksmith, A. Schellart (2022) Optimal positioning of RTC actuators and SUDS for sewer overflow mitigation in urban drainage systems.

6.1 Abstract

Real-Time Control (RTC) and Sustainable Drainage Systems (SuDS) can be simultaneously implemented to enhance the performance of existing urban drainage systems (UDS). However, significant challenges arise when choosing optimal locations due to hydraulic interactions between the different interventions and the high number of possible configurations. This paper presents a novel optimisation-simulation framework to optimise the spatial allocation of Flow Control Devices (FCDs) combined with SuDS, for Combined Sewer Overflow (CSO) spill mitigation within UDS. Optimal intervention schemes are identified by a genetic algorithm (GA), combining different numbers of FCDs installed in existing manholes with simplified SuDS implemented in different portions of the catchment. The methodology is tested on two case study catchments with different characteristics to mitigate CSO spills over synthetic storm events. FCD-SuDS configurations are then validated over continuous rainfall series, resulting in CSO spill volume reduction ranging between 11% and 45% compared to baseline networks. Results demonstrate how the GA-based method can efficiently identify optimal placement schemes within UDS characterised by different distribution of in-pipe storage potential as well

as hydrological response to rainfall-runoff events, enhancing the combined benefits of the two decentralised solutions in mitigating CSO spills.

6.2 Introduction

The enlargement of impervious areas, combined with the increase in the frequency of extreme precipitations due to climate change, pose increasing challenges for the management and operation of urban drainage systems (UDS) (Hosseinzadehtalaei et al., 2020; McGrane, 2016; Miller and Hutchins, 2017; Zhou et al., 2019; Zittis et al., 2021). Without adapting UDS, the frequency and magnitude of combined sewer overflows (CSOs) are expected to increase. Overflow discharges are recognised as a source of pollution for receiving water bodies, and CSO spill reduction is promoted and supervised by regulatory bodies (CEC, 1991; Environment Agency, 2018; Pistocchi et al., 2019). Conventional urban drainage solutions consider the enlargement of the drainage infrastructure or expansion of the storage capacity with construction-based solutions. Both feature high up-front investment costs and are coming under increased scrutiny due to potentially high embedded carbon and/or carbon emission associated with pumping (De Sousa et al., 2012; Liu et al., 2020). Therefore, there is increasing interest in the water sector in developing decentralised and distributed technologies to manage sources of pollution and runoff volumes (Altobelli et al., 2020), as well as increase the flexibility of existing drainage infrastructure in response to future climate trends (Gersonius et al., 2013).

SuDS (Sustainable Drainage Systems), also known as LIDs (Low Impact Developments) or BMPs (Best Management Practices), are distributed source controls implemented to manage runoff volumes within urban catchments (Fletcher et al., 2015). These systems aim to enhance natural processes such as infiltration, percolation, evaporation, and attenuation with green infrastructures, reducing or removing stormwater volumes entering the existing sewage system.

SuDS may include green roofs, bio-retention cells, permeable pavement, vegetative swales, and infiltration trenches among others (Islam et al., 2021), and are known to provide water quality, biodiversity, and amenity benefits (Woods Ballard et al., 2015). However, the widespread implementation and management of distributed LID-BMPs-SuDS practices may be challenging due to space availability, especially in highly urbanised areas (Zhang and Chui, 2018), and spatially varied socio-economic constraints (e.g. lack of public interest and support, private and public lands owned by different parties) (Mandarano and Meenar, 2017; Montalto et al., 2013).

Another alternative to increase the capacity of UDS are real-time control (RTC) systems. RTC is designed to achieve real-time management of existing UDS through continuous monitoring of process data (e.g. water levels, flow) and dynamic adjustment of flow conditions with flow control devices (FCDs, e.g. pumps, sluice gates, moveable weirs) (EPA, 2006; Schütze et al., 2008). RTC systems can be classified as local control systems, or system-wide control systems, based on their complexity and control scope (EPA, 2006; García et al., 2015; Schütze et al., 2003) 2006; García et al., 2015; Schütze et al., 2003). RTC systems can potentially be a cost-effective solution, depending on the type and size of the system. Practical applications of RTC systems are mostly documented for large case studies, with many operators still reluctant to adopt RTC systems (Kroll et al., 2018). In engineering practice, the opinion often prevails that RTC requires more effort than conventionally operated systems (Beeneken et al., 2013).

CENTAUR is a local RTC system designed to mitigate CSO spills and/or urban flooding in sewer networks, increasing the performance of existing drainage infrastructure (Mounce et al., 2020; Ostojin et al., 2017). CENTAUR consists of FCDs inserted into existing manholes, that mobilise existing in-pipe storage capacity to regulate water level at pre-defined target locations (e.g. CSO chamber, manhole prone to urban flooding). FCDs are composed of a movable sluice gate coupled with an emergency overflow weir. Sluice gate opening degree is controlled by an autonomous Fuzzy Logic algorithm based on real-time in-sewer level information, while the emergency overflow weir prevents sewer overflow upstream of the FCD installation site. FCDs can be easily relocated in different locations (i.e. manholes) with limited civil works to address changes in land use and future climate trends. Therefore, CENTAUR offers a flexible solution to increase the resilience of UDS when managing stormwater volumes during rainfall events, with low costs when compared to traditional alternatives (e.g. storage tanks).

The performance of both SuDS and RTC structures for CSO spill mitigation can be maximised by optimising their spatial distribution, type, and size. However, due to the high number of possible implementation schemes especially in large catchments, as well as a large number of constraints (e.g. physical, socio-economic) potentially involved in the selection, traditional trial-and-error approaches often deliver sub-optimal designs and optimisation-based methodologies are preferred (Zhang and Chui, 2018). Numerous studies have considered the spatial optimisation of either SuDS or distributed RTC systems, commonly achieved coupling SWMM or SUSTAIN models with evolutionary algorithms in a simulation-optimization framework (Giacomoni and Joseph, 2017; Mao et al., 2017; Wu et al., 2019; Zhen et al., 2004). An extensive bibliometric review on design optimization (allocation, type, dimensioning) and performance evaluation of multiple SuDS in UDS can be found in Islam et al. (2021). Similarly, the efficient placement of flow control devices is a crucial step in the design of cost-effective RTC systems in UDS (Campisano et al., 2000; Leitão et al., 2017). Eulogi et al. (2021) developed a simulation-optimisation framework to identify optimal FCD placement schemes for overflow spill mitigation at a single CSO, combining a Genetic Algorithm with a SWMM model. Eulogi et al. (2022) further developed the method, extending its applicability to larger UDS featuring multiple CSO locations. However, limited research has been found on aiming to understand how RTC and SuDS systems interact hydraulically and/or achieve added benefits through combining these systems. Experimental and modelling studies reviewed by Brasil et al. (2021) demonstrate how potential benefit achieved by nature-based solutions (i.e. detention basins, bioretention cells, green roofs) can be enhanced by coupling the system with RTC. For example, in Gaborit et al. (2013) the performance of stormwater detention basins is improved through dynamic control of regulators (i.e. outlet valves) using rainfall forecasts, while Shen et al. (2020) conducted an experimental study on the application of RTC systems to stormwater biofilters for rainfall harvesting and reuse. Altobelli et al. (2020) found that the RTC performance in reducing CSO spill volumes, consisting of FCDs installed at different locations within the sewer network, can be further enhanced by coupling the system with SuDS implemented in the catchment level.

However, currently, there is a lack of consideration on how the relative placement and design of RTC and SuDS systems affect the performance of the UDS at the urban catchment level, and how these technologies hydraulically interact. As far as the authors are aware, to date, no robust and efficient methodology to optimise implementation strategies for RTC combined with SuDS systems, or design such decentralised systems to achieve a given level of performance, can be found in the literature. Furthermore, most existing spatial optimization studies focus on single case study catchments, with little consideration of how the type and nature of the catchment influence the effectiveness of the solution. Current challenges include the time-consuming nature of optimisation in large UDS and the need to accurately simulate the hydraulics within the UDS to fully capture the interaction between different systems (e.g. green infrastructure plus FCDs).

This research aims to investigate the hydraulic interaction and potential enhancement when implementing both CENTAUR local RTC and SuDS for CSO spill volume reduction in two case study catchments with varying characteristics, and to develop a methodology for the placement of such schemes to achieve a given level of performance. The specific objectives are: (1) Adapt a Genetic Algorithm methodology for optimisation of placement of RTC actuators as well as simplified SuDS systems in a UDS. (2) Simulate the performance of different optimised combinations of SuDS and RTC solutions for CSO spill mitigation in two study catchments, against benchmark networks with no intervention. (3) Validate the performance of RTC coupled with SuDS using a continuous rainfall time series and consider the relative performance in the different catchments.

6.3 Methodology

6.3.1 Case studies

Performance of the CENTAUR RTC and SuDS systems in reducing CSO spills is evaluated in two case studies: the *Arendonk* catchment (Flanders, Belgium) and the *Zona Central* catchment (Coimbra, Portugal). Case studies are modelled using EPA Storm Water Management Model (SWMM) (Rossman, 2015), a dynamic rainfall-runoff and network hydraulics simulation model widely used for optimisation problems in sewer networks. SWMM hydraulic simulations are carried out using the MatSWMM interface (Riaño-Briceño et al., 2016). MatSWMM is an open-source software package that further extends the default functionalities of RTC systems in SWMM models, allowing the FCDs to be controlled by the CENTAUR fuzzy logic algorithm. Characteristics of the two case studies are summarized in Table 6.1. The Arendonk model is mostly a flat catchment, with pipe slopes varying between -0.044 m/m and 0.88 m/m (90% between 0m/m and 0.006 m/m), and a total of 16 CSOs distributed in different portions of the catchment. The Zona Central model features steep slopes in the upper/mid-portion of the catchment, leading into more gentle lower slopes (pipe slopes varying between -0.51 and 2.26 m/m, 90% between -0.08 and 0.22 m/m). When runoff volumes exceeded the maximum hydraulic capacity of the sewer network, flows are discharged at a single CSO located immediately upstream of the final outlet. In both case study catchments, optimal placement schemes are identified minimising overflow volumes discharged at a single CSO, located close to the final outlet in the Zona Central model and in the central portion of the catchment in the Arendonk model.

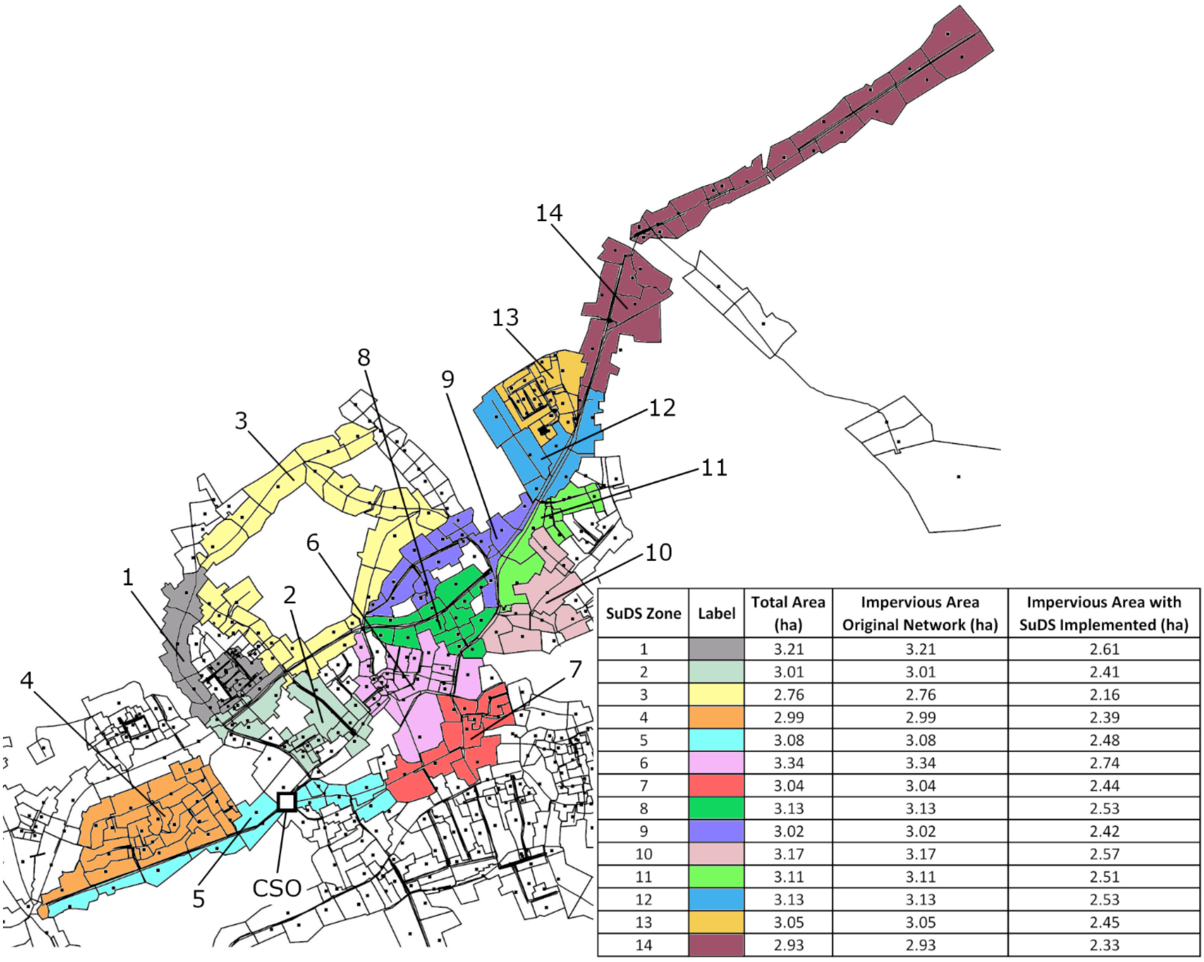
Table 6.1: summary of characteristics of the selected case study catchments.

