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Towards the long term implementation of real time control of combined sewer systems: a review of performance and influencing factors

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ABSTRACT

Real Time Control (RTC) is widely accepted as a cost-effective way to operate urban drainage systems (UDS) effectively. However, what factors influence RTC efficacy and how this might change in the long term remains largely unknown. This paper reviews the literature to understand what these factors likely are, and how they can be assessed in the future. Despite decades of research, inconsistent definitions of the performance of RTC are used, hindering an objective and quantitative examination of the benefits and drawbacks of different control strategies with regard to their performance and robustness. Furthermore, a discussion on the changes occurring and projected to occur to UDS reveals that the potential impact of these changes on the functioning of RTC systems can be significant and should be considered in the design stage of the RTC strategy. Understanding this 'best-before' characteristic of an RTC strategy is the key step to ensure long term optimal functioning of the UDS. Additionally, unexplored potential for RTC systems might exist in the transitions, rehabilitation and construction of drainage systems. The research gaps highlighted here could guide the way for further development of RTC strategies, and enabling more optimal, long term implementation of RTC for urban drainage systems.

Key words: adaptability, longevity, real-time control, robustness, sustainability

HIGHLIGHTS

- This paper critically assesses the current knowledge of Real Time Control for Urban Drainage Systems.
- It looks at what changes in the long term are likely to happen to drainage systems and relates this to RTC performance.
- It explorers the roles Real Time Control will play in the future.

1. INTRODUCTION

Urban Drainage Systems (UDS) are designed to convey, treat and dispose of wastewater and urban runoff. Combined Sewer Systems (CSS) combine these flows into a single conduit for treatment at a wastewater treatment plant (WWTP). To ensure no flooding occurs when the system becomes surcharged, combined sewer overflows (CSOs) are fitted in the system. Through CSOs water is discharged into receiving water bodies, with potential ecological damage and public health risk as a consequence (Passerat *et al.* 2011; Hata *et al.* 2014). Despite the presence of CSO structures, during intense rainfall events, flooding might occur nonetheless, potentially causing considerable structural (Freni *et al.* 2010), environmental (Leitão *et al.* 2013) and public health hazards (ten Veldhuis *et al.* 2010). These issues also apply to separated sewer systems, by which the urban runoff and wastewater are conveyed through separate conduits.

Due to the large investments needed to minimise the aforementioned effects, the optimal operation of the existing infrastructure is important. Additionally, digitisation of the water sector has increased information flows and understanding of UDS behaviour (Blumensaat *et al.* 2019). These factors have given rise to the use of real-time control (RTC): the use of real-time data from the system to make decisions about actuator settings (Schütze *et al.* 2004). Looking at measures to reduce pollution from CSO events, RTC can be one of the more cost-effective measures compared to the construction of more storage capabilities or increased pumping capacity (Dirckx *et al.* 2011; Botturi *et al.* 2020) and has been applied to

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real catchments as early as the 1960s (Borsányi *et al.* 2008). Advances in computer science have given rise to an increase in research interest in more complex forms of control (Lund *et al.* 2018).

Various literature reviews have examined the state-of-the-art of RTC and give an overview of the nomenclature and modelling and computational requirements of RTC (Schütze *et al.* 2004; García *et al.*, 2015). More recently, Lund *et al.* (2018) examined Model Predictive Control (MPC), a commonly investigated sub-set of RTC. These reviews, however, did not look at the performance potential of the RTC strategies and factors affecting their practical longevity. To understand the potential of RTC over the long term, an understanding of the performance of RTC strategies and factors affecting it needs to be developed. This paper aims to analyse RTC strategies to examine their performance and influencing factors on their performance.

The scope of this review is set to RTC strategies applied to grey infrastructure in the UDS. Although the implementation of Sustainable Drainage Systems (SuDS) has become more widespread, (Fletcher *et al.* 2015; Andrés-Doménech *et al.* 2021) RTC related to specific parts of SuDS (e.g Lund *et al.* 2019; Kändler *et al.* 2020; Brasil *et al.* 2021; Oberascher *et al.* 2021) are excluded and readers are directed to Xu *et al.* (2021) for a review of the literature. RTC applied to the wastewater treatment plant (WWTP) as part of the UDS (e.g. van Daal-Rombouts *et al.* 2017a) are considered here given the importance of the interaction between the WWTP and the UDS (Langeveld *et al.* 2002) and additional control potential due to actuators at the WWTP influencing both UDS and WWTP dynamics (Nielsen *et al.* 1996).

In this review, a comprehensive overview of various performance definitions is given first, followed by an assessment of the performance potential of RTC for different UDS. Then, the influence of the chosen RTC strategy regarding the objective function and control architecture on the performance of the RTC system are assessed, followed by an assessment of the RTC procedures. An overview of these and the topics assessed can be found in Figure 1.

The rest of this paper is structured as follows: Section 2 gives an overview of RTC aspects and highlights some limitations regarding the comparison of performances of reported RTC strategies, both implemented in practice and model-based studies. Section 3 sets out expected changes to the system and their impact on RTC strategies and Section 4 draws conclusions.

2. FACTORS AFFECTING REAL TIME CONTROL EFFICACY

RTC can be implemented in a variety of ways, which influence the final efficacy and potential of the RTC strategy. The implementation of RTC to UDS can be divided into the overarching strategy, the RTC procedure and the RTC algorithm (Schütze *et al.* 2004). The RTC strategy refers to the design of the RTC: including the positioning of potentially new actuators, the definition of the objective function and architecture. The RTC procedure entails the part of the RTC strategy that determines the optimal settings of the actuators in the system. The RTC algorithm refers to the way in which the settings from the RTC procedures are implemented by the actuators. When comparing the efficacy of RTC, this distinction is important.