Case Study	**Population equivalents**	**Number of nodes**	**Number of links**	**Number of subcatchments**	**Total contributing area (ha)**	**Pipe diameter (m)**		**Pipe slope (m/m)**		**Number of CSOs**
						Min	Max	Min	Max	
Arendonk	15100	1572	1563	572	113	0.1	2	-0.04	0.88	16
Zona Central	-	536	538	434	89	0.2	1.7	-0.51	2.26	1

6.3.2 SuDS zones

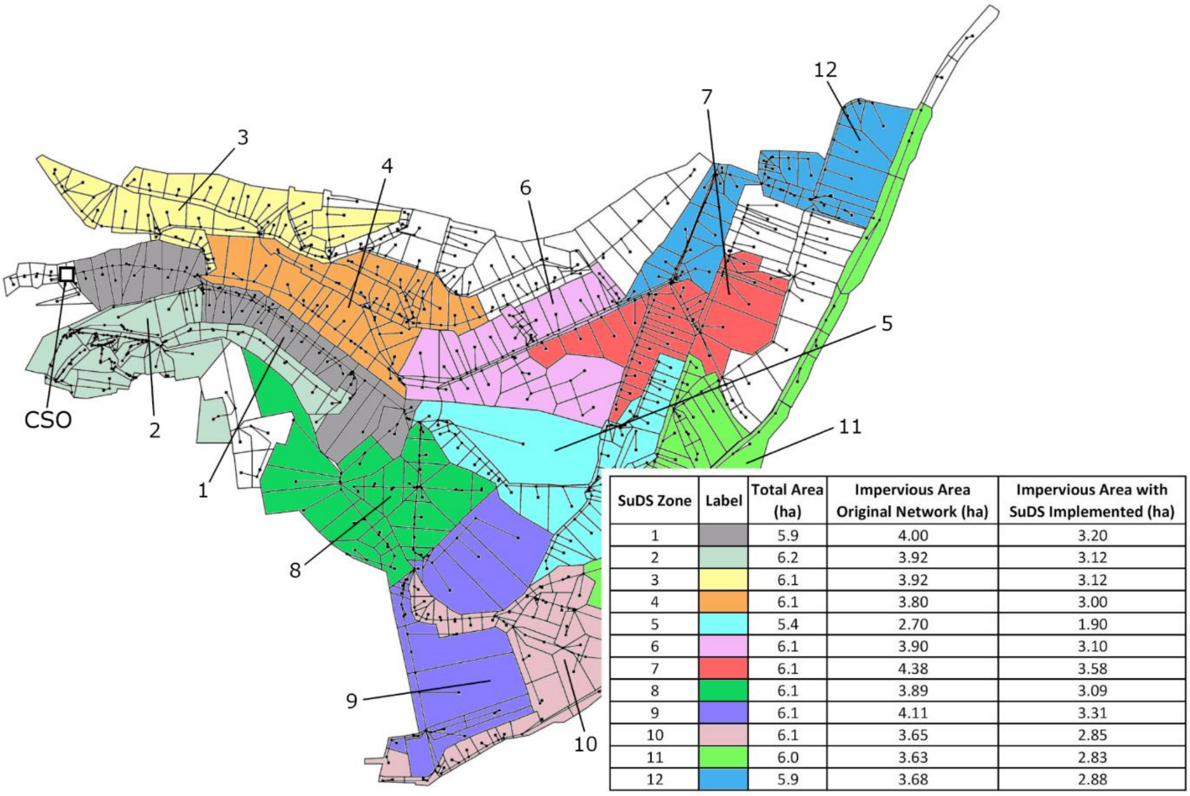
SuDS can take many forms (e.g. infiltration trenches, bioretention basins, green roofs, swales, etc…) each developing different hydrological and hydraulic mechanisms for managing runoff volumes. For this investigation, SuDS are simulated within a subcatchment by converting the impervious area into a pervious area. While the reduction of impervious area is a highly simplified representation of SuDS, this provides a reasonable representation of infiltration-based structures within subcatchments. This study investigates a higher-level planning and design case of CSO spill volume reduction and not the detailed design of the SuDS themselves. When implementing Sustainable Drainage Systems within a catchment, SuDS are applied to groups of subcatchments (*SuDS zones*) instead of single subcatchments. A SuDS zone corresponds to a group of subcatchments in which a fixed impervious area (ha) is converted into a pervious area. This ensures that equivalent rainfall depth is collected and processed in each SuDS zone (homogeneous rainfall intensity within the catchments), providing a more rigorous comparison between SuDS placement schemes. Moreover, the implementation of green infrastructure into clusters of subcatchments allows to drastically reduce the number of combinations between the number and location of SuDS, limiting the computational time required by the optimisation-based solver to identify optimal placement schemes.

Subdivision of the Arendonk and Zona Central catchment models into SuDS zones is shown in Figure 6.1 and Figure 6.2 respectively. In this study, SuDS zones feature similar total surface area (3±0.3 ha in the Arendonk model, 6±0.6 ha in the Zona Central model) and are selected so that runoff volumes generated in each SuDS zone are collected by the same branches within the sewer network (SuDS zones linked to different segments of the sewer network). While the optimisation-based methodology can be performed using different clusters of subcatchments, the proposed selection of SuDS zones ensures a rigorous evaluation of the hydraulic interaction between green infrastructure in the catchment level and FCDs in the sewer network level. The number and position of SuDS zones were selected prior to the optimisation process, to ensure an efficient trade-off between computational load and area of search of the optimisation-based method, as well as a feasible and realistic implementation of green infrastructures within the catchments (~20% of impervious area converted to the pervious area in each SuDS zone).



SuDS Zone	Label	Total Area (ha)	Impervious Area Original Network (ha)	Impervious Area with SuDS Implemented (ha)
1	⬛	3.21	3.21	2.61
2	▨	3.01	3.01	2.41
3	🟨	2.76	2.76	2.16
4	🟧	2.99	2.99	2.39
5	🟦	3.08	3.08	2.48
6	🟪	3.34	3.34	2.74
7	🟥	3.04	3.04	2.44
8	🟩	3.13	3.13	2.53
9	🟪	3.02	3.02	2.42
10	▨	3.17	3.17	2.57
11	🟩	3.11	3.11	2.51
12	🟦	3.13	3.13	2.53
13	🟨	3.05	3.05	2.45
14	🟫	2.93	2.93	2.33

Figure 6.1: SuDS zones selected within SWMM Arendonk sewer network model (0.6 hectares of impervious area converted to pervious area in each SuDS zone).



SuDS Zone	Label	Total Area (ha)	Impervious Area Original Network (ha)	Impervious Area with SuDS Implemented (ha)
1	⬛	5.9	4.00	3.20
2	🟩	6.2	3.92	3.12
3	🟨	6.1	3.92	3.12
4	🟧	6.1	3.80	3.00
5	🟦	5.4	2.70	1.90
6	🟪	6.1	3.90	3.10
7	🟥	6.1	4.38	3.58
8	🟩	6.1	3.89	3.09
9	🟪	6.1	4.11	3.31
10	🟫	6.1	3.65	2.85
11	🟩	6.0	3.63	2.83
12	🟦	5.9	3.68	2.88

Figure 6.2: SuDS zones selected within SWMM Zona Central sewer network model (0.8 hectares of impervious area converted to pervious area in each SuDS zone).

6.3.3 Flow control devices

The potential installation sites for flow control devices are manholes positioned upstream of the CSO spill regulated by the RTC system, and connected to one entering conduit and one exiting conduit. FCDs are modelled as circular sluice gate (orifice) coupled with a rectangular overflow weir (link). The orifice-link element is implemented within the SWMM model connecting the FCD-node to an auxiliary node (same properties, e.g. invert level, maximum depth, initial depth…) positioned immediately upstream. Sluice gate diameter is set equal to the upstream pipe diameter to avoid restrictions in the cross-section. Overflow weir acts as a fail-safe in case of gate failure, preventing urban flooding upstream of the FCD location. In the Zona Central sewer network, weir heights are calculated using a synthetic design storm based on Portuguese IDF curves (RGSPPDADAR, 1995) (return period of 50 years, duration of 45 minutes), and in the Arendonk sewer network by using a historical rainfall event recorded in the year 2004 (return period of 14 years, duration of 27 minutes).

While FCDs hydraulically interact to reduce CSO spill volumes during storm events, each actuator is autonomous and independently operated by the RTC system. Each FCD is locally handled by the CENTAUR control algorithm by measuring water level at the CSO chamber and immediately upstream of the FCD installation site. During rainfall events, each FCD opening degree is computed at a predefined time-step of 30 seconds to properly capture the fast runoff processes and quick response time of the case study catchments, varying between 0% (fully close) and 100% (fully open). The CENTAUR control algorithm is linked with the SWMM model in the Matlab environment, as described by Shepherd et al. (2016).

6.3.4 Selection of optimal SuDS and FCD location

A scenario-based analysis is conducted to evaluate the effectiveness of flow control devices and SuDS in mitigating overflow volumes, as well as investigate the hydraulic interaction between the 2 different technologies when managing stormwater volumes during rainfall events. Three scenarios are thus presented, based on the type of solution implemented: RTC only, SuDS only, RTC coupled with SuDS. The analysis is carried out for different numbers of installed FCDs and/or SuDS zones, reducing overflow volumes discharged at a single CSO in the two case study catchments during synthetic storm events. Placement schemes are then validated over continuous rainfall series. Overflow spill volume reduction is calculated by comparing CSO spill volumes with and without the FCDs and/or SuDS implemented within the sewer network models.

6.3.4.1 Genetic algorithm

Spatial allocation of SuDS and/or FCDs within the urban drainage systems is optimised using a Genetic Algorithm (GA). While type, size, and location of SuDS can be optimised simultaneously (Eckart et al., 2018), more simplified approaches can be used for a rapid assessment of potential intervention schemes for decentralised runoff management solutions, such as fixed combinations of BMPs (Shen et al., 2013; Srivastava et al., 2002), or fixed-size BMPs units with constant design configurations (Mao et al., 2017; Wu et al., 2019). Moreover, significant reduction of computational load and level of complexity is achieved representing the implementation of BMP/LID with a binary 0/1 decision variable (0=measure not implemented; 1=measure implemented) (Arabi et al., 2006; Bakhshipour et al., 2019; Damodaram and Zechman, 2013; Harrell and Ranjithan, 2003; Limbrunner et al., 2013b). Type selection, design and sizing can be also completely screened out, solely optimising the location of BMPs in a binary optimisation approach (Perez-Pedini et al., 2005). A similar approach has been implemented by Eulogi et al. (2021) and Eulogi et al. (2022) to identify optimal FCD placement schemes for overflow spill mitigation in sewer networks, combining a Genetic Algorithm with a SWMM model: the implementation of a FCD at a potential control location is represented with the binary decision variable x_i [0=FCD not implemented; 1=FCD implemented], providing a simple screening-level methodology to design FCD placement schemes in a wide range of sewer systems.

In this study, the implementation of a flow controller in a given potential installation site (i.e. manhole), or SuDS in a given cluster of subcatchments (i.e. SuDS zone), is represented by a binary 0/1 integer variable: [0 = FCD/SuDS not implemented; 1 = FCD/SuDS implemented]. In the case of benchmark network with RTC, FCD placement schemes are represented by the one-dimensional binary array $[x_1, x_2, \dots, x_i, \dots, x_N]$, in which x_i corresponds to the i-th FCD location tested by GA within the sewer network model. In the case of benchmark network with SuDS, placement schemes are represented by the one-dimensional binary array $[y_1, y_2, \dots, y_i, \dots, y_N]$ (impervious area decreased at the i-th SuDS zone). In the case of RTC combined with SuDS, the 2 binary arrays are combined into a single binary one-dimensional string (Figure 6.3), optimised by GA to minimize a single objective function (CSO spill volume [m^3]). In each scenario (RTC only, SuDS only, RTC coupled with SuDS), the number of flow controllers and/or SuDS zones implemented is forced using the following linear equality constraints: $\sum_{i=1}^{m} x_i =$ number of FCDs implemented (m equal to the total number of FCD locations evaluated) and $\sum_{i=1}^{n} y_i =$ number of SuDS zones implemented (n equal to the total number of SuDS zones evaluated). Through initial trials, population size per GA generation equal to 200 was found to provide an efficient trade-off between computational time, search space and rate of convergence. The GA solver is implemented using the Global Optimization Toolbox available in Matlab 2018a (Matlab, 2018) to solve the mixed-integer constrained optimization problem. The mutation rates and crossover were 0.1 and 0.9, respectively. GA optimisation runs stop if the average relative change in CSO spill volume is less than 1 m^3, or if the number of GA generations is greater than 20. More details on the GA options are shown in Table 4.1.

Performance of potential RTC and/or SuDS placement schemes is evaluated through hydraulic analysis, linking the GA solver to the MatSWMM hydraulic simulation interface in the Matlab environment. The optimisation is performed using standard computational resources (Windows10 computer, Intel E5-2637 processor, 32GB of RAM). Hydraulic simulations are carried out using the dynamic wave routing method (routing step set to 15 s, minimum variable time step set to 0.5 s), so that backwater effect, flow reversal and pressurised flow generated by partially or fully closed actuators are considered during hydraulic analysis.

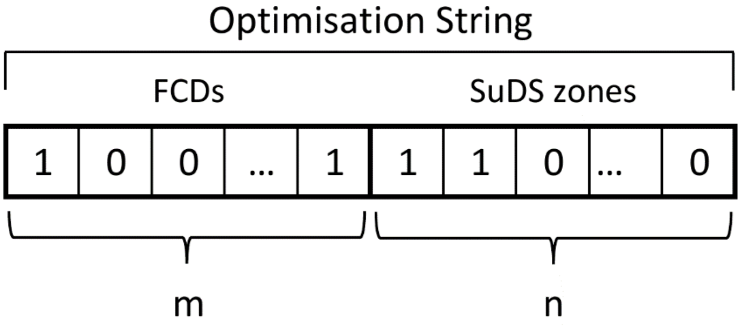


Figure 6.3: binary optimisation string representing a unique intervention scheme featuring FCDs coupled with SuDS zones; m and n are equal to the number of FCD locations and SuDS zones evaluated by the GA solver, respectively.

6.3.4.2 FCD locations evaluated by GA

For the case study network investigated, the wide range of possible combinations between the number and location of FCDs and/or SuDS is found to significantly limit the capability of the optimisation-based framework in selecting optimal placement schemes within a feasible timeframe. This is due to the computational runtime required to run a hydraulic simulation of a drainage model and assess potential candidates, which is by far the most time-consuming element for optimisation problems in UDS (Butler et al., 2018). Therefore, in order to reduce the search space of all feasible solutions evaluated by the GA solver, FCD locations with insufficient in-sewer storage capacity are discarded from the GA-based optimisation. This pre-screening analysis based on pipe storage potential, used in the early stages of RTC designs in sewer networks (Eulogi et al., 2022, 2021; Kroll et al., 2018; Leitão et al., 2017; Philippon et al., 2015), results in a drastic reduction of computational load, in which FCD locations judged highly unlikely to have significant impact in reducing CSO spills are discarded prior to the GA optimisation. In this study, in-sewer storage capacity corresponds to the maximum pipe volume that can be mobilised by the actuator to store stormwater volumes, calculated as the sum of in-pipe volumes upstream of the FCD location under the reference level RL (m A.D.). For each FCD location evaluated, reference level RL is computed under the static assumption (horizontal energy line) and is equal to the ground level decreased by a safety margin (0.1 m, see Leitão et al. (2017)).

In the Zona Central model, the pre-screening analysis based on in-sewer storage potential reduced the number of FCD locations tested by GA from 389 to 25 (minimum storage capacity set equal to 50 m^3), as shown by Eulogi et al. (2021). On the contrary, the pre-screening analysis shows limited impact in reducing the number of FCD locations tested in the Arendonk model, due to the mostly flat catchment (90% of pipe slopes vary between 0 m/m and 0.006 m/m) and hence the homogeneous distribution of in-sewer storage capacity within the drainage system. Therefore, additional constraints are added in the selection based on the position of the actuators within the sewer network, as proposed by Eulogi et al. (2022): FCD locations featuring in-sewer storage volume greater than 100 m^3 are selected along individual tributary branches only if positioned at the most downstream manholes, or positioned further upstream along the branches if different in-sewer storage capacity is mobilised by the flow controllers. The total number of FCD locations tested by GA in the Arendonk model is then decreased from

533 to 32. The total number of FCD locations and SuDS zones tested by GA are summarised in Table 6.2.

Table 6.2: number of SuDS zones and FCD locations tested by GA for each case study catchment investigated.