The following sections discuss the influence of the different factors on the efficacy potential of RTC, based on 17 studies (Table 1). These studies were selected to cover the full range in type of RTC and UDS characteristics, as specified in Table 1. Other studies might be referenced to reinforce or challenge the lessons learned from the studies in Table 1.

2.1. Performance definition

The performance of an RTC strategy is its ability to improve the system functioning with respect to the set objective. This can be calculated by either model-based or data-driven methods (van Daal-Rombouts *et al.* 2017b). The former involves running simulations of the system of different rainfall events for the system with and without the RTC rules implemented, the latter compiles datasets before and after the implementation of RTC and ensures they are sufficiently comparable in terms of rainfall characteristics. Both methods are subject to uncertainties arising from model results (Deletic *et al.* 2012) and monitoring (Bertrand-Krajewski *et al.* 2003).

2.1.1. Types of performances

Here we make the distinction between three forms of performance: Implemented RTC Performance, Theoretical RTC Performance and Maximum Potential Performance (Figure 2). The implemented RTC performance refers to real improvement possible for an RTC strategy after implementation. This can only be assessed using data-driven methods, as the uncertainties and common system failures cannot be accurately incorporated in model-based assessments. Using the model-based approach, the theoretical RTC performance can be calculated. This theoretical RTC performance assumes ideal functioning of the RTC, and can therefore be seen as the upper-bound of the practical RTC performance. The maximum

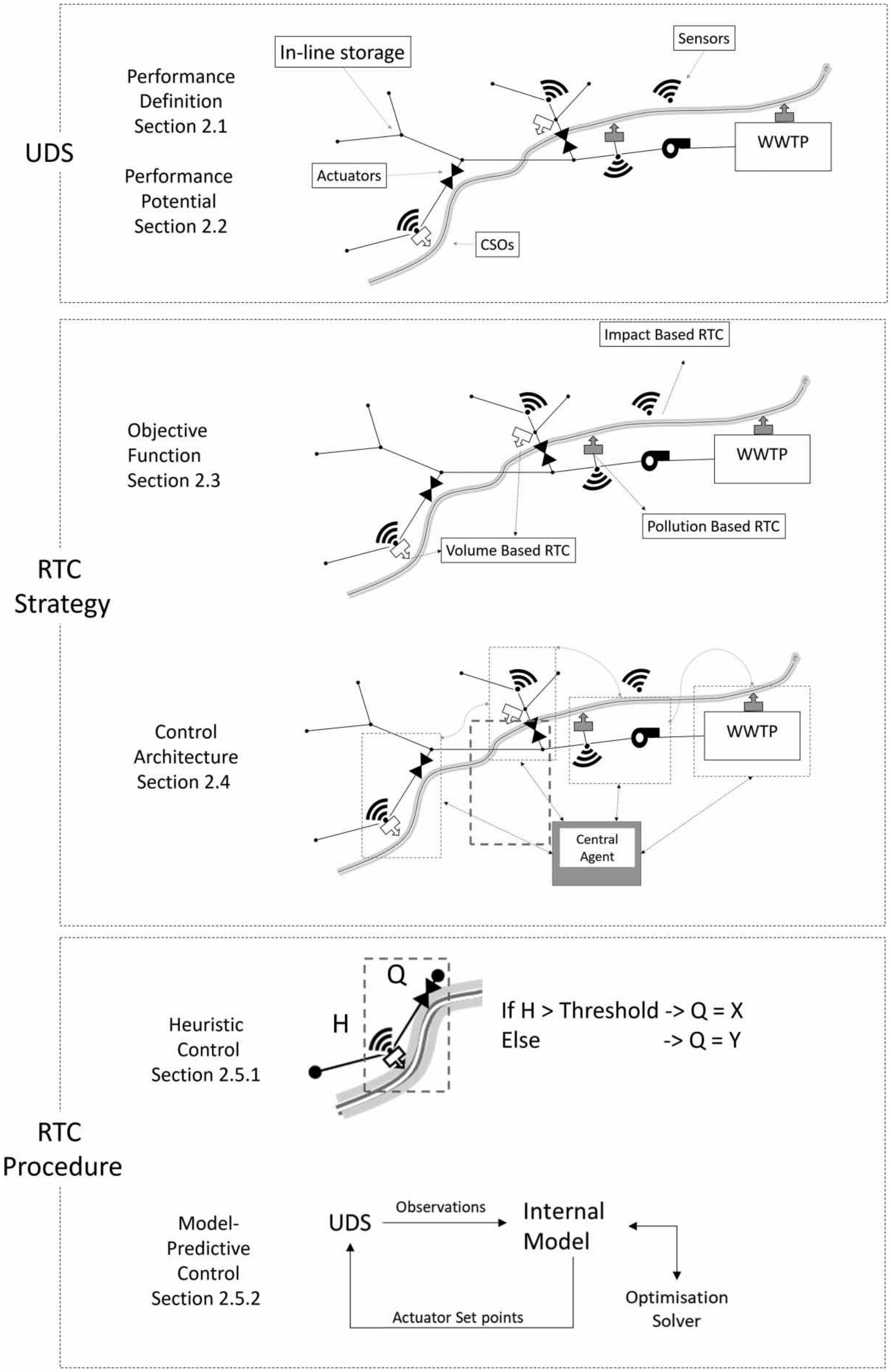

Figure 1 | Schematic overview of the topics related to RTC performance as assessed in this review.