Case Study	Number of FCD locations in the baseline network	Number of FCD locations evaluated by GA	Number of SuDS zones evaluated by GA
Zona Central	389	25	12
Arendonk	533	32	14

6.4 Rainfall events

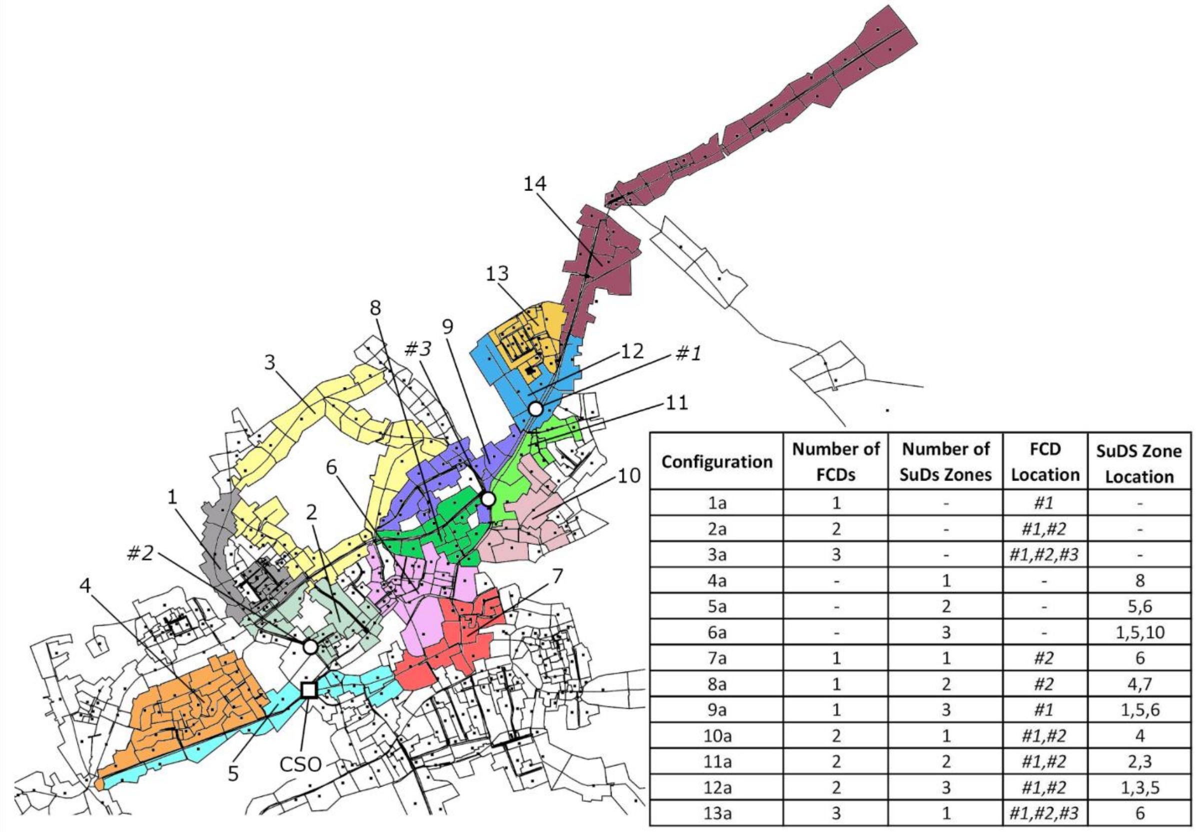
FCD and SuDS placement schemes are optimised by GA to minimise CSO spill volumes discharged during a synthetic storm event. In the Arendonk model, the synthetic storm has been selected following Flanders Environment Agency (VMM) design guidelines for sewer systems (Coördinatiecommissie Integraal Waterbeleid, 2012b), with return frequency of 7 times per year (storm occurring 7 times per year) and duration of 48 hours (time of aggregation 5 minutes). In the Zona Central model, the synthetic storm is based on Portuguese IDF curves (RGSPPDADAR, 1995) and obtained using the alternating block method (Chow et al., 1988), with a return period equal to 1 year and duration of 30 minutes (time of aggregation 5 minutes). Effectiveness of FCDs controlled by the RTC and SuDS in reducing CSO spill volumes is then evaluated during continuous rainfall time series. Different FCD-SuDS configurations are validated using regional long-term rainfall series (temporal resolution of 1 minute): a 3-year continuous rainfall series for the Arendonk catchment model (January 2006 - December 2008, Kroll et al., (2018)), and a 1-year continuous rainfall series for the Zona Central catchment model (January 2017 - December 2017). Hydraulic simulations were carried out using regional rainfall data available at Waterinfo.be. (n.d.) (station ‘Herentals’) and shared by the water utility Aqua de Coimbra (personal communication, November 2, 2021), in the Arendonk and Zona Central catchment models respectively. The rainfall temporal resolution and the RTC resolution (frequency of water level reading) are found suitable to properly capture the fast runoff processes and response time of the sewage systems during storm events.

6.5 Results

6.5.1 Arendonk catchment

Optimal FCDs and SuDS locations selected by GA for the synthetic storm in the Arendonk model are shown in Figure 6.4, for each configuration tested. In each RTC configuration investigated, FCDs are placed in different portions of the sewer network, with different pipe branches mobilised by the flow controllers to store stormwater volumes. GA does not always favour FCD locations close to the CSO regulated by the RTC system, flow controllers are instead placed in the upstream portion of the catchment in most of the configurations investigated. In the benchmark with SuDS scenario, SUDS are mostly located in the downstream and central portion of the catchment. When combining RTC with SuDS, flow controllers and SuDS zones are placed in separate portions of the catchment.

When reducing CSO spill volumes solely based on RTC, FCD placement schemes are found to be inclusive sets of solutions, such that FCDs can be potentially deployed in stages whilst maintaining an optimal spatial layout. For example FCD location #1 is selected by GA regardless of the total number of FCDs implemented to reduce CSO spill volumes. In contrast, non-inclusive sets of solutions are obtained in the *benchmark with SuDS* and *benchmark with RTC+SuDS* scenarios, in which implementation schemes are found to drastically change depending on the type and number of intervention measures implemented. When combining the RTC with SuDS, different FCD locations are obtained depending on the number of SuDS zones implemented. For example, when positioning 1 FCD within the catchment, FCD location #2 is selected by GA when combining the RTC with 2 SuDS zones (configuration #8a), while FCD location #1 is preferred when combining the RTC with 3 SuDS zones (configuration #9a). Similarly, in the *benchmark with RTC+SuDS* scenario, different SuDS locations are found by GA depending on the number of FCDs implemented.



Configuration	Number of FCDs	Number of SuDs Zones	FCD Location	SuDS Zone Location
1a	1	-	*#1*	-
2a	2	-	*#1,#2*	-
3a	3	-	*#1,#2,#3*	-
4a	-	1	-	8
5a	-	2	-	5,6
6a	-	3	-	1,5,10
7a	1	1	*#2*	6
8a	1	2	*#2*	4,7
9a	1	3	*#1*	1,5,6
10a	2	1	*#1,#2*	4
11a	2	2	*#1,#2*	2,3
12a	2	3	*#1,#2*	1,3,5
13a	3	1	*#1,#2,#3*	6

Figure 6.4: Optimal FCD and/or SuDS locations selected by GA in the Arendonk catchment.

Under the design rainfall event spill volume at the target CSO was found to be 731 m^3. The CSO spill volume reduction obtained in the Arendonk catchment for each configuration is shown in Figure 6.5, based on the number of FCDs and/or SuDS implemented. Overall, the implementation of RTC provides a higher CSO spill volume reduction compared to the implementation of SuDS. RTC enables to reduce CSO spill volumes between 31% (1 FCD) and 91% (3 FCDs), while the implementation of simplified infiltration-based SuDS provides a CSO spill volume reduction ranging between 5% and 21% (1 SuDS zone and 3 SuDS zones, respectively). Performance of the existing drainage infrastructure can be significantly improved by combining both intervention measures, with CSO discharges completely prevented when coupling 2 FCDs with 2 SuDS zones, or 3 FCDs with 1 SuDS zones.

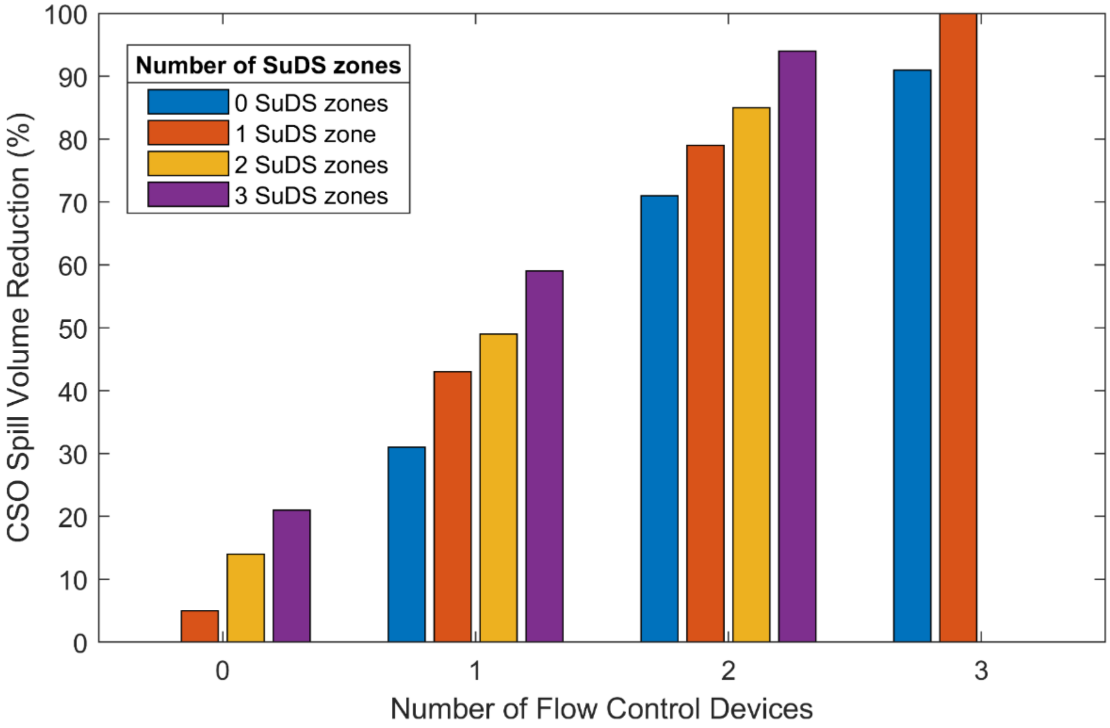


Figure 6.5: CSO spill volume reduction obtained in the Arendonk catchment, for different combinations of intervention measures implemented (CSO spill volume in baseline network equal to 731 m^3).

Results shown in Figure 6.5 also demonstrate how the combined implementation of RTC and SuDS leads to CSO spill volume reduction greater than the sum of the individual performance obtained by the two intervention measures. For example, overflow volumes discharged in the original network are reduced by 31% implementing 1 FCD and by 5% implementing 1 SuDS zone, while the 1-FCD 1-SuDS placement scheme provides a CSO spill volume reduction equal to 43%.

To consider the effectiveness of simultaneously optimising RTC and SuDS in contrast to optimising each system independently, CSO spill volume reductions obtained in the *benchmark with RTC+SuDS* scenario are compared to the performance obtained by combining FCDs and SuDS zones placed at optimal locations found in the *benchmark with RTC* and *benchmark with SuDS* scenarios respectively. As shown in Table 6.3, equal or higher CSO spill volume reductions are achieved when optimising the spatial allocation of the two intervention measures simultaneously rather than individually. The simultaneous optimisation of FCD and SUDS locations results in additional CSO spill volume reduction ranging between 4% (configuration #11a) and 10% (configuration #7a).

Table 6.3: Comparison between CSO spill volume reductions obtained by simultaneous and separate optimisation of FCD and SuDS locations within the Arendonk catchment.

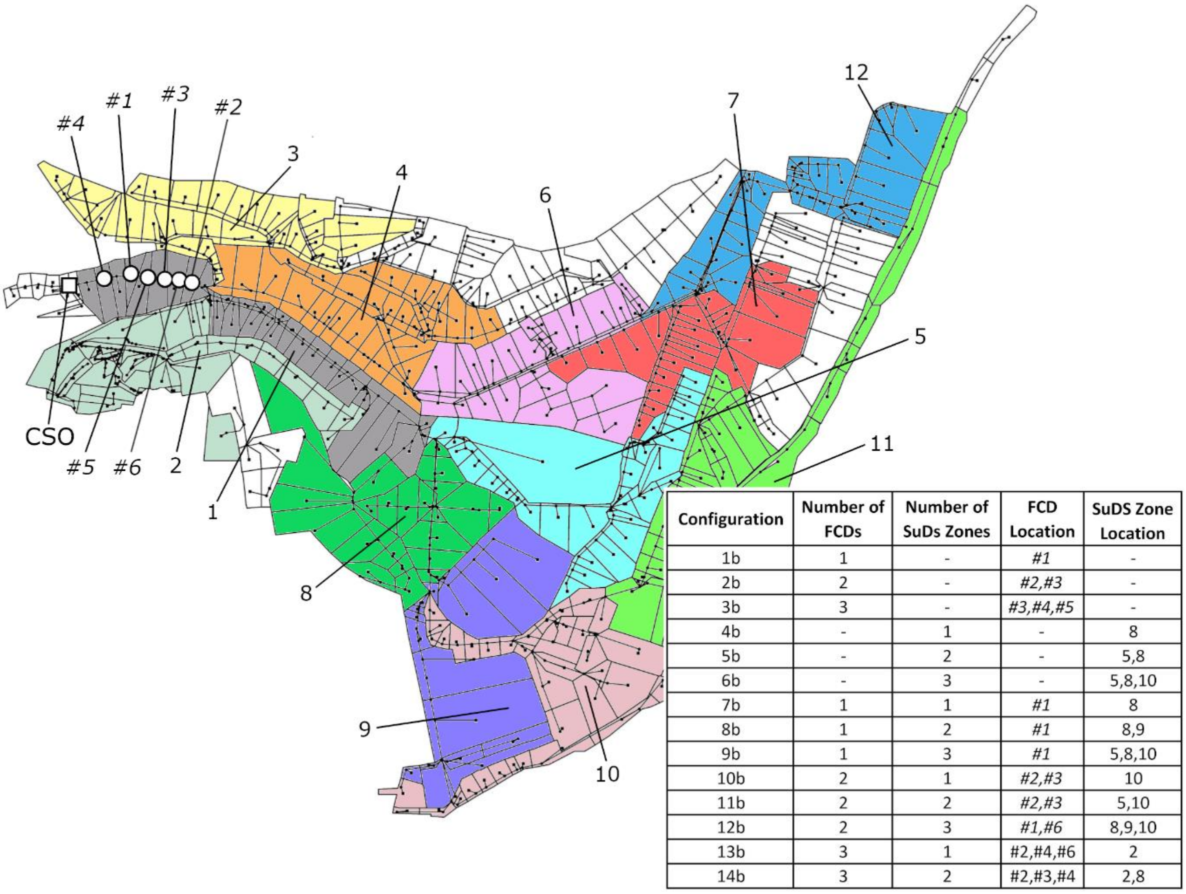
			FCD and SuDS locations obtained by GA in *benchmark with RTC+SuDS* scenario	FCD and SuDS locations obtained by GA in *benchmark with RTC* and *benchmark with SuDS* scenarios respectively
Number of FCDs	Number of SuDS zones	Configuration	CSO spill volume reduction (%)	
1	1	7a	43	33
1	2	8a	49	49
1	3	9a	59	51
2	1	10a	79	74
2	2	11a	85	81
2	3	12a	94	87
3	1	13a	100	100

6.5.2 Zona Central catchment

FCDs and SuDS locations found by GA in the Zona Central catchment are shown in Figure 6.6. Selected FCD positions are always located along the pipe branch immediately upstream of the CSO regulated by the RTC, while SuDS are mostly positioned in the central/upper portion of the catchment. Placement schemes found by GA in the *benchmark with RTC* and *benchmark with SuDS* scenarios still apply to a large extent when optimising the spatial allocation of the two intervention measures simultaneously. For example, FCD placement schemes obtained in the *benchmark with RTC* scenario still apply when combining 1 FCD with SuDS (configuration #7b, #8b and #9b), as well as when combining 2 FCDs with 1 or 2 SuDS zones (configuration #10b and #11b). Similarly, 1-FCD solution obtained in the *benchmark with RTC* scenario, together with the 1-SuDS and 3-SuDS solutions obtained in the *benchmark with SuDS* scenario, still apply when combining FCDs and SuDS zones in the *benchmark with RTC+SuDS* scenario. When reducing CSO spill volumes solely based on SuDS, placement schemes are found to be inclusive sets of solutions, with SuDS zones potentially deployed in subsequent stages while maintaining optimal spatial layout. Non-inclusive sets of solutions are instead obtained in the *benchmark with RTC* and *benchmark with RTC+SuDS* scenarios, in which the location of FCDs and/or SuDS zones may change depending on the number and type of intervention measures implemented.