Table 1 | Overview of the different study details used in this analysis

Reference	Minimisation function	Architecture	Procedure	System size	Number of actuators	Rainfall data type and size	Max. potential*	Reduction*
Gelormino & Ricker (1994)	CSO volume	Centralised	MPC	264,000 m^3 [a]	23	Rain gauges – 10 events	Not calculated	26%
Schilling *et al.* (1996)	River impact	Local	Heuristic rules	80 ha	3	Rain gauge – 5 years	50%[b]	25%[b]
Fuchs *et al.* (1997)	CSO volume	Centralised	Heuristic rules	56,400 m^3 [a]	3	Rain gauge – 10 events	Not calculated	91%
Fuchs Günther & Scheffer (1999)	CSO volume	Centralised	Fuzzy logic rules and rainfall forecast	7500 h	16	13 Rain gauges – 24 events	Not calculated	37.5%
Rauch & Harremoës (1999)	DO concentration in river	Centralised	MPC	1020 ha	5	Rain gauge – Single event	Not calculated	50%
Fuchs & Beeneken (2005)	CSO pollution load	Centralised	Heuristic rules	260 km^2	*Not Specified*	25 Rain gauges – 15 events	Not calculated	13.4%
Pleau *et al.* (2005)	CSO volume	Centralised	Global optimal control	325 km^2	22	Radar rainfall – 2 years	Not calculated	87%
Langeveld *et al.* (2013)	River impact	Local	Heuristic rules	4000 ha	5	Rain gauges - 10 years	Not calculated	11–18%[c]
Montestruque & Lemmon (2015)	CSO volume	Distributed	Various	Not Specified	12	Rain gauges - 8 years	Not calculated	50%
Garofalo *et al.* (2017)	CSO volume	Distributed	Gossip-based algorithm	202 ha	91–322	Rain gauge - 15 events	Not calculated	23–46%
Duy Khiem *et al.* (2019)	TSS emission	Centralised	MPC	45.9 ha	4	Rain gauge - 31 events	Not calculated	10%
Kroll *et al.* (2018a)	CSO volume	Local	Heuristic rules	251 ha	24	Rain gauge – 850 events	Not calculated	60%
Sun *et al.* (2020a)	CSO volume	Centralised	MPC	180 ha	6	Rain gauges – 10 years	19.7%	13%
Maiolo *et al.* (2020)	Flooding volume	Distributed	Heuristic rules	7.6 ha	5–26	Rain gauge - 20 events	Not calculated	89–95%
Mounce *et al.* (2020)	Flooding	Local	Fuzzy logic rules	17 ha	1	Rain gauge – 3 events	Not calculated	83%
Cembellín *et al.* (2020)	CSO volume	Distributed	Fuzzy negotiations	540 ha	6	Rain gauge - 20 days	Not calculated	70%
Bachmann-Machnik *et al.* (2021)	TSS emission	Local	Heuristic rules	109 ha	5	Synthetic rain gauge – 30 years	3.2%	3%

[a] Catchment size not specified, pertains to the storage in the sewer network.

[b] Refers to the potential additional activation of storage in the system.

[c] Reduction in occurrence of ammonium and dissolved oxygen concentrations exceeding thresholds.

*With respect to the objective function.

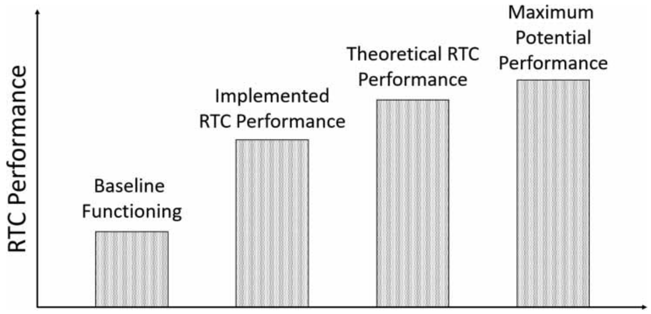

Figure 2 | Overview of the different types of performances.

potential performance is the absolute upper limit of what could be achieved with any RTC strategy for the studied catchment. Research should clearly indicate which of the performances was assessed.

A significant difference can exist between the theoretical RTC performance and practical RTC performance, suggesting that results from model-based studies should be treated as an upper limit on the performance (Seggelke *et al.* 2013). However, the adaptability of RTC after implementation might increase the performance of RTC for unanticipated events in practice, which cannot be included in performance analyses (Pleau *et al.* 2005). This re-emphasises that practical RTC performance cannot be compared to the theoretical RTC performance. Future studies dealing with RTC should explicitly mention which type of performance was assessed, and additional studies aiming to understand the relative difference in performance between these types should be undertaken.

2.1.2. Inter-catchment performance comparison

One of the hurdles preventing cross-comparing RTC performance in different studies is the lack of a common methodology and reporting on implemented case studies (van Daal-Rombouts *et al.* 2017a, 2017b). A key inconsistency identified was the difference in number of rainfall events used for performance evaluations. To get an accurate understanding of the real RTC potential (for both practical and theoretical performance), multiple year simulation should be done to converge to the real potential, as the performance of an RTC strategy was found to be highly dependent on rainfall characteristics (Tränckner *et al.* 2007; van Daal-Rombouts *et al.* 2017a, 2017b). Despite this, longer time periods are not always used (Table 1). Another hurdle is the lack of a commonly applied baseline to which the RTC improvement should be compared. Typically, the 'pre-RTC' functioning of the system is used to show the performance potential; however, it has been shown that using the 'pre-RTC' functioning as a baseline can lead to large overestimations of the performance potential due to suboptimal operation of the system before the RTC was implemented (van der Werf *et al.* 2021). Reliance on the 'pre-RTC' baseline can therefore give a skewed understanding of the real benefits of RTC. Statically optimising the system (whereby the baseline is the optimal functioning of the system with a single if-then rule per actuator in the system) as a baseline was proposed (Schutze *et al.* 2016); however, this method is not commonly applied.

Performance assessment on longer time series might not be possible because of a lack of long-term reliable rainfall data, or impractical due to the long computational times necessary for optimisation problems. Extrapolation methods from smaller data sets have been proposed (Meneses *et al.* 2018), but their underlying assumption of linearity between increased rainfall depth with CSO volume is one that does not hold (Vezarro 2021). For the design of optimal RTC, on the other hand, convergence to an optimum can happen faster, within 10 events for the catchment studied by Bachmann-Machnik *et al.* (2021). However, the size of the catchment and lack of uncertainty analysis contribute to this relatively fast convergence. Using radar data rather than a single rain gauge as an input can necessitate more rainfall data, as the spread of potential rainfall characteristics increases.

2.1.3. Other performance metrics

Rather than focussing on the difference between the improvement of the system with RTC compared to before the implementation, other methods to describe the performance of RTC have been proposed. A rating algorithm, akin to the one used for the ranking of chess players, was proposed to describe the relative performance increase of a UDS after RTC implementation

(Garbani-Marcantini *et al.* 2017). Fast convergence using little rainfall data was found using this method. This abstract framing of RTC performance, however, may not be interesting from an operators' perspective and is therefore unlikely to be widely adopted. A Relative Performance Indicator (RPI), based on general definitions of a baseline and maximum potential performance, was proposed to describe the improvement made by an RTC strategy compared to its maximum potential (van der Werf *et al.* 2021). This has the benefit of maintaining practically important information for operators and allowing a more objective inter-catchment comparison of results.

Despite recent advances in the field, most papers do not explicitly describe how their RTC performs compared to a well-defined baseline nor do they describe that all statistically relevant types of storm events have been captured. This makes comparisons of RTC strategies and procedures from different case studies difficult. Using the aforementioned RPIs might be the most objective form of performance definition, though it has not been extended to pollution or impact-based RTC strategies. As large scale monitoring systems become more widespread in UDS, direct monitoring of the objective of the RTC strategy (CSO volume, CSO pollutant load, receiving water impact) is key to understanding the implemented performance of RTC systems.

2.2. RTC performance potential

The RTC potential, or the improvement of the operation of a UDS through RTC regarding the set objective, is not guaranteed to be significant for every catchment while potentially requiring significant investment needs (Villeneuve *et al.* 2000; Beeneken *et al.* 2013; Campisano *et al.* 2013). To give an indication of whether RTC investments are justified, a scoring tool, *Planning Aid for Sewer Systems RTC* (PASST), was proposed (Schütze *et al.* 2008). This tool attempts to relate physical characteristics of a UDS to the performance potential of RTC. Similarly, Zacharof *et al.* (2004) developed a screening exercise based on the SYNOPSIS tool (Schütze *et al.* 1999) to assess if a UDS would have sufficient RTC potential to warrant investment. Their application to a single semi-hypothetical UDS suggested that storage volume is the most important property determining RTC potential, a key feature in PASST as well. Nelen (1992), however, showed that for three catchments temporal differences in peak flow (temporal heterogeneity) for parts of the UDS are the key indicator of the RTC potential. Even when the potential for CSO reduction through RTC is low, other objectives can be achieved through RTC (van Daal-Rombouts *et al.* 2017a, 2017b).

The dependence of RTC potential on the underlying UDS means that generalisation of control strategies and procedures is difficult. To facilitate implementation, a framework was proposed (Schütze *et al.* 2008) and later extended to include uncertainty analysis of the models (Breinholt *et al.* 2008). Investigative studies to see if there is dynamic flexibility in the system are a key part of these frameworks. To identify which pre-existing actuators in a system are of the most interest from a control perspective, a global sensitivity analysis can be performed (Langeveld *et al.* 2013), a technique later applied to a benchmark case study (Saagi *et al.* 2016; Saagi *et al.* 2018). When actuators are added as part of the RTC strategy, locations of interest can be determined through hydrodynamic models (Zhang *et al.* 2018; Eulogi *et al.* 2021), by looking for underutilised capacity in the sewer system, independent of the RTC strategy.

Few papers directly quantify the maximum potential performance of RTC for the studied catchment (Table 1), although a maximum potential performance for CSO volume was already used in the 1990s (Schilling *et al.* 1996) and formulated as a 'central-basin approach' (Einfalt & Stölting 2002). This methodology treats the entire UDS as a single basin, a hypothetical situation in which all the storage in the UDS can be activated, also applied in Bachmann-Machnik *et al.* (2021) and Schütze *et al.* (2018). The central-basin approach was extended to include pump limitations, making the real potential more realistic (van der Werf *et al.* 2021). No equivalent methods to the central-basin approach have been formulated for RTC strategies using other objective functions than the reduction of CSO or flooding volume. Using the proposed optimisation function with perfect infinite forecast to approach a more realistic maximum potential of the RTC might fit this role even though it was initially applied to volume-based control only (Fiorelli *et al.* 2013). Assessment of the total RTC potential should be included in all studies, to gain an objective insight in the real RTC potential and enabling improvements to the PASST tool.

The optimisation of the use of existing infrastructure can be a cost-efficient way of ensuring the desired functioning of UDS (Dirckx *et al.* 2011). A study on the application of RTC to the city of Quebec, Canada, showed a reduction of 83% of total CSO volume (Pleau *et al.* 2005) and exploratory studies for the city of Flensburg, Germany, show a theoretical reduction of 91% of overflow volumes (Fuchs *et al.* 1997). Considering the cases of Dresden, Germany, and Vienna, Austria, more modest yet significant theoretical reductions of 37.5 and 13.4% of CSO volume could be reached (Fuchs *et al.* 1999; Fuchs & Beeneken

2005). On the other hand, several studies report low efficacies of RTC, some with a CSO volume reduction as low as 0.3% (Bachmann-Machnik *et al.* 2021), despite indications that RTC might be a useful optimisation tool given the catchment characteristics as outlined in PASST. These discrepancies are a factor that might limit the uptake of RTC in practice, as the significant upfront costs to find out if there is potential for RTC might deter operators from exploring the potential.

A reliable method of estimating the potential *a priori* should be further developed, as more case studies with high quality data results are now available. Communication of the maximum RTC performance potential is thereby an important part of reporting of RTC case studies.