Under the design rainfall event spill volume at the target CSO was found to be 2287 m^3. CSO spill volume reduction obtained in the Zona Central catchment is shown in Figure 6.7, based on the number of FCDs and/or SuDS zones implemented. Overflow volumes discharged in the original network are thus reduced between 18% and 48% in the *benchmark with RTC* scenario (up to 3 FCDs), while CSO spill volume reductions achieved in the *benchmark with RTC* scenario do not exceed 9% (with up to 2 SuDS zones). The performance of the existing drainage infrastructure can be further enhanced by combining both intervention measures, obtaining a

CSO spill volume reduction between 21% (1 FCD combined with 1 SuDS zone) and 54% (3 FCDs combined with 2 SuDS zones).



Configuration	Number of FCDs	Number of SuDs Zones	FCD Location	SuDS Zone Location
1b	1	-	*#1*	-
2b	2	-	*#2,#3*	-
3b	3	-	*#3,#4,#5*	-
4b	-	1	-	8
5b	-	2	-	5,8
6b	-	3	-	5,8,10
7b	1	1	*#1*	8
8b	1	2	*#1*	8,9
9b	1	3	*#1*	5,8,10
10b	2	1	*#2,#3*	10
11b	2	2	*#2,#3*	5,10
12b	2	3	*#1,#6*	8,9,10
13b	3	1	#2,#4,#6	2
14b	3	2	#2,#3,#4	2,8

Figure 6.6: Optimal FCDs and/or SuDS locations selected by GA in the Zona Central catchment.

In Table 6.4, CSO spill volume reductions obtained in the *benchmark with RTC+SuDS* scenario are compared to the performance obtained by placing FCDs and SuDS zones at locations found by GA in the *benchmark with RTC* and *benchmark with SuDS* scenarios respectively. The capability of RTC and SuDS zones in reducing overflow spills within the catchment can be maximised by optimising their spatial allocation simultaneously rather than individually, resulting in additional CSO spill volume reduction ranging between 0% (configuration #7b and #9b) and 7% (configuration #11b).

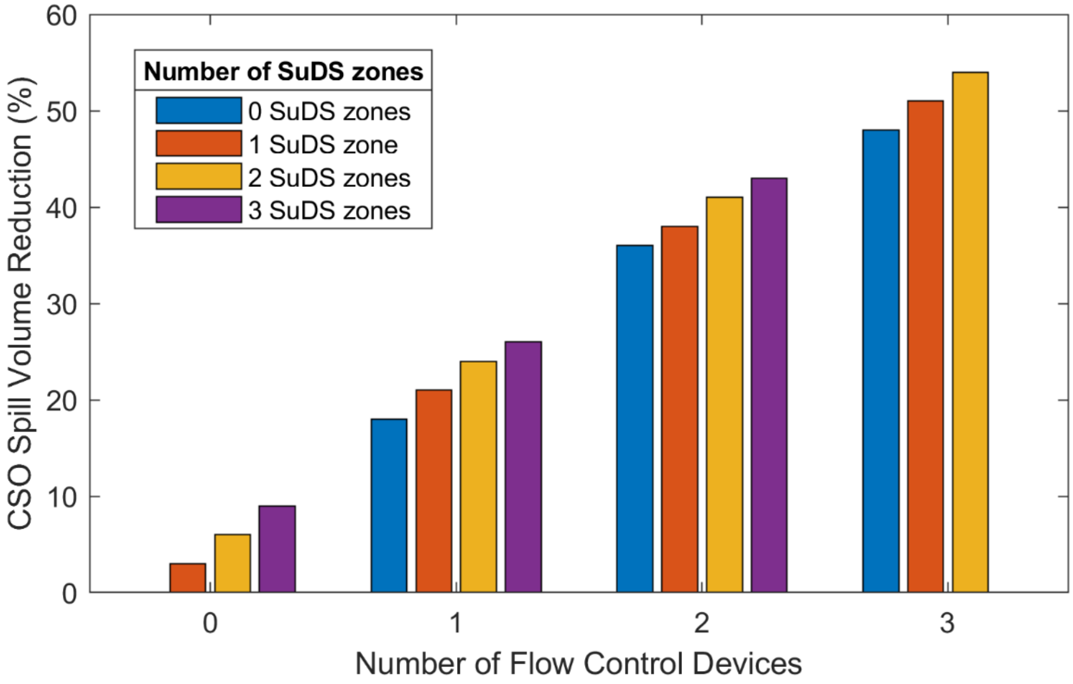


Figure 6.7: CSO spill volume reduction obtained in the Zona Central catchment, for different combinations of intervention measures implemented (CSO spill volume in baseline network equal to 2287 m^3).

Table 6.4: Comparison between CSO spill volume reductions obtained by simultaneous and separate optimisation of FCD and SuDS locations within the Zona Central catchment.

			FCD and SuDS locations obtained by GA in *benchmark with RTC+SuDS* scenario	FCD and SuDS locations obtained by GA in *benchmark with RTC* and *benchmark with SuDS* scenarios respectively
Number of FCDs	Number of SuDS zones	Configuration	CSO spill volume reduction (%)	
1	1	7b	21	21
1	2	8b	24	23
1	3	9b	26	26
2	1	10b	38	32
2	2	11b	41	34
2	3	12b	43	37
3	1	13b	51	50
3	2	14b	54	51

6.5.3 Validation with continuous rainfall series

The RTC and SuDS effectiveness in reducing CSO spill volumes is evaluated during continuous rainfall time series. Total CSO spill volume reduction obtained in the Arendonk and Zona Central models is shown in Table 6.5 and Table 6.6 respectively, based on the number and type of intervention measure implemented.

In the Arendonk catchment, the 3-SuDS placement scheme implementation enables to reduce by 11% the overflow volumes discharged at the regulated CSO during the 3-year rainfall series, while higher CSO spill volume reduction is obtained by combining SuDS with FCDs: 23% by coupling 1 FCD with 3 SuDS zones, 36% by coupling 2 FCDs with 3 SuDS zones and 3 FCDs with 1 SuDS zone. In the Zona Central catchment, total CSO spill volume discharged during the 1-year rainfall series is reduced by 13% by implementing 3 SuDS zones, while the implementation of FCDs combined with SuDS provides a total CSO spill volume reduction ranging between 30% (1-FCD 3-SuDS placement scheme) and 45% (3-FCDs 2-SuDS placement scheme). Overall, results demonstrate how CSO spill volumes can be efficiently reduced by combining green infrastructure in the catchment level with FCDs controlled by the RTC system in the sewage level, with equivalent CSO spill volume reduction obtained by different numbers and types of intervention measures in the Arendonk catchment.

Table 6.5: Overflow spill volume reduction achieved in the Arendonk catchment model for the 3-year rainfall series, based on the number and type of intervention measures implemented (overflow spill volume discharged at the regulated CSO in the baseline network equal to 86230 m^3).

Configuration	Number of FCDs	Number of SuDS Zones	Spill volume reduction compared with baseline network (%)
6a	-	3	11
9a	1	3	23
12a	2	3	36
13a	3	1	36

Table 6.6: Overflow spill volume reduction achieved in the Zona Central catchment model for the 1-year rainfall series, based on the number and type of intervention measures implemented (overflow spill volume discharged at the regulated CSO in the baseline network equal to 23650 m^3).

Configuration	Number of FCDs	Number of SuDS Zones	Spill volume reduction compared with baseline network (%)
6b	-	3	13
9b	1	3	30
12b	2	3	38
14b	3	2	45

6.6 Discussion

In this study, spatial allocation of locally controlled FCDs and simplified SuDS systems is optimised using a GA-based methodology to reduce CSO spill volumes in two case study catchments. Three scenarios are evaluated: CSO spill reduction solely based on RTC, CSO spill reduction solely based on SuDS, and CSO spill reduction achieved by RTC combined with SuDS.

When reducing overflow spills with the local RTC, large differences in spatial allocation of FCDs are obtained by GA depending on the case study catchment evaluated. This is mainly due to the different topography, pipe geometry and resulting distribution of storage capacity within the two case studies. In the flatter Arendonk catchment, the effect of a single partially or fully closed gate on flows and levels propagates far upstream along the pipe branches. The usage of existing storage capacity is thus maximised by GA by favouring FCDs positioned in different segments of the drainage system. In the Arendonk catchment GA also does not always favour FCD locations close to the CSO regulated by the RTC system, which might increase overflow spill volumes discharged at the other CSOs located in the central-upper portion of the catchment. Maximum capacity has been reached in several segments of the sewer network immediately upstream of the CSO, preventing the FCDs in successfully mobilise additional in-sewer storage capacity to store stormwater during rainfall events. In contrast, the Zona Central catchment features a single combined sewer overflow, steep pipe gradients in the central/upper portion of the catchment, and flatter pipe gradients in the downstream area where the CSO is located. This uneven distribution of in-sewer storage capacity leads to FCDs to be always positioned along the pipe branch immediately upstream of the CSO, where pipe diameters are significantly higher compared to other portions of the UDS. Due to the proximity between the FCDs, partially joint storage volume capacity is mobilised by the gates along the same pipe branch when storing run-off volumes during rainfall events.

SuDS zones are generally located in the central/upper portion of the Zona Central catchment, while central/lower catchment areas are preferred when allocating SuDS in the Arendonk model. This is mostly due to the different hydrological response of the catchments to rainfall inputs. Zona Central has steeper slopes and faster response time, with runoff attenuation in the upper part of the catchment resulting in efficient reduction of overflow volumes discharged at the single downstream CSO at the time of peak. Whereas Arendonk features a flatter network with multiple CSOs in the central/upstream part of the catchment, with the highest reduction of overflow volumes achieved by SUDs located closer to the regulated CSO.

In this study SuDS are implemented into clusters of subcatchments (i.e. SuDS zones), limiting the number of potential SuDS placement schemes tested by GA through hydraulic analysis. The impact of the SuDS in reducing CSO spills is influenced by the subdivision of the watershed into clusters of subcatchments, with different zonation potentially leading to higher CSO spill volume reduction achieved by smaller SuDS zones. The choice of SuDS zones' size is also expected to have a significant impact on the computational load required by the optimisation-simulation framework. Smaller SuDS zones can provide more tailored solutions to efficiently manage runoff volumes in the catchment level, limiting the conversion of impervious area to pervious area needed to achieve a given level of performance. However, smaller SuDS zones result in a higher number of possible combinations between the number and position of SuDS zones within the catchment, and therefore higher computational time needed by GA to identify near-optimal solutions. Bigger clusters of subcatchments instead lead to lower computational load at the expense of less refined SuDS placement schemes. In this study, the size of the SuDS zones has been found through initial trials to provide an efficient balance between the number of potential placement schemes tested by GA, rate of convergence and computational time. The impact of the choice of SuDS zones' size and location in reducing CSO spill volumes is left for future research, as this study is mainly focused on developing a simulation-optimisation framework to identify the optimal placement of RTC actuators combined with simplified SuDS systems within UDS.

SuDS are simulated as impervious area converted to pervious area, a highly simplified representation of green infrastructures that enhances the capability of the proposed GA-based method in identifying optimal SuDS placement schemes in a reasonable timeframe. Nonetheless, the methodology can be extended to consider specific types of SuDS (e.g. infiltration trenches, green roofs, detention basins…). Following the experience from this paper, it is hypothesized that it may be quicker to optimise their location selection by simulating the effect of simplified SuDS as a small number of changes to the runoff hydrograph from the sub-catchments (e.g. peak delay and/or reduction). After that, SuDS could be designed suiting the location selected by the optimisation-based framework while providing a desired runoff hydrograph. This process is thought to be more efficient than simultaneously optimising individual SuDS locations and design parameters such as type selection, infiltration capacity, SuDS dimensions, medium, especially when combining SuDS with FCDs controlled by RTC systems. Implementation of green infrastructures in highly urbanised areas is highly influenced by space availability and opportunity for retrofitting (e.g. land and home/commercial area ownership). When optimising specific types of SuDS, a more detailed spatial analysis of landscape and topographic conditions of the catchment through geographic information systems (GIS) can be used to exclude unfeasible SuDS placement schemes due to practical or socio-economic limitations (e.g. land use, land ownership), reducing the search space of all feasible solutions evaluated by the GA solver. As solution time may rise exponentially, a sensitivity analysis is recommended to better investigate the trade-off between computational time and number of SuDS decision variables included in the optimisation-based method. This analysis is left for further research, as this study is mainly focused on higher-level planning and design case of infiltration-based structures.

In both case studies, the implementation of locally controlled FCDs always correspond to higher CSO spill volume reduction compared to the implementation of simplified infiltration-based SuDS. Large portions of unused in-sewer storage capacity are mobilised by the flow controllers to regulate water level at the CSO, with significant CSO spill volume reduction obtained in both *benchmark with RTC* and *benchmark with RTC+SuDS* scenarios. The attenuation of runoff volumes obtained by SuDS results in limited CSO spill mitigation within the sewer networks, with SuDS performing slightly better during the less severe storm event in the Arendonk catchment (design storm occurring 7 times per year). FCD-SuDS configurations have also been tested during continuous rainfall time series, resulting in a reduction of CSO spill volumes discharged in the baseline networks ranging between 23% and 45% when combining the local RTC with green infrastructure. In the Arendonk catchment model, during the 3-year rainfall series equivalent CSO spill volume reduction is achieved by different combinations between number and position of FCDs and SuDS, providing different alternatives to mitigate the impact of CSO spills and fulfil environmental targets within the urban drainage system.