2.3. RTC objectives

The objective of the RTC strategy typically falls under one of three concepts: volume-based, pollution-based and impact-based control (García *et al.* 2015). Volume-based (VB-RTC) aims to reduce the total CSO or flooding volume and is generally considered the simplest objective function, considering only the hydrodynamics of the UDS system. Pollution-based RTC (PB-RTC) integrates concentration of pollutants in the system outflows and Impact-based RTC (IB-RTC) additionally considers the effects of these pollutants on the receiving water bodies. Here PB-RTC, IB-RTC and integrating the WWTP into the objective functions are discussed considering their relative potential benefits and drawbacks compared to VB-RTC.

2.3.1. Pollution-based RTC

The additional potential for pollution reduction through PB-RTC is dependent on the dynamics of the pollutants. Mass-Volume (MV) curves describe the dynamics of pollutants (using total suspended solids as a proxy for total pollution load) and volume of CSOs during an event (Bertrand-Krajewski *et al.* 1998). Dependent on the shape of the MV-curve, the performance improvement from VB-RTC to PB-RTC changes (Duy Khiem *et al.*, 2019). If the start of the event has a relatively higher pollutant concentration than the rest of the event, a decrease in potential was found when compared to relatively higher pollution loads during the middle or late parts of the event. This is in agreement with Lacour & Schütze (2011), who similarly conclude a decrease in PB-RTC potential when a strong first flush effect was added to their highly simplified catchment. First flush phenomena were found to occur scarcely (Saget *et al.* 1996), consequently improving the theoretical potential of PB-RTC. Catchment specific dynamics should always be considered and integration of continuous monitoring, such as turbidity measurements as a means of understanding pollution dynamics, is a necessary first step towards PB-RTC (Suárez & Puertas 2005; Lacour *et al.*, 2009) as long as accurate short-term predictive models cannot deterministically predict these dynamics (Willems, 2006; Jia *et al.* 2021).

PB-RTC can become a multi-objective optimisation function due to the different relevant pollutants. Lumping together all pollutants into an effluent quality index as a single value for optimisation can solve this issue (Rathnayake & Tanyimboh 2015). The effects of the formulation of the index, however, were not explicitly investigated, leaving the applicability to real control problems to be further investigated. Reduction of pollutants can also be a direct competition (allowing more stormwater to go to the WWTP might reduce pollution related to CSO events, but can increase the ammonium concentration in the WWTP effluent, Langeveld *et al.* 2013), and using a single index might miss the dynamics which can be explored with different priorities possible.

2.3.2. Impact-based RTC

IB-RTC considers the receiving waterbody's water quality state as the optimisation function, typically focussing on dissolved oxygen (Rauch & Harremoës 1999) and/or ammonium (Langeveld *et al.* 2013). From these two parameters, a Pareto front can be generated and operational preferences used to set the optimal strategy (Fu *et al.* 2008). However, adding a simple cost function to different CSOs due to sensitivity differences in receiving water bodies is a simplified version of IB-RTC (Vezzaro & Grum 2014), allowing additional overflows in one part of the catchment to relieve another. Using a minimisation objective related to the impact of CSO events might cause additional overflow volume or frequency (Rauch & Harremoës 1999), which could require legislative changes (Meng *et al.* 2020), with a similar discussion applying to WWTP emission (Hendriks & Langeveld 2017).

The non-linear dynamics of solid discharge and impact of waste discharge makes comparing IB-RTC and PB-RTC performance to VB-RTC performance in terms of a simple metric impossible (Rauch & Harremoës 1996) and methods to attempt this have not been found in the literature. Whether PB-RTC and IB-RTC are more effective than VB-RTC therefore remains a largely open question. Methods to appreciate the trade-offs between various pollution loads and their impacts on receiving bodies are necessary to appreciate these benefits but were not found in the literature.

2.3.3. WWTP integration in the objective

When considering the impacts of an urban drainage system on the receiving water body, including the dynamics at the WWTP becomes a necessity. IB-RTC in particular should include the WWTP and its dynamics rather than using it as a downstream boundary condition. Here we consider WWTP control affecting the interactions between the WWTP and the drainage system. Process control within the WWTP to optimise activated sludge return, aeration and dosing (e.g. Demey *et al.* 2001) are not considered here and readers are directed to Newhart *et al.* (2019) for an overview of data-driven control of these processes.

Reduction of the inflow of the WWTP during wet weather flow (WWF) conditions to avoid ammonium peaks in the WWTP effluent is a viable RTC strategy (van Daal-Rombouts *et al.* 2017a, 2017b). Flow reduction to the WWTP, however, can cause additional CSO events. This should be weighed against potential reduced pollutant loading from the WWTP (Hernebring *et al.* 1998). For the Badalona, Spain, catchment, a rule-based RTC including the inlet pump to the WWTP could reduce the total CSO volume relative to an optimisation-based control system with the WWTP inlet pump as a fixed boundary condition (Romero *et al.* 2021), showing VB-RTC can also benefit from including the WWTP in the control settings. Similar to the efficacy of the RTC applied to UDS without WWTP consideration, the potential of RTC depends on the WWTP characteristics.

The balance between WWTP intake and CSO events should be regarded from an integrated point of view. This balance can be a key factor, depending on the WWTP capacity, as it could be ecologically beneficial to cause a CSO rather than overload the WWTP (Frehmann *et al.* 2002). Overflow of the sludge blanket of secondary clarifiers as a result of overloading the WWTP can cause significant ecological damage (Schilling *et al.* 1996). However, a higher uptake of the WWTP, if designed accordingly, can significantly reduce the total emission load (Seggelke *et al.* 2005).