When coupling the local RTC with SuDS, higher performance is obtained when the spatial allocation of the two intervention measures is optimised simultaneously rather than individually, enhancing the combined benefits of FCDs and SuDS in managing runoff volumes. For example, in the Arendonk catchment, CSO spill volume reduction equal to 71% achieved by 2 FCDs can be further increased by 8% combining the RTC with 1 SuDS zone, and by 21% combining the RTC with 2 SuDS zones preventing the sewer overflow spill in the baseline network. Moreover, comparable CSO spill volume reduction can be achieved by different FCD-SuDS configurations, widening the choice of potential intervention schemes with a similar level of performance.

In this study, FCD and SuDS locations mostly change depending on the number of intervention measures implemented, resulting in largely different unique optimal placement schemes. While installation site accessibility and road/traffic management might delay or restrict the deployment of FCDs at specific control sites (i.e. manholes), an advantage of FCDs controlled by local RTC is that implemented FCDs can generally be repositioned at different locations, so that additional FCDs can be installed in the UDS while maintaining the optimal spatial layout. The GA-based optimisation can also be re-run to cope with new urban development and rainfall trends, adjusting the location of earlier placed FCDs if needed. Location of SuDS at catchment level is instead largely influenced by the opportunity of retrofitting and other factors such as land use and home/commercial area ownership, which may impede the implementation of optimal SuDS or RTC+SuDS configurations in stages. It would not be possible to relocate SuDS once implemented, it would only be possible to add more SuDS. However, compared to FCDs, SuDS can have various advantages such as amenity (Fletcher et al., 2015), increasing biodiversity (Pinho et al., 2016; Snäll et al., 2016), water quality improvement (Wu et al., 2019; Yang and Best, 2015) and restoration of infiltration, interception, and detention/retention regimes (Zhang and Chui, 2018).

6.7 Conclusion

In this paper, a novel simulation-optimisation framework is developed to optimise the spatial allocation of FCDs and simplified SuDS for CSO spill mitigation. SuDS are simulated by converting impervious area into pervious area within clusters of subcatchments, allowing the rapid assessment of a high number of potential placement schemes in a reasonable timeframe. Impacts of FCDs and SuDS in reducing CSO spills are maximised by implementing the two intervention measures simultaneously rather than individually, enhancing the combined benefits achieved by the two decentralised systems. When combining the local RTC with SuDS in the two case study networks evaluated, CSO spill volumes discharged over synthetic storm events are reduced between 21% and 100%, with efficient attenuation of runoff volumes achieved by green infrastructure in the catchment level, and optimised use of existing in-sewer storage capacity achieved by flow controllers in the drainage level. Placement schemes comprising of FCDs coupled with SuDS are also validated by comparing performance relative to the uncontrolled networks during continuous rainfall time series, showing how the simultaneous implementation of the two intervention measures allows to efficiently reduce overflow spill volumes over a wide range of rainfall inputs. Optimal FCDs and SuDS deployment is found to be largely influenced by the distribution of in-sewer storage capacity within the existing drainage infrastructure and the hydrological response of the catchment to rainfall inputs, especially in looped networks and flat catchments where the hydraulic interaction between FCDs and SUDS can be difficult to predict. The method can be applied to mitigate the consequences of population growth, urbanisation, and climate change, extending the range of applications of RTC combined with SuDS for CSO spill mitigation in urban drainage systems.

7 General discussion

In this research, a novel optimisation-simulation framework has been developed to determine the optimal spatial allocation of FCDs commanded by RTC systems in sewer networks. While in current methodologies FCD locations are usually ranked based on the static in-sewer storage volume mobilised by the flow controllers within the pipe network, the proposed framework consists of full hydraulic modelling of the RTC deployment and operation within the UDS. The impact of the FCD placement strategy on the RTC performance is evaluated through hydraulic analysis, considering the hydraulic interactions occurring between the flow controllers, their impact on the operation of existing UDS assets (e.g., pump stations, storage tanks), as well as the overall sewer system performance (e.g. CSO spill volumes, flood volumes, flow to wastewater treatment). This ensures a more robust selection of FCD placement strategies compared to current methods found in the literature, enhancing the benefits obtained by the RTC system when managing stormwater volumes in UDS. GA was found to be a suitable optimisation technique for designing FCD placement schemes through hydraulic modelling, easily adaptable to the chosen objective function (CSO spill volume reduction), featuring setting parameters and operators (selection, crossover and mutation) with clear impact on the overall optimisation outputs and easily adjustable, as well as an adequate trade-off between computational time, search space and rate of convergence. In future work, the proposed methodology for FCD location selection could be tested using other single point (e.g. simulated annealing) or population-based (e.g. particle swarm optimisation) heuristic methods, to better investigate the impact of the chosen optimisation solver on the RTC performance / time of convergence.

The proposed method has been tested in two case study catchments with different characteristics (shape, dimension, time of concentration, number and position of UDS assets, distribution of in-pipe storage capacity, hydraulic response to precipitation) identifying optimal locations for FCDs commanded by a local RTC called CENTAUR, for CSO spill volume reduction. FCD locations identified by the method resulted in significant reduction of CSO spills discharged in the baseline networks over typical design storms. For example, in the Coimbra catchment, CSO spill volumes were reduced between 40% and 90% when implementing 5 FCDs (1-year return period design storm, Section 4.4.1.2), while overflow volumes discharged at a single CSO in the Arendonk catchment were completely prevented when implementing 3 FCDs (design storm with a return frequency of 7 times per year, Section 5.4.1). The efficiency of the selected FCD placement schemes in mitigating sewer overflows was also assessed over a series of historical rainfall events and continuous rainfall time series (Section 5.4.3). In the Arendonk catchment, all CSO spills were prevented during storms with a return frequency of 10 times per year, while total CSO spill volumes were reduced by 80% and 19% for storms occurring 7 times per year and storms with return period between 1 and 3 years, respectively (overflow mitigation at a single CSO, see Table 5.1). In the latter catchment evaluated, the maximum hydraulic capacity was reached in large portions of the pipe network during more intense storm events, which affected the capability of the local RTC in controlling water level at the regulated CSOs. The benefits of the proposed FCD location selection methodology were more evident when placing gates in a flat sewer network, resulting in CSO spill volume reduction significantly higher compared to existing volume-based approaches (Arendonk model, Sections 5.4.1 and 5.4.2). When placing FCDs in a steeper dendritic sewer network, the uneven distribution of in-sewer storage capacity resulted in a limited number of potential FCD locations featuring sufficient upstream in-pipe storage potential to efficiently control stormwater volumes entering the sewage system, with backwater effects caused by partially or fully closed FCDs easier to predict without the need of hydraulic simulations (Coimbra model, Section 4.4.1.1). In future work, the proposed method for FCD location selection could be tested with a wider range of case study networks, to better investigate the correlation between optimal FCD positioning and specific catchment characteristics.

FCD placement schemes were found to be influenced by the storm event used in the optimisation process, with a decrease of up to 18% in CSO spill volume reduction achieved under storm events other than those used within the original optimisation (Section 4.4.1.2). This outcome was then further investigated by assessing the performance obtained by the RTC system during different classes of storms (Section 5.4.3.1): CSO spill volumes were found to be very sensitive to the spatial allocation of FCDs over high-frequency storms, while limited difference in CSO spill volume reduction was obtained by the RTC during storms with higher return periods. This is due to the type of design storm used in the optimisation-simulation framework, regardless of the number of FCDs implemented. Since FCD placement schemes were optimised over a high-frequency design storm, the spare in-pipe storage volume mobilised by the gates during similar storm events was instead completely utilised in all cases during more severe storms, which highly affected the capability of the RTC in efficiently managing stormwater volumes and controlling water levels at the regulated CSO structures. Results obtained in this research demonstrate how the choice of design storm used in the optimisation-simulation framework should be driven by the type of storm/overflow spill regulated (i.e., intensity, duration, return frequency), offering a tailored implementation of the local RTC to specific operational targets (e.g., reduction/prevention of frequent CSO spills multiple times per year, reduction of high-intensity CSO spills few times per year). In this regard, future research could investigate the potential benefits achieved by the local RTC when combined with on-line and off-line storage tanks: frequent CSO spills could be reduced and/or prevented by the RTC, while the RTC could operate concurrently with storage tanks to manage more severe storms once the maximum hydraulic capacity is reached within the existing pipe network.

The validation of the proposed method in different case study catchments also allowed a more rigorous evaluation of the computational efficiency of the GA-based solver, investigating the capability of the method in designing FCD placement schemes with low computational cost using accessible computational resources. In the case of a dendritic sewer network model featuring a reduced number of objects (i.e., nodes, links, subcatchments), the quick simulation times allowed a systematic performance evaluation of a high number of potential FCD placement strategies through hydraulic analysis, changing the number of FCDs implemented and using different types of storm events in the optimisation process (Coimbra model, Section 4.4.1.1). In the case of a more complex and computationally intensive sewer network model, the higher simulation times required additional constraints in the selection of potential FCD locations tested by the GA solver, which successfully reduced the computational time at the expense of a slightly less performing RTC (Arendonk model, Section 5.4.1). In this regard, the analysis of the static in-sewer storage volume within the baseline network offered a simple and efficient methodology to rapidly adjust the number of potential FCD locations hydraulically tested in the optimisation-based approach, and therefore lower its computational burden. A more refined selection of potential FCD locations could be developed in future work to further enhance the computational efficiency of the proposed optimisation-simulation framework, increasing its range of applications for stormwater management problems in UDS. Based on the results obtained in this research, a preliminary analysis of the spatial and temporal distribution of unused in-pipe storage capacity within the sewer network with no intervention (in-pipe volume unoccupied by stormwater volumes during rainfall events) could be used to discard control locations with upstream storage potential completely utilised in the baseline system, and combined to other indicators (e.g., relative distance between FCDs and regulated CSOs, catchment characteristics) to better identify potential FCD locations prior to optimisation. One could speculate that this indicator-based selection approach could potentially bypass the more time-consuming optimisation process, identifying sets of FCD locations with similar or equivalent performance to the GA-based solutions. However, the current work suggests that it is unfeasible to select optimal FCD locations based on the sewage system and catchment characteristics alone, especially in the case of complex case study networks with RTC commanding a high number of flow controllers. This is due to the complexity of the hydraulic interactions occurring between RTC actuators, and their impacts on existing UDS assets (e.g. filling/emptying cycles in storage tanks) as well as the overall sewer system performance (e.g. CSO spill volumes, flood volumes).

In the last decades, high-performance computing (HPC) systems and parallel processing enabled a wider implementation of GA-based methodologies for water and wastewater management problems in UDS, fastening the processing of numerical calculations and obtaining the optimal designs quicker. In parallel processing, the computational burden is split between multiple computational units, shifting the conventional computing architecture from conventional single central processing units (CPUs) to multi-CPU systems, high-speed networks, computing clusters, and more recently to multiple graphic processing units (GPUs) and high-speed cloud services. Parallelisation can be implemented at the algorithm level (Schryen, 2020) (e.g. decomposing the domain of search, computing the fitness of a solution in multiple parallel machines) as well as at the hydraulic model level (e.g. Li et al. 2011; Morales-Hernández et al., 2020). Since parallel processing and HPC are available in many water utilities modelling teams for urban catchment modelling, the GA pre-screening method discussed in Section 5.3.2.2 might not be necessary in case of parallel machine architectures capable of solving intensive computational tasks. However, the method remains valid to speed up the optimisation process in cases where the quality of the optimisation outputs does not justify the higher costs to create, debug and maintain parallel processing (e.g. analysis of RTC benefits at a planning / preliminary stage and/or using simplified sewer network models), or when parallel processing is simply not available for the task (Schryen, 2020). Alternatively, the proposed GA pre-screening method could be implemented to assess FCD placement schemes at a high-level planning, and the solutions later used as starting points by GA with a more detailed version of the hydraulic model and less stringent constraints in the FCD location selection, applying parallel processing.

The proposed framework can be used to assess the potential benefits of a local RTC in managing stormwater volumes within UDS, determining the optimal number and position of FCDs required by the system to fulfil specific operational targets (e.g. CSO spill volume reduction), or to adapt the RTC design and implementation to future scenarios of climate change, population growth and urban development, adjusting the location of earlier placed FCDs or planning the deployment of additional flow controllers in the sewage system. Future trends in precipitation are usually extrapolated from global and regional climate simulations with low temporal/spatial resolution (Fortier and Mailhot, 2015; Iles et al. 2020; Strandberg and Lind, 2020), making it difficult to predict how RTC will perform when mitigating CSO spills under future precipitation patterns and more extreme storms (Dirckx et al. 2018). In this regard, in case of local and distributed RTC such as CENTAUR, FCD placement schemes can be optimised using design storms featuring current rainfall characteristics, without incorporating future precipitation trends and therefore higher uncertainties in the design process. Thanks to the flexible deployment of such control systems, the positioning of FCDs can be progressively adapted to address the effects of climate change, guaranteeing a more refined and robust RTC deployment during its entire life cycle. In this research, the “best” FCD placement scheme was identified by the GA solver by minimising the arithmetic sum of the overflow spill volumes discharged at the regulated CSOs. In future work, a more comprehensive overview of the optimal trade-off between the number and position of FCDs and operational benefits of the system could be achieved by including other factors associated with the RTC deployment and operation (e.g., initial investment, operational costs, installation site accessibility, road and traffic management), unavailable in this research, within a cost-benefit analysis. Alternatively, the decision-making process could combine the total CSO spill volume and/or frequency reduction obtained by the RTC with the water quality of the receiving water bodies (e.g., prioritise mitigation of CSO spills for channels at highest risk, allow additional CSO spill volumes for channels at lower risk). This water quality analysis could be embedded in the RTC control algorithm, regulating both water volumes and pollutants discharged at the CSOs in real-time, or part of the GA-based methodology for the FCD location selection, requiring more data and computational power to model the concentration of pollutants within the sewage system. However, there are still significant research questions on how heterogeneous decision variables (e.g., CSO spill volume, installation site accessibility, pollutant concentration) should be weighted a priori when assessing FCD installation sites within a single-objective optimisation approach, or how results should lead the decision-making process in case of a multi-objective optimisation approach. Regarding the impact of the RTC deployment on the sewage system operation, WWTPs located downstream of the CSOs regulated by the RTC are expected to operate more smoothly with decreased fluctuations in flow patterns. The higher residence times and reduced flow velocities, due to the partially or fully closed FCDs, might increase the sedimentation of suspended solids (Song et al., 2018) as well as the production of hydrogen sulfide and methane under anaerobic conditions (Auguet et al. 2016). This can be mitigated by setting a minimum FCD opening degree in the RTC control algorithm, reducing the upstream storage volume mobilised by the gates. Overall, in future work the proposed GA-based methodology could be further developed by integrating the analysis of pollutant loads associated with stormwater runoffs to the hydraulic modelling, to further investigate the impact of the FCD placements schemes on the water quality of the sewage and receiving water bodies.