Depending on the WWTP configuration, the efficiency of the treatment steps can be sensitive to variations in the influent loading. Variance of the hydraulic, chemical and biological loading to the WWTP can therefore reduce operational performance of the WWTP (Leitão *et al.* 2006). A control strategy to mitigate influent variance under dry weather flow (DWF) conditions focussing on pollutant concentrations, changing its objective under WWF conditions, can improve the functioning of the WWTP (Risholt *et al.* 2002; Troutman *et al.* 2020). This type of DWF control relies on the attenuation of wastewater in the system during DWF conditions, which can therefore be applied to CSSs with sufficient redundancy. The efficacy of this method should be extended by adding long-term forecasts, to ensure that the system is ready to change from its optimal DWF setting to WWF functioning when rainfall risk is on the horizon.

Including the WWTP in the design of the RTC strategy can lead to significant benefits for all types of control. Understanding when there is the most potential, given the UDS and WWTP characteristics remains unknown. The trade-off between pollutants emitted from the system is a key parameter, and factors influencing the optimality of this trade-off should be further considered. A well-considered choice between sectoral (only UDS) and integral (including WWTP) control approaches should be part of the development of RTC, and a methodology to make this decision is missing in the literature.

2.4. RTC architecture: performance and benefits

2.4.1. Local control

Local control, arguably the simplest form of real-time control procedure, excludes any communication between actuators and relies on the ability of each actuator to optimise its relevant part of the UDS to optimise the system as a whole. Because of this low level of information integration, local control utilises mainly heuristic procedures, thereby relying on an extensive understanding of the system or through prior set point optimisation. This form of control is widely implemented, as even simple on-off rules for pump sumps can be argued to fall within this category. If-then rules and fuzzy logic rules are the two options available in a local control architecture (García *et al.* 2015). Although information integration might be low, it could be argued that there is indirect communication between actuators through the dynamics influenced by the actuators.

The relatively simple, and therefore adjustable nature of local control can make it more appealing for operators compared to centralised control (Mounce *et al.* 2020), provided that the benefits of the higher-tier architectures are not significant enough. Local control can also lend itself for more generalised framing of the control strategy, in the form of equal filling degree (whereby the aim is to fill upstream and downstream of a node equally, a strategy sometimes naturally emergent from centralised optimisation-based RTC (Cen & Xi 2007)) showing reductions ranging from 20–50% of CSO volume for five small catchments in Flanders, Belgium (Table 1, Kroll *et al.*, 2018a). Similar attempts at transference of strategies in-between catchments showed less successful results (Borsányi *et al.* 2008).

The design of heuristic rules, if done automatically, is dependent on the event characteristics used for the calibration of the rules (Eulogi *et al.* 2021) and will perform better for events with similar characteristics. A set of rainfall events which are representative for the catchment should be used for rule calibration and multiple years of rain data for the validation of the rules (van Daal-Rombouts *et al.* 2017b).

New methods within the local control architecture are rare, as they are stuck on if-then rules and fuzzy logic. New approaches better able to utilize digital advances of the last decades are not studied. Methods to allow for the gradual transformation of simple local RTC towards a more complex control system are also not reported, which could help the more widespread adoption of higher-tier RTC systems.

2.4.2. Centralised control

In a centralised control structure, all the information relevant to the RTC procedure is received by a central agent, which computes the optimal settings for all actuators and returns those to be implemented. The central agent determines the set points either through a heuristic procedure or using real-time optimisation, for example through MPC. This form of RTC is regularly shown to outperform other forms of control (Gelormino & Ricker 1994; Giraldo *et al.* 2010), although the margins are not always significant (Sun *et al.* 2020a) and other architectures can similarly optimise the system (Table 1). Verification of the potential of this type of RTC for a given catchment is therefore more important prior to making the necessary investments.

A centralised control structure does not have to be automated. Catchments can rely on local control, with the flexibility of being over-ruled from a central control location if desired by operators. This application leads to a 50 and 10% reduction in CSO frequency and volume respectively, based on operational data (Weyand 2002). Verification of these forms of RTC compared to other control options, however, are impossible given the ad-hoc nature of manual control. Increased cost for personnel might also be problematic and an increase of this has been set as a hard constraint for other projects (Pleau *et al.* 2005).

The reliance on extensive wireless telecommunication networks is a potential drawback for centralised control systems. Any RTC strategy should have built-in contingencies to ensure resilience against information loss. Integration of data-filling techniques using artificial intelligence to supplement missing data or validate real-time data has been shown to be promising (Palmitessa *et al.* 2021). Application of these techniques could enhance the resilience of RTC to likely incidents of data loss, one of the major faults previously found to occur (Weyand 2002) and accounted for in more recent applications (Seggelke *et al.* 2013). This resilience should go beyond returning to passive or local control strategy.

The largest potential for centralised control seems to come from larger, complicated UDS with a high (>5) number of actuators (Table 1). The layout of such larger systems ensures that complicated dynamics emerge, which are more difficult to optimally control with a local control strategy, especially when a high level of control is present due to the number of actuators. Additional benefits of the predictive nature of MPC can arise, especially in a large catchment where the spatial heterogeneity of the inflow can be anticipated and accounted for in the control procedure.

The arising abundance of cheaper options for monitoring networks and legal necessity to accurately report on CSO discharges means that information flows for sewer systems are being established, regardless of an implementation of RTC. With this plethora of newly available information and telecommunication structures in place (Montserrat *et al.* 2015), one of the main hurdles for the implementation of more complex centralised control strategies is decreasing. This is combined with increasing computing power and optimisation algorithms, able to handle more complex control problems.

Although centralised control architectures have been widely studied, it remains unclear when centralised control can outperform other architectures significantly enough to warrant the additional investments needed. Worsening of the performance due to invalid underlying assumptions can also happen in practice and ensuring this does not happen should be an integral part of centralised RTC.