Uncertainties associated with the hydraulic modelling of the sewage system (e.g. input data, calibration data, model structure), as well as the temporal resolution of the rainfall data, are expected to impact the overall spatial distribution of FCDs found by the GA solver. The intrinsic errors embedded in the modelling process cannot be eliminated, a well-known limitation of the mathematical representation of physical phenomenon in the water cycle (Deletic et al. 2012). Final FCD implementation schemes are expected to rarely coincide exactly with simulation results in practice, due to practical considerations involved with the RTC deployment: installation site accessibility, road and traffic management, as well as the higher flood risk caused by the obstruction of flow in sewers that might dissuade water companies to install FCDs in sensitive areas (e.g. private properties, commercial buildings, schools). Therefore, simulation results are especially beneficial in the planning / preliminary stages to quickly assess potential RTC benefits and costs using hydraulic models and relatively fast optimisation methods. This analysis can then be followed by higher-accuracy modelling simulations, and/or CCTV inspections in later stages of the project to carry out a more refined performance evaluation and flood risk assessment of the RTC with a higher level of confidence. Lastly, the proposed GA-based method was further developed to optimise the spatial allocation of FCDs combined with simplified SuDS in urban catchments, for CSO spill volume reduction. SuDS were implemented into clusters of subcatchments (i.e. SuDS zones), to limit the number of potential SuDS placement schemes tested by GA through hydraulic analysis, and reduce the computational burden of the optimisation-simulation approach. Optimal FCD-SuDS intervention schemes were identified in two case study catchments with different characteristics, with a significant reduction of CSO spill volumes obtained during design storm events (Sections 6.5.1 and 6.5.2) as well as continuous rainfall time series (Section 6.5.3). The relative placement and design of RTC and SuDS systems were found to highly affect the overall performance of the UDS, with higher CSO spill volume reduction achieved by optimising the spatial allocation of FCDs and SuDS locations simultaneously rather than individually. This result shows how the proposed GA-based method can successfully maximise the combined benefits of the two technologies when increasing the water storage capacity of urban catchments, highlighting the unexplored potential of FCD-SuDS intervention schemes as a flexible decentralised solution for stormwater management. Results suggest that the combined benefits of SuDS and FCDs in mitigating CSO spills are linked to the hydraulic interactions occurring between the two measures when managing run-off volumes within the UDS. In the steeper Zona Central sewer network, the most effective RTC+SuDS configurations are composed by FCDs located close to the outlet and SuDS positioned in the central-upper portion of the catchment. The attenuation/retention of run-off volumes achieved by placing SuDS in the central-upper portion of the network (such that the travel time between SuDS structures and CSO outlet is at least half the time of concentration or more, for runoff towards CSO outlet), which ensures higher in-pipe storage volumes available for the gates along the downstream pipe branches of the sewer system. This leads to a more effective regulation of water level at the CSO at the time of peak flow. In contrast, in the flatter Arendonk sewer network which fills up more like a ‘bathtub’, SuDS and FCDs work concurrently in attenuating flows contributing to the CSO location. In Arendonk, the SuDS were found more effective when retaining run-off volumes at the time of peak flow if positioned closer to the regulated CSO, and FCDs mobilising unused packages of storage capacity in upper portions of the sewage system. Hence more research is needed to understand how SuDS and flow controllers hydraulically interact in different types of catchments, when implemented for CSO spill mitigation in UDS, and why specific RTC+SuDS configurations outperform the sum of individual performance obtained by the two intervention measures. In future work, additional case study catchments or artificial sewer network models might be used to better correlate single catchment characteristics (shape, dimension, time of concentration, position of UDS assets, distribution of in-pipe storage capacity, hydraulic response to precipitation) with the relative placement of SuDS and FCDs, potentially giving general rules or indicators on how to design RTC+SuDS placement schemes and further enhance the combined benefits of the two systems. Moreover, since different types of SuDS (e.g., infiltration trenches, green roofs, detention basins…) have a diverse impact on combined sewer overflows (Joshi et al., 2021), the highly simplified representation of SuDS used in this research (Section 6.3.2) provides only a partial understanding on how FCDs and green infrastructures hydraulically interact when managing run-off volumes in sewage systems for real case scenarios. This could be further investigated by combining the local RTC with specific SuDS configurations, assessing how different green-based strategies for retrofitting existing developed areas influence the dynamic control of stormwater volumes achieved by the RTC in the drainage system. A spatial analysis of the catchment land use, slope, soil properties and elevation, together with economic and social criteria (Bach et al., 2020; Makropoulos et al., 2008) could be used to select feasible sets of SuDS configurations (i.e. number and type of SuDS) in each SuDS zone evaluated by the GA-based method, then optimised along with the location of flow controllers with an integer optimisation approach.

8 General conclusion

In this research, a novel optimisation-simulation framework is developed to determine the optimal spatial allocation of FCDs commanded by RTC systems in sewer networks. The analysis of the static in-pipe storage capacity within the pipe network, currently found as the main criteria to place flow controllers in the literature, is replaced by full hydraulic modelling of the RTC deployment and operation during storm events. In the proposed framework, the performance of a high number of possible FCD implementation strategies is tested through hydraulic analysis, and the optimal set of FCD locations identified through single objective optimisation (i.e. CSO spill volume reduction). While current static volume-based approaches can be used for a rapid assessment of potential FCD locations, the proposed method allows to fully examine how the choice of FCD placement strategy affects the RTC performance, offering a more efficient deployment of FCDs commanded by RTC in sewer networks.

The proposed optimisation-simulation framework is tested in two case study catchments with different characteristics: a steeper dendritic combined sewer network in Portugal (Coimbra model, pipe slopes varying between -0.51 and 2.26 m/m with 90% between -0.08 and 0.22 m/m, contributing area of 89 ha, single CSO structure), and a flatter combined sewer network in Flanders (Arendonk model, pipe slopes varying between -0.044 m/m and 0.88 m/m with 90% between 0m/m and 0.006 m/m, contributing area of 113 ha, 16 CSO structures). Placement schemes are selected for FCDs commanded by a local and decentralised RTC called CENTAUR, for CSO spill volume reduction over typical design storms. RTC designs are then validated during selected historic rainfall events as well as a continuous rainfall time series. Overall, results demonstrate how the proposed method is capable of identifying optimal FCD placement schemes in a reasonable timeframe (days) using standard computational resources (Intel E5-2637 processor, 32GB of RAM), in small as well as medium-size/large networks. The design method can be used by modellers and operators to determine the optimal trade-off between the number and position of FCDs required by RTC to fulfil specific operational targets (e.g. CSO spill volume and frequency reduction), adjusting the locations of earlier placed FCDs to address future changes in run-off volumes, and determining the optimal location of additional flow controllers once resources are available to expand the RTC.

The local RTC was capable of reducing/preventing CSO spills during frequent storms, while diminishing the total CSO spill volume discharged over more intense storms. An example is the implementation of CENTAUR as a 3-gate system in the Coimbra model, which allowed to prevent all overflow spills for storms with a return frequency of 10 times per year, while reducing the total CSO spill volume by 80% and 19% for storms occurring 7 times per year and storms with return period between 1 and 3 years, respectively. FCD placement schemes selected by the optimisation-based method always result in higher CSO spill volume reduction compared to those obtained by a conventional static volume-based approach. This is due to the capability of the method in assessing the hydraulic interactions occurring between the FCDs, their influence on the operation of other UDS assets, and the impact of the FCD placement strategy on the dynamic control of run-off volumes in the pipe network. Optimal spatial allocation of FCDs is found to be highly influenced by the catchment characteristics (shape, dimension, time of concentration, position of UDS assets, distribution of in-pipe storage capacity, hydraulic response to precipitation). An optimisation technique that utilises a full hydraulic modelling is especially recommended for flatter sewer networks, where the effect of partially or fully closed gates on flows and levels propagates far upstream along the pipe branches. Backwater effects caused by flow controllers are instead easier to predict in a steeper sewer network, without the need of detailed hydraulic modelling.

The simulation-optimisation framework is then further developed to optimise the spatial allocation of FCDs combined with simplified infiltration-based SuDS. FCD-SuDS configuration schemes are designed in two case study catchments with different characteristics, minimising CSO spill volumes discharged over typical design storms as well as continuous rainfall time series. The simultaneous implementation of RTC and SuDS significantly reduced the total CSO spill volumes discharged in the catchments over a wide range of rainfall inputs, retaining run-off volumes before they enter the drainage system while maximising the use of available storage in the sewer network. Higher CSO spill volume reduction is obtained by optimising their spatial allocation simultaneously rather than individually, demonstrating how the proposed FCD location selection can successfully maximise the combined benefits of the two systems when controlling stormwater and wastewater volumes in urban catchments.

Overall, the proposed method provides a quicker and more efficient placement of FCDs compared to current trial-and-error approaches commonly used by water utilities and consultancies, facilitating the design and implementation of RTC in sewer networks. Findings of this research also demonstrate the still unexplored potential of local RTC as decentralised multi-gate control systems to manage CSO spills, offering an adaptable and easy-to-deploy alternative to more complex global RTC. Outcomes of this research are expected to deliver further options in adapting existing UDS to future scenarios of climate change, population growth and urban development, and expand the range of applications of RTC systems for stormwater management problems in UDS.

References

Abdel-Aal, M., Shepherd, W., Mounce, S.R., Ostojin, S., Schellart, A., Shucksmith, J., P.J, S., Tait, S., 2016. Alleviating The Risk of Sewer Flooding using Fuzzy Logic in a Real Time Control System – An Experimental Study, in: 8th International Conference on Sewer Processes and Networks. Rotterdam, The Netherlands.

Altobelli, M., Cipolla, S.S., Maglionico, M., 2020. Combined Application of Real-Time Control and Green Technologies to Urban Drainage Systems. Water 12, 3432. https://doi.org/https://doi.org/10.3390/w12123432

Arabi, M., Govindaraju, R.S., Hantush, M.M., 2006. Cost-effective allocation of watershed management practices using a genetic algorithm. Water Resour. Res. 42. https://doi.org/10.1029/2006WR004931

Auguet, O., Pijuana M., Borrego C. M., Gutierrez, O., 2016. Control of sulfide and methane production in anaerobic sewer systems by means of Downstream Nitrite Dosage. Sci. Total Environ. 550, 1116–1125. https://doi.org/10.1016/j.scitotenv.2016.01.130

Bach, P.M., Kuller, M., McCarthy, D.T., Deletic, A., 2020. A spatial planning-support system for generating decentralised urban stormwater management schemes. Sci. Total Environ. 726, 138282. https://doi.org/10.1016/j.scitotenv.2020.138282

Baek, S.S., Choi, D.H., Jung, J.W., Lee, H.J., Lee, H., Yoon, K.S., Cho, K.H., 2015. Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: Experimental and modeling approach. Water Res. 86, 122–131. https://doi.org/10.1016/j.watres.2015.08.038

Bakhshipour, A.E., Dittmer, U., Haghighi, A., Nowak, W., 2019. Hybrid green-blue-gray decentralized urban drainage systems design , a simulation-optimization framework. J. Environ. Manage. 249, 109364. https://doi.org/10.1016/j.jenvman.2019.109364

Beeneken, T., Erbe, V., Messmer, A., Reder, C., Rohlfing, R., Scheer, M., Schuetze, M., Schumacher, B., Weilandt, M., Weyand, M., 2013. Real time control (RTC) of urban drainage systems – A discussion of the additional efforts compared to conventionally operated systems. Urban Water J. 10, 293–299. https://doi.org/10.1080/1573062X.2013.790980

Berggren, K., Olofsson, M., Viklander, M., Svensson, G., Gustafsson, A., 2012. Hydraulic Impacts on Urban Drainage Systems due to Changes in Rainfall Caused by Climatic Change. J. Hydrol. Eng. 17, 92–98. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000406

Brasil, J., Macedo, M., Lago, C., Oliveira, T., Júnior, M., Oliveira, T., Mendiondo, E., 2021. Nature-Based Solutions and Real-Time Control: Challenges and Opportunities. Water 13, 651. https://doi.org/https://doi.org/ 10.3390/w13050651

Butler, D., James, D.C., Makropoulos, C., Davies, J.W., 2018. Urban Drainage, Fourth ed. Taylor & Francis Group, Boca Raton, FL.

Butler, D., McEntee, B., Onof, C., Hagger, A., 2007. Sewer storage tank performance under climate change. Water Sci. Technol. 56, 29–35. https://doi.org/10.2166/wst.2007.760

Campisano, A., Cabot Ple, J., Muschalla, D., Pleau, M., Vanrolleghem, P.A., 2013. Potential and limitations of modern equipment for real time control of urban wastewater systems. Urban Water J. 10, 300–311.

Campisano, A., Schilling, W., Modica, C., 2000. Regulators' setup with application to the Roma-Cecchignola combined sewer system. Urban Water J. 2, 235–242. https://doi.org/10.1016/s1462-0758(00)00061-3

Carbone, M., Garofalo, G., Piro, P., 2014. Decentralized real time control in combined sewer system by using smart objects, in: Procedia Engineering. pp. 473–478. https://doi.org/10.1016/j.proeng.2014.11.237

CEC, 1991. Council Directive of 21 May 1991 concerning urban waste water treatment

(91/271/EEC), Official Journal of the European Communities.

Cembrano, G., Quevedo, J., Salamero, M., Puig, V., Figueras, J., Martí, J., 2004. Optimal control of urban drainage systems. A case study. Control Eng. Pract. 12, 1–9.

Cho, J., Seok Sung, K., Ryong Ha, S., 2004. A river water quality management model for optimising regional wastewater treatment using a genetic algorithm. J. Environ. Manage. 73, 229–242. https://doi.org/10.1016/j.jenvman.2004.07.004

Chow, V.T., Maidment, D.R., Mays, L.W., 1988. Applied Hydrology.

Cimorelli, L., Morlando, F., Cozzolino, L., Covelli, C., Della Morte, R., Pianese, D., 2015. Optimal Positioning and Sizing of Detention Tanks within Urban Drainage Networks. J. Irrig. Drain. Eng. 142. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000927

Coördinatiecommissie Integraal Waterbeleid, 2012a. Composite storms for the design of sewer systems [in Dutch]. URL https://www.integraalwaterbeleid.be/nl/publicaties/code-goede-praktijk-rioleringssystemen/composietbuien2013_csv.zip/view (accessed 25/02/2021).

Coördinatiecommissie Integraal Waterbeleid, 2012b. Code of good practice for the design, construction and the maintenance of drainage systems [in Dutch]. Erembodegem, Belgium.

Cunha, M.C., Zeferino, J.A., Simões, N.E., Saldarriaga, J.G., 2016. Optimal location and sizing of storage units in a drainage system. Environ. Model. Softw. 83, 155–166. https://doi.org/10.1016/j.envsoft.2016.05.015

Damodaram, C., Zechman, E.M., 2013. Simulation-optimization approach to design low impact development for managing peak flow alterations in urbanizing watersheds. J. Water Resour. Plan. Manag. 139, 290–298. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000251

Darsono, S., Labadie, J.W., 2007. Neural-optimal control algorithm for real-time regulation of in-line storage in combined sewer systems. Environ. Model. Softw. 22, 1349–1361.

https://doi.org/10.1016/j.envsoft.2006.09.005

De Sousa, M.R.C., Montalto, F.A., Spatari, S., 2012. Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies. J. Ind. Ecol. 16, 901–913. https://doi.org/10.1111/j.1530-9290.2012.00534.x

Deletic, A., Dotto, C.B.S., McCarthy, D.T., Kleidorfer, M., Freni, G., Mannina, G., Uhl, M., Henrichs, M., Fletcher, T.D., Rauch, W., Bertrand-Krajewski, J.L., Tait, S., 2012. Assessing uncertainties in urban drainage models. Phys. Chem. Earth 42–44, 3–10. https://doi.org/10.1016/j.pce.2011.04.007

Dirckx, G., Schütze, M., Kroll, S., Thoeye, C., De Gueldre, G., Van De Steene, B., 2011. Cost-efficiency of RTC for CSO impact mitigation. Urban Water J. 8, 367–377. https://doi.org/10.1080/1573062X.2011.630092

Dirckx, G., Van Assel, J., Weemaes, M., 2014. Real Time Control From Desk Study to Full Implementation, in: 13th International Conference on Urban Drainage. Sarawak, Malaysia.