2.4.3. Distributed control

Utilising the relatively small tele-communicative footprint of local control, distributed control incorporates communication between actuators, rather than a central controlling agent as per centralised control. Subsections of actuators find the best solution for each actuator, through Nash-equilibria, gossip-based algorithms (Garofalo *et al.* 2017) or through heuristic rules (Alex *et al.* 2008). Similarly, Ramirez-Jaime *et al.* (2016) achieve comparable results between a distributed control system and a centralised MPC scheme for a small catchment without the relative complexities associated with MPC, a point reiterated for water distribution networks by Barreiro-Gomez *et al.* (2017). Furthermore, they find improved fault-tolerant properties to information loss in the distributed architecture compared to centralised control architectures, resulting in a higher performance of the RTC strategies under realistic operating conditions.

The virtual catchments studied have a high level of controllability over the dynamics in the system, with the percentage of conduits able to control the flow rate passed through them being 26%, 28–99% and 19–100% by Ramirez-Jaime *et al.* (2016), Garofalo *et al.* (2017) and Maiolo *et al.* (2020) respectively (Table 1). This density of actuators is far higher than can be reasonably expected in real systems, which will likely lead to an underestimation of the difference with a centralised control approach. A distributed RTC was implemented in South Bend, US (Wan & Lemmon 2007; Montestruque & Lemmon 2015), where the discharge rate into the main interceptor from trunk lines in the UDS was set based on various control algorithms. Simulations predict a potential 25% reduction in CSO volume, but operational data indicated a reduction closer to 50%. This large discrepancy can, in part, be attributed to inter-annual variation in rainfall characteristics and model uncertainty. Changes to the system during operation, however, were not considered in the simulation, which likely contributed significantly to the difference between the simulated and observed RTC potential, highlighting the potential impact changes to the system can have on the performance of a UDS. From this data it is therefore impossible to attribute the monitored system efficacy to the RTC alone (although a 12% mass balance error was reported), despite the application of RTC reducing the cost of the CSO mitigation plan by around $150 million.

A standardisation of the distributed control design was proposed and close proximity to the theoretical maximum performance was achievable (48% CSO volume reduction, Alex *et al.* 2008). The oversimplified system on which this was tested, however, meant that the extrapolation to other systems is unlikely to yield the same result. Implementation of the standardised procedure in other catchments has not yet been reported in literature.

The addition of actuators in the context of distributed control can also lead to negative outcomes: increased risk of flooding (Ramirez-Jaime *et al.* 2016) or decreased flooding volume reduction (Maiolo *et al.* 2020). The latter claimed flooding volume reductions for a UDS without CSO structure of 89% and 62% for a partially and fully controlled small drainage system respectively for a 1-in-20 year storm compared to a UDS with only unrestricted flow. Some inconsistencies in mass-balance through conduits seem to arise, which was not explored further in the study. Using fewer actuators also showed a higher potential, which is left unexplained, but likely due to sub-optimalities in the RTC procedure. A coordinating, centralised control might have avoided decreases in efficacy, as the overarching layer uses the state of the entire system to activate the appropriate storage.

The potential of distributed control could increase with the expansion of low-power wide-area networks (LoRaWAN). Wireless telecommunication networks are cheap and can be paired with cheap, low-battery powered sensors, but suffer from a relatively small transmission range and high data loss through signal suppression and interference. However, it can be used to monitor in-sewer processes (Ebi *et al.* 2019) and application to industrial control systems is being tested (Hoang *et al.* 2020). This combined with recent advances in cheap sensor (Shi *et al.* 2021) can lead to increased potential of decentralised control.

The potential of distributed control has been shown on theoretical case studies, but their implementation into real case studies remains limited. Understanding of the true difference in potential with centralised control can therefore not yet be asserted.

2.4.4. Architecture discussion

All previously discussed control architectures have their merit and should be applied in different contexts. Centralised control enables the highest efficacy with respect to CSO and flooding reduction. However, their relatively high cost can be a major hurdle for implementation. For small and simple UDS, local control generally performs as well as centralised control, and should therefore be seen as either the best solution, or an initial step towards optimal control.

Distributed control appears to be particularly useful when the density of actuators is high, or when the controlled sections discharge into a single transport conduit. Its fault tolerant properties, however, might ensure that the long-term performance is better compared to centralised control, if faults have not been explicitly integrated in the centralised strategy and occur frequently. The right architecture therefore depends on the preferences of the operator. Centralised control, however, has more options in terms of utilising forecasts and improvement in computing power. Additional models and insights are also relatively easy to integrate in a centralised control architecture, but are not exclusive. A systematic assessment of the benefits of the different architectures for different catchments with a wide variety of properties in terms of size, actuator numbers and loading should be undertaken. Limiting to a single catchment for benchmarking, such as the Astlingen case study (Schütze *et al.* 2018) should be replaced with a set of catchments (Lund *et al.* 2018), as the benefits of the different architectures are highly dependent on the UDS.

2.5. RTC procedures

The procedures of RTC, the way in which the system determines the set points for the actuators (Schütze *et al.* 2004), can be divided into heuristic and optimisation-based control (García *et al.* 2015). Heuristics are based on extensive knowledge of the system (through set point of actuators, or fuzzy logic based control) and optimisation-based control computes the best settings for the actuators at every specified time interval based on a model of the system. Heuristic control procedures are widely adopted in practice due to their relative simplicity and intuitive way of working, although significant efforts (modelling and monitoring campaigns) can still be required.

2.5.1. Heuristic control

To test different procedures in terms of computational speed and efficiency, a benchmarking case study has been proposed (Schütze *et al.* 2018) and is freely available. However, the catchment is highly simplified, meaning the step of simplifying the system to a control-orientated model (García *et al.* 2015) is not part of the benchmarking section. This simplification step is a key part in the development of an RTC strategy and procedure, thus using a simplified catchment as a benchmark therefore does not do justice to the complexity of RTC. Furthermore, using a single catchment as a benchmark will likely limit potential insights to be gained. Using several catchments with different characteristics as a benchmarking set should therefore be encouraged (Lund *et al.* 2018). More datasets and models, similar to Pedersen *et al.* (2021), should be made available.