Duan, H.F., Li, F., Yan, H., 2016. Multi-Objective Optimal Design of Detention Tanks in the Urban Stormwater Drainage System: LID Implementation and Analysis. Water Resour. Manag. 30, 4635–4648. https://doi.org/10.1007/s11269-016-1444-1

Eckart, K., McPhee, Z., Bolisetti, T., 2018. Multiobjective optimization of low impact development stormwater controls. J. Hydrol. 562, 564–576. https://doi.org/10.1016/j.jhydrol.2018.04.068

Environment Agency, 2018. Storm Overflow Assessment Framework. URL https://www.water.org.uk/wp-content/uploads/2018/12/SOAF.pdf (accessed 25/02/2022).

EPA, 2006. Real Time Control of Urban Drainage Networks. U.S. Environmental Protection Agency, Washington, DC, Technical report EPA/600/R- 06/120. URL https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryID=159366 (accessed 25/02/2022)

Erbe, V., Schütze, M., Haas, U.., 2007. Application of a guideline document for sewer system real time control, in: Novatech 2007. Lyon, France.

Eulogi, M., Ostojin, S., Skipworth, P., Kroll, S., Shucksmith, J.D., Schellart, A., 2022. Comparing methods to place adaptive local RTC actuators for spill volume reduction from multiple CSOs. J. Hydroinformatics 24, 78–92. https://doi.org/10.2166/hydro.2021.085

Eulogi, M., Ostojin, S., Skipworth, P., Shucksmith, J.D., Schellart, A., 2021. Hydraulic optimisation of multiple flow control locations for the design of local real time control systems. Urban Water J. 18, 91–100. https://doi.org/10.1080/1573062x.2020.1860238

EurEau, 2016. Overflows from collecting systems. Brussels, Belgium. URL https://www.eureau.org/resources/position-papers/119-overflows-from-collecting-systems-may-2016/file (accessed 25/02/2022)

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2015. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water J. 12, 525–542. https://doi.org/10.1080/1573062X.2014.916314

Fortier, C., Mailhot, A., 2015. Climate Change Impact on Combined Sewer Overflows. J. Water Resour. Plan. Manag. 141. https://doi.org/10.1061/(asce)wr.1943-5452.0000468

Fortier, C., Mailhot, A., 2015. Climate Change Impact on Combined Sewer Overflows. J. Water Resour. Plan. Manag. 141. https://doi.org/10.1061/(asce)wr.1943-5452.0000468

Fu, G., Butler, D., Khu, S.T., 2008. Multiple objective optimal control of integrated urban wastewater systems. Environ. Model. Softw. 23, 225–234.

Fuchs, L., Beeneken, T., 2005. Development and implementation of a real time control strategy for the sewer system of the city of Vienna. Water Sci. Technol. 52, 187–194. https://doi.org/10.2166/wst.2005.0133

Gaborit, E., Muschalla, D., Vallet, B., Vanrolleghem, P.A., Anctil, F., 2013. Improving the performance of stormwater detention basins by real-time control using rainfall forecasts. Urban Water J. 10, 230–246. https://doi.org/10.1080/1573062X.2012.726229

García, L., Barreiro-Gomez, J., Escobar, E., Téllez, D., Quijano, N., Ocampo-Martinez, C., 2015. Modeling and real-time control of urban drainage systems: A review. Adv. Water Resour. 85, 120–132. https://doi.org/10.1016/j.advwatres.2015.08.007

Garofalo, G., Giordano, A., Piro, P., Spezzano, G., Vinci, A., 2016. A distributed real-time approach for mitigating CSO and flooding in urban drainage systems. J. Netw. Comput. Appl. 78, 30–42. https://doi.org/https://doi.org/10.1016/j.jnca.2016.11.004

Gersonius, B., Ashley, R., Pathirana, A., Zevenbergen, C., 2013. Climate change uncertainty: Building flexibility into water and flood risk infrastructure. Clim. Change 116, 411–423. https://doi.org/10.1007/s10584-012-0494-5

Giacomoni, M.H., Joseph, J., 2017. Multi-Objective Evolutionary Optimization and Monte Carlo Simulation for Placement of Low Impact Development in the Catchment Scale. J. Water Resour. Plan. Manag. 143, 04017053. https://doi.org/10.1061/(asce)wr.1943-5452.0000812

Grum, M., Thornberg, D., L Christensen, M., A Shididi, S., Thirsing, C., 2011. Full-Scale Real Time Control Demonstration Project in Copenhagen’s Largest Urban Drainage Catchments, in: 12th International Conference on Urban Drainage. Porto Alegre, Brazil.

Guthrie, G., 2019. Real options analysis of climate-change adaptation: investment flexibility and extreme weather events. Clim. Change 156, 231–253. https://doi.org/10.1007/s10584-019-02529-z

Harrell, L.J., Ranjithan, R.S., 2003. Detention pond design and land use planning for watershed management. J. Water Resour. Plan. Manag. 129, 98–106. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:2(98)

Hosseinzadehtalaei, P., Tabari, H., Willems, P., 2020. Climate change impact on short-duration extreme precipitation and intensity–duration–frequency curves over Europe. J. Hydrol. 590, 125249. https://doi.org/10.1016/j.jhydrol.2020.125249

Iles, C.E., Vautard, R., Strachan, J., Joussaume, S., Eggen, B.R., Hewitt, C.D., 2020. The benefits of increasing resolution in global and regional climate simulations for European climate extremes. Geosci. Model. Dev. 13, 5583–5607. https://doi.org/10.5194/gmd-13-5583-2020

Islam, A., Hassini, S., El-dakhakhni, W., 2021. A systematic bibliometric review of optimization and resilience within low impact development stormwater management practices. J. Hydrol. 599, 126457. https://doi.org/10.1016/j.jhydrol.2021.126457

Jean, M., Morin, C., Duchesne, S., Pelletier, G., Pleau, M., 2022. Real-time model predictive and rule-based control with green infrastructures to reduce combined sewer overflows. Water Res. 221, 118753. https://doi.org/10.1016/j.watres.2022.118753

Joshi, P., Leitão, J.P., Maurer, M., Bach, P.M., 2021. Not all SuDS are created equal: Impact of different approaches on combined sewer overflows. Water Res. 191, 116780. https://doi.org/10.1016/j.watres.2020.116780

Karamouz, M., Nazif, S., 2013. Reliability-Based Flood Management in Urban Watersheds Considering Climate Change Impacts. J. Water Resour. Plan. Manag. 139, 520–533. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000345

Klepiszewski, K., Schmitt, T.G., 2002. Comparison of conventional rule based flow control with control processes based on fuzzy logic in a combined sewer system. Water Sci. Technol. 46, 77–84.

Kokash, N., 2005. An introduction to heuristic algorithms. Department of Informatics and

Telecommunications, University of Trento, Italy. URL https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.105.8050&rep=rep1&type=pdf (accessed 25/02/2022).

Kroll, S., Weemaes, M., Van Impe, J., Willems, P., 2018. A Methodology for the Design of RTC Strategies for Combined Sewer Networks. Water 10, 1675. https://doi.org/10.3390/w10111675

Leitão, J.P., Carbajal, J.P., Rieckermann, J., Simões, N.E., Sá Marques, A., de Sousa, L.M., 2017. Identifying the best locations to install flow control devices in sewer networks to enable in-sewer storage. J. Hydrol. 556, 371–383. https://doi.org/https://doi.org/10.1016/j.jhydrol.2017.11.020

Li, T., Wang, G., Chen, J., Wang, H., 2011. Dynamic parallelization of hydrological model simulations. Environ. Model. Softw. 26, 1736–1746. https://doi.org/10.1016/j.envsoft.2011.07.015

Limbrunner, J.F., Vogel, R.M., Chapra, S.C., Kirshen, P.H., 2013. Optimal location of sediment-trapping best management practices for nonpoint source load management. J. Water Resour. Plan. Manag. 139, 478–485. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000316

Limbrunner, J.F., Vogel, R.M., Chapra, S.C., Kirshen, P.H., 2013a. Classic Optimization Techniques Applied to Stormwater and Nonpoint Source Pollution Management at the Watershed Scale. J. Water Resour. Plan. Manag. 139, 486–491.

Limbrunner, J.F., Vogel, R.M., Chapra, S.C., Kirshen, P.H., 2013b. Optimal location of sediment-trapping best management practices for nonpoint source load management. J. Water Resour. Plan. Manag. 139, 478–485. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000316

Lin, M., Tsai, J., Yu, C., 2012. A Review of Deterministic Optimization Methods in

Engineering and Management. Math. Probl. Eng. 2012, 1–15. https://doi.org/10.1155/2012/756023

Lin, M., Tsai, J., Yu, C., 2012. A Review of Deterministic Optimization Methods in Engineering and Management. Math. Probl. Eng. 2012, 1–15. https://doi.org/10.1155/2012/756023

Liu, J., Wang, J., Ding, X., Shao, W., Mei, C., Li, Z., Wang, K., 2020. Assessing the mitigation of greenhouse gas emissions from a green infrastructure-based urban drainage system. Appl. Energy 278, 115686. https://doi.org/10.1016/j.apenergy.2020.115686

Lund, N.S. V., Falk, A.K. V., Borup, M., Madsen, H., Mikkelsen, P.S., 2018. Model predictive control of urban drainage systems: A review and perspective towards smart real-time water management. Crit. Rev. Environ. Sci. Technol. 48, 279–339. https://doi.org/https://doi.org/10.1080/10643389.2018.1455484

Madsen, H., Lawrence, D., Lang, M., Martinkova, M., Kjeldsen, T.R., 2014. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. J. Hydrol. 519, 3634–3650. https://doi.org/10.1016/j.jhydrol.2014.11.003

Maeda, M., Mizushima, H., Ito, K., 2002. Development of the Real-Time Control (RTC) system for Tokyo Sewage system, in: Ninth International Conference on Urban Drainage (9ICUD). Lloyd Center Doubletree Hotel, Portland, Oregon, United States.

Makropoulos, C.K., Natsis, K., Liu, S., Mittas, K., Butler, D., 2008. Decision support for sustainable option selection in integrated urban water management. Environ. Model. Softw. 23, 1448–1460. https://doi.org/10.1016/j.envsoft.2008.04.010

Maluf, L., Shepherd, W., Ostojin, S., Simões, N., Sá Marques, A., Mounce, S., Skipworth, P., 2017. Real time flow control to utilise existing in- sewer storage, in: 14th IWA/IAHR International Conference on Urban Drainage. Prague, CZ.

Mandarano, L., Meenar, M., 2017. Equitable distribution of green stormwater infrastructure: a capacity-based framework for implementation in disadvantaged communities. Local Environ. 22, 1338–1357. https://doi.org/10.1080/13549839.2017.1345878

Mao, X., Jia, H., Yu, S.L., 2017. Assessing the ecological benefits of aggregate LID-BMPs through modelling. Ecol. Modell. 353, 139–149. https://doi.org/10.1016/j.ecolmodel.2016.10.018

Matlab (2018). Global Optimization Toolbox, version 9.4.0.813654 (R2018a). Natick, Massachusetts: The MathWorks Inc. URL: https://uk.mathworks.com/help/gads/ga.html (accessed 28/06/2022)

McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol. Sci. J. 61, 2295–2311. https://doi.org/10.1080/02626667.2015.1128084

Meneses, E.J., Gaussens, M., Jakobsen, C., Mikkelsen, P.S., Grum, M., Vezzaro, L., 2018. Coordinating Rule-Based and System-Wide Model Predictive Control Strategies to Reduce Storage Expansion of Combined Urban Drainage Systems: The Case Study of Lundtofte, Denmark. Water 10, 76. https://doi.org/10.3390/w10010076

Miguez, M.G., Rezende, O.M., Veról, A.P., 2015. City Growth and Urban Drainage Alternatives: Sustainability Challenge. J. Urban Plan. Dev. 141, 04014026. https://doi.org/10.1061/(asce)up.1943-5444.0000219

Milieu, 2016. Assessment of impact of storm water overflows from combined waste water collecting systems on water bodies (including the marine environment) in the 28 EU Member States. Specific Contract No. 070201/2014/SFRA/693725/ENV/C.2. Brussels, Belgium.

Miller, J.D., Hutchins, M., 2017. The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. J. Hydrol. Reg. Stud. 12, 345–362.

https://doi.org/https://doi.org/10.1016/j.ejrh.2017.06.006

Mollerup, A.L., Mikkelsen, P.S., Sin, G., 2016. A methodological approach to the design of optimising control strategies for sewer systems. Environ. Model. Softw. 83, 103–115. https://doi.org/10.1016/j.envsoft.2016.05.004

Mollerup, A.L., Mikkelsen, P.S., Thornberg, D., Sin, G., 2017. Controlling sewer systems–a critical review based on systems in three EU cities. Urban Water J. 14, 435–442. https://doi.org/10.1080/1573062X.2016.1148183

Mollerup, A.L., Thornberg, D., Mikkelsen, P.S., Johansen, N.B., Sin, G., 2013. 16 Years of Experience with Rule Based Control of Copenhagen's Sewer System, in: 11th IWA Conference on Instrumentation Control and Automation. Narbonne, France.

Montalto, F.A., Bartrand, T.A., Waldman, A.M., Travaline, K.A., Loomis, C.H., McAfee, C., Geldi, J.M., Riggall, G.J., Boles, L.M., 2013. Decentralised green infrastructure: The importance of stakeholder behaviour in determining spatial and temporal outcomes. Struct. Infrastruct. Eng. 9, 1187–1205. https://doi.org/10.1080/15732479.2012.671834

Morales-Hernández, M., Sharif, M.B., Gangrade, S., Dullo, T.T., Kao, S.C., Kalyanapu, A., Ghafoor, S.K., Evans, K.J., Madadi-Kandjani, E., Hodges, B.R., 2020. High-performance computing in water resources hydrodynamics. J. Hydroinformatics 22, 1217–1235. https://doi.org/10.2166/hydro.2020.163

Mounce, S.R., Shepherd, W., Ostojin, S., Abdel-Aal, M., Schellart, A.N.A., Shucksmith, J.D., Tait, S.J., 2020. Optimisation of a fuzzy logic-based local real-time control system for mitigation of sewer flooding using genetic algorithms. J. Hydroinformatics 22, 281–295. https://doi.org/10.2166/hydro.2019.058

Muñoz, A.F., Torres, M.N., Fontecha, J.E., Zhu, Z., Rodriguez, J.P., 2020. A participatory approach based on stochastic optimization for the spatial allocation of Sustainable Urban Drainage Systems for rainwater harvesting. Environ. Model. Softw. 123.

https://doi.org/10.1016/j.envsoft.2019.104532

Muñoz, A.F., Torres, M.N., Fontecha, J.E., Zhu, Z., Rodriguez, J.P., 2017. A methodology for optimal sitting of sustainable urban drainage system. Case study: Universidad de los Andes campus, in: 14th International Conference on Urban Drainage. Prague, Czech Republic.