In various studies, heuristic control underperforms compared to optimisation-based control regarding the objective function (Mollerup *et al.*, 2016b) although the difference in efficacy can be too little to warrant the additional expenditure required (Mollerup *et al.* 2016a, 2017). Generalisation of relatively simple heuristic rules for application in different catchments can be possible, if the catchment variation is limited (Kroll *et al.* 2018a). These generalisations, based on the 'equal-filling degree' principle (ensuring that the catchment aims to minimise the difference in filling degree between various parts), can ensure further uptake of heuristic control in currently uncontrolled UDS.

Short-term rainfall forecasts (nowcasting) can be integrated in heuristic control (Fuchs *et al.* 1999). Studies to investigate the added potential of nowcasting in heuristic control, however, were not found. Furthermore, the influence of nowcasting uncertainty on the control potential has not been investigated, though it might be assumed that the effects are similar compared to those observed in model-predictive control (MPC).

2.5.2. Model predictive control

The benefits of real-time optimisation-based control appear to arise in more dynamic and heterogeneous systems, whereby multiple actuators influence the sections in different proportions (Table 1). Indeed, the relatively small benefits of optimisation-based control mentioned earlier applied to small catchments, whereas real-time optimisation-based control showed greater benefits over heuristic control for the large system of Quebec (Pleau *et al.* 2005). The size of the catchment alone, however, cannot be used as a proxy for potential, as also acknowledged in the PASST tool.

Model-predictive control (MPC) relies on nowcasting and an optimisation model to determine the optimal settings for the actuators. Numerical nowcasting, however, remains a large source of uncertainty and can contribute to efficacy loss when real radar forecasts are used (Krämer *et al.* 2007; Löwe *et al.* 2016) compared to perfect forecasts (Vezzaro & Grum 2014). The effect of the uncertainty within the nowcast is reduced due to the updating of the initial conditions for every time-step (Fiorelli *et al.* 2013) and the discount factor in the optimisation function places less emphasis on the further horizon values. Accurate estimations of the initial conditions are therefore key to successful implementation of MPC. Furthermore, limited impact of inaccurate rainfall prediction on the performance of control strategies was shown earlier (Trotta *et al.*

1977; Nelen 1992). Given this, the actual added benefit of nowcasting in RTC compared to other real-time optimisation methods remains the question.

The influence of the uncertainty of the updated initial conditions in the internal-MPC model has not been accounted for in the literature. Especially the runoff module in the optimisation model requires information not normally included in the MPC procedure (e.g. infiltration parameters) and can thereby lead to uncertainty about the future states. Some researchers use a full-hydrodynamic model to estimate the state at every time interval (Cembrano *et al.* 2004; Joseph-Duran *et al.* 2014); however, the assumption that this can reflect the real initial condition adequately has not been tested.

To deal with this uncertainty in the rainfall forecast in the MPC context, chance-constrained stochastic optimisation (Svensen *et al.*, 2020) and risk-based optimisation (Courdent *et al.* 2015) have been proposed. Both formulate the inflows as a probabilistic value rather than deterministic and search for an optimum for all situations within given bounds. Courdent *et al.* (2015) uses the ensemble of rainfall predictions to determine the risk of settings with respect to weighted CSO volumes. This is a realistic and more reliable way as it uses the real way in which nowcast data can be available to operators.

Critically, when assessing the influence of nowcast uncertainty, the full dynamics of forecast uncertainty should be acknowledged: spatial, temporal and magnitudinal. Adding a normal distribution to the rainfall intensity, as is the case in the aforementioned papers (with the exception of Courdent *et al.* 2015), cannot accurately represent all uncertainties. Investigation of the full range of nowcast uncertainties and their effect on the optimisation outcomes remains an important open question in the literature.

Most papers considering forecasting use a relatively small horizon (typically of 2 hours) as this type of data is often available in a commercial setting. The influence of the nowcast horizon on the potential of RTC depends on the characteristics of the UDS and the RTC strategy used. The RTC potential was found to level off after 1.5 hours for a conceptual catchment (Rauch & Harremoës 1999), which was unsurprising given its small size. The optimisation potential of using forecasts described by Nelen (1992) follows a similar pattern. It should be noted, however, that the potential for long-term forecasts (>12hours) through numerical weather prediction were not considered in these papers. These forecasts can contribute to the safe and optimal emptying of larger UDS or solid settling tanks.

The lack of adoption in practice of MPC can also be attributed to the more complicated nature of the control set up. The availability of pre-made MPC algorithms for EPA SWMM model (Sadler *et al.* 2019) can benefit the implementation of optimisation-based control. It allows operators to have a low entry level point to MPC, with tweaking possibilities available in the open-source nature of the code. Selection of the optimisation algorithm, given the plethora of different algorithms, is less important (Jahandideh-Tehrani *et al.* 2020).

The real benefits of optimisation-based over heuristics are highly dependent on the UDS characteristics, though factors influencing this have not been studied explicitly. Specific attention to the uncertainties in optimisation-based algorithms should always be included to ensure that the optimal settings computed are sufficiently reflective of the system. Risk-based approaches are promising, although their application in real systems has not been reported. Case studies with data on optimisation-based functioning should be encouraged to be published to gain better insights in the RTC potential.

2.6. RTC related risks

Despite the benefits of RTC, as set out in the previous chapters, consideration of the risks that are associated with RTC should always be explicitly considered. The main risks emerge from information failure, actuator failure, forecast error (see Section 2.4), system behaviour and malicious attacks. Inclusion of fault diagnosis to respond to potential failures can therefore improve the system. Puig (2010) showed a set-membership approach to redefine the constraints set on the optimisation function, able to mitigate additional damage from actuator failings. The