Muñoz, D.F., Simões, N.E., de Sousa, L.M., Maluf, L., Sá Marques, A., Leitão, J.P., 2019. Generalizing multi-reward functions aimed at identifying the best locations to install flow control devices in sewer systems. Urban Water J. 16, 564–574. https://doi.org/10.1080/1573062X.2019.1700284

Murnleitner, E., Becker, T.M., Delgado, A., 2002. State detection and control of overloads in the anaerobic wastewater treatment using fuzzy logic. Water Res. 36, 201–211.

Muschalla, D., 2008. Optimization of integrated urban wastewater systems using multi-objective evolution strategies. Urban Water J. 5, 57–65.

Newton, C., Jarman, D., Memon, F., Andoh, R., Butler, D., 2014. Developing a Decision Support Tool for the Positioning and Sizing of Vortex Flow Controls in Existing Sewer Systems. Procedia Eng. 70, 1231–1240. https://doi.org/10.1016/j.proeng.2014.02.136

Nicklow, J., Reed, P., Savic, D., Dessalegne, T., Harrell, L., Chan-Hilton, A., Karamouz, M., Minsker, B., Ostfeld, A., Singh, A., Zechman, E., 2010. State of the Art for Genetic Algorithms and Beyond in Water Resources Planning and Management. J. Water Resour. Plan. Manag. 136, 412–432. https://doi.org/10.1061/(asce)wr.1943-5452.0000053

Ochoa-Rodriguez, S., Wang, L., Gires, A., Pina, R.D., Reinoso-Rondinel, R., Bruni, G., Ichiba, A., Gaitan, S., Cristiano, E., van Assel, J., Kroll, S., Murlà-Tuyls, D., Tisserand, B., Schertzer, D., Tchiguirinskaia, I., Onof, C., Willems, P., ten Veldhuis, M., 2015. Impact of spatial and temporal resolution of rainfall inputs on urban hydrodynamic modelling outputs: A multi-catchment investigation. J. Hydrol. 531, 389–407.

Oraei Zare, S., Saghafian, B., Shamsai, A., 2012. Multi-objective optimization for combined quality-quantity urban runoff control. Hydrol. Earth Syst. Sci. 16, 4531–4542. https://doi.org/10.5194/hess-16-4531-2012

Ostojin, S., Mounce, S.R., Boxall, J.B., 2011. An artificial intelligence approach for optimizing pumping in sewer systems. J. Hydroinformatics 13, 295–306.

Ostojin, S., Shepherd, W., Williams, K., Simões, N., Steinhardt, J., 2017. CENTAUR: Smart Utilisation of Wastewater storage capacity to prevent flooding, in: CIWEM Urban Drainage Group Autumn Conference & Exhibition 2017. pp. 1–8.

Perez-Pedini, C., Limbrunner, J.F., Vogel, R.M., 2005. Optimal location of infiltration-based best management practices for storm water management. J. Water Resour. Plan. Manag. 131, 441–448. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:6(441)

Philippon, V., Riechel, M., Stapf, M., Sonnenberg, H., Schütze, M., Pawlowsky-Reusing, E., Rouault, P., 2015. How to find suitable locations for in-sewer storage? Test on a combined sewer catchment in Berlin, in: 10th International Urban Drainage Modelling Conference. Mont-Sainte-Anne, QC, Canada, pp. 295–298.

Pinho, P., Correia, O., Lecoq, M., Munzi, S., Vasconcelos, S., Gonçalves, P., Rebelo, R., Antunes, C., Silva, P., Freitas, C., Lopes, N., Santos-Reis, M., Branquinho, C., 2016. Evaluating green infrastructure in urban environments using a multi-taxa and functional diversity approach. Environ. Res. 147, 601–610. https://doi.org/10.1016/j.envres.2015.12.025

Pistocchi, A., Dorati, C., Grizzetti, B., Udias, A., Vigiak, O., Zanni, M., 2019. Water quality in Europe: Effects of the Urban Wastewater Treatment Directive. https://doi.org/10.2760/303163

Rao, S.S., 2009. Engineering Optimization: Theory and Practice, Fourth ed., John Wiley & Sons Inc, Hoboken, New Jersey.

Rauch, W., Harremoës, P., 1999. Genetic Algorithms in Real Time Control Applied To Minimize Transient Pollution From Urban Wastewater Systems. Water Res. 33, 1265–1277.

Regneri, M., Klepiszewski, K., Ostrowski, M., Vanrolleghem, P.A., 2010. Fuzzy Decision Making for Multi-criteria Optimization in Integrated Wastewater System Management, in: 6th International Conference on Sewer Processes and Networks. Surfers Paradise, Gold Coast, Australia.

RGSPPDADAR, 1995. Regulamento Geral de Sistemas públicos e prediais de distribuição de águas e de drenagem de águas [in Portuguese].

Riaño-Briceño, G., Barreiro-Gomez, J., Ramirez-Jaime, A., Quijano, N., Ocampo-Martinez, C., 2016. MatSWMM - An open-source toolbox for designing real-time control of urban drainage systems. Environ. Model. Softw. 83, 143–154. https://doi.org/10.1016/j.envsoft.2016.05.009

Rossa, A., Liechti, K., Zappa, M., Bruen, M., Germann, U., Haase, G., Keil, C., Krahe, P., 2011. The COST 731 Action: A review on uncertainty propagation in advanced hydro-meteorological forecast systems. Atmos. Res. 100, 150–167. https://doi.org/10.1016/j.atmosres.2010.11.016

Rossman, L.A., 2006. Storm water management model, quality assurance report: dynamic wave flow routing. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

Rossman, L.A., 2015. Storm Water Management Model User's Manual Version 5.1. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

Sá Marques, J.A.A., Simões, N.E., Maluf, L.S., Jajarmizadeh, M., 2017. Report on initial strategy for CENTAUR system deployment in Coimbra.

Sá Marques, J.A.A., Simões, N.E., Maluf, L.S., Shepherd, W., 2018. Report on the performance of the pilot CENTAUR and recommendations.

Schellart, A., Liguori, S., Krämer, S., Saul, A., Rico-Ramirez, M.A., 2014. Comparing quantitative precipitation forecast methods for prediction of sewer flows in a small urban area. Hydrol. Sci. J. 59, 1418–1436. https://doi.org/10.1080/02626667.2014.920505

Schilling, W., Andersson, B., Nyberg, U., Aspegren, H., Rauch, W., Harremoës, P., 1996. Real time control of wastewater systems. J. Hydraul. Res. 34, 785–797.

Schryen, G., 2020. Parallel computational optimization in operations research: A new integrative framework, literature review and research directions. Eur. J. Oper. Res. 287, 1–18. https://doi.org/10.1016/j.ejor.2019.11.033

Schütze, M., Alex, J., 2011. A generic algorithm for real time control of urban drainage systems - applied in practice, in: Watermatex – 8th IWA Symposium on Systems Analysis and Integrated Assessment. Copenhagen, Denmark.

Schütze, M., Campisano, A., Colas, H., Schilling, W., Vanrolleghem, P.A., 2004. Real time control of urban wastewater systems - Where do we stand today? J. Hydrol. 299, 335–348.

Schütze, M., Campisano, A., Colas, H., Vanrolleghem, P., Schilling, W., 2003. Real-Time Control of Urban Water Systems, in: International Conference on Pumps, Electromechanical Devices and Systems Applied to Urban Water Management. Valencia, Spain.

Schütze, M., Erbe, V., Haas, U., Scheer, M., Weyand, M., 2008. Sewer system real-time control supported by the M180 guideline document. Urban Water J. 5, 69–78. https://doi.org/10.1080/15730620701754376

Schütze, M., To, T.B., Jumar, U., Butler, D., 2002. MULTI-OBJECTIVE CONTROL OF URBAN WASTEWATER SYSTEMS, in: International Federation of Automatic Control

- 15th IFAC World Congress. Barcelona, Spain.

Seggelke, K., Löwe, R., Beeneken, T., Fuchs, L., 2013. Implementation of an integrated real-time control system of sewer system and waste water treatment plant in the city of Wilhelmshaven. Urban Water J. 10, 330–341. https://doi.org/10.1080/1573062X.2013.820331

Shen, P., Deletic, A., Bratieres, K., Mccarthy, D.T., 2020. Real time control of biofilters delivers stormwater suitable for harvesting and reuse. Water Res. 169, 115257. https://doi.org/10.1016/j.watres.2019.115257

Shen, Z., Chen, L., Xu, L., 2013. A Topography Analysis Incorporated Optimization Method for the Selection and Placement of Best Management Practices. PLoS One 8, 1–12. https://doi.org/10.1371/journal.pone.0054520

Shepherd, W., Mounce, S.R., Ostojin, S., Abdel-Aal, M., Schellart, A., Skipworth, P., Tait, S., 2017. Optimising a Fuzzy logic real-time control system for sewer flooding reduction using a genetic algorithm, in: CCWI 2017 - 15th International Conference on Computing and Control for the Water Industry. Sheffield, United Kingdom.

Shepherd, W., Ostojin, S., Mounce, S., Skipworth, P., Tait, S., 2016. CENTAUR : Real time flow control system for flood risk reduction, in: CIWEM Urban Drainage Group Autumn Conference & Exhibition 2016. Blackpool, United Kingdom.

Shishegar, S., Duchesne, S., Pelletier, G., 2018. Optimization methods applied to stormwater management problems: a review. Urban Water J. 15, 276–286. https://doi.org/10.1080/1573062X.2018.1439976

Shishegar, S., Duchesne, S., Pelletier, G., 2018. Optimization methods applied to stormwater management problems: a review. Urban Water J. 15, 276–286. https://doi.org/10.1080/1573062X.2018.1439976

Simões, N., Girão, L., Maluf, L., Shepherd, W., Ostojin, S., Marques, A.S., Mounce, S., Skipworth, P., Tait, S., Leitão, J.P., 2018. Real-time CSO spill control using existing in-sewer storage, in: 11th Int. Conference on Urban Drainage Modelling. Palermo, Italy.

Snäll, T., Lehtomäki, J., Arponen, A., Elith, J., Moilanen, A., 2016. Green Infrastructure Design Based on Spatial Conservation Prioritization and Modeling of Biodiversity Features and Ecosystem Services. Environ. Manage. 57, 251–256. https://doi.org/10.1007/s00267-015-0613-y

Song, Y.H., Yun, R., Lee, E.H., Lee, J.H., 2018. Predicting sedimentation in urban sewer conduits. Water (Switzerland) 10. https://doi.org/10.3390/w10040462

Srivastava, P., Hamlett, J.M., Robillard, P.D., Day, R.L., 2002. Watershed optimization of best management practices using AnnAGNPS and a genetic algorithm. Water Resour. Res. 38, 1–14. https://doi.org/10.1029/2001WR000365

Sriwastava, A.K., Torres-Matallana, J.A., Schellart, A., Leopold, U., Tait, S., 2021. Implications of model uncertainty for investment decisions to manage intermittent sewer overflows. Water Res. 194, 116885. https://doi.org/10.1016/j.watres.2021.116885

Strandberg, G., Lind, P., 2020. The importance of model resolution on simulated precipitation in Europe - from global to regional model. Weather and Climate Dynamics (in review August 2020). https://doi.org/10.5194/wcd-2020-31

Tagherouit, W.B., Bennis, S., Bengassem, J., 2011. A Fuzzy Expert System for Prioritizing Rehabilitation of Sewer Networks. Comput. Civ. Infrastruct. Eng. 26, 146–152.

Tao, T., Wang, J., Xin, K., Li, S., 2014. Multi-objective optimal layout of distributed storm-water detention. Int. J. Environ. Sci. Technol. 11, 1473–1480. https://doi.org/10.1007/s13762-013-0330-0

Todeschini, S., 2012. Trends in long daily rainfall series of Lombardia (northern Italy) affecting urban stormwater control. Int. J. Climatol. 32, 900–919. https://doi.org/10.1002/joc.2313

Vezzaro, L., Grum, M., 2014. A generalised Dynamic Overflow Risk Assessment (DORA) for

Real Time Control of urban drainage systems. J. Hydrol. 515, 292–303. https://doi.org/10.1016/j.jhydrol.2014.05.019

Wang, M., Sun, Y., Sweetapple, C., 2017. Optimization of storage tank locations in an urban stormwater drainage system using a two-stage approach. J. Environ. Manage. 204, 31–38. https://doi.org/10.1016/j.jenvman.2017.08.024

Wang, M., Wang, Y., Gao, X., Sweetapple, C., 2019. Combination and placement of sustainable drainage system devices based on zero-one integer programming and schemes sampling. J. Environ. Manage. 238, 59–63. https://doi.org/10.1016/j.jenvman.2019.02.129

Waterinfo.be., n.d. WATERINFO.be - download section [in Dutch]. URL https://www.waterinfo.be/default.aspx?path=NL/Rapporten/Downloaden (accessed 25/02/2022).

Weyand, M., 2002. Real-time control in combined sewer systems in Germany - Some case studies. Urban Water 4, 347–354.

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., Kellagher, R., 2015. The SuDS Manual. CIRIA, London, UK. ISBN: 979-0-86017-760-9.

Woods-Ballard, B., Cherrier, V., 2019. Review of the UWWTD implementation, and the treatment of CSOs in the EU, in: CIWEM UDG Autumn Conference 2019. Nottingham, United Kingdom.

Wu, J., Kauhanen, P.G., Hunt, J.A., Senn, D.B., Hale, T., Mckee, L.J., 2019. Optimal Selection and Placement of Green Infrastructure in Urban Watersheds for PCB Control. J. Sustain. Water Built Environ. 5, 04018019. https://doi.org/10.1061/JSWBAY.0000876

Yang, G., Best, E.P.H., 2015. Spatial optimization of watershed management practices for nitrogen load reduction using a modeling-optimization framework. J. Environ. Manage. 161, 252–260. https://doi.org/10.1016/j.jenvman.2015.06.052

Yeh, C., Labadie, J.W., 1997. Multiobjective watershed-level planning of storm water detention systems. J. water Resour. Plan. Manag. 123, 336–343.

Zhang, K., Chui, T.F.M., 2018. A comprehensive review of spatial allocation of LID-BMP-GI practices : Strategies and optimization tools. Sci. Total Environ. 621, 915–929. https://doi.org/10.1016/j.scitotenv.2017.11.281

Zhen, J.X., Yu, S.L., Zhai, Y., 2004. A Planning Tool for Watershed LID-BMP Implementation, in: Critical Transitions in Water and Environmental Resources Management.

Zhou, Q., Leng, G., Su, J., Ren, Y., 2019. Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. Sci. Total Environ. 658, 24–33. https://doi.org/10.1016/j.scitotenv.2018.12.184

Zittis, G., Bruggeman, A., Lelieveld, J., 2021. Revisiting future extreme precipitation trends in the Mediterranean. Weather Clim. Extrem. 34, 100380. https://doi.org/10.1016/j.wace.2021.100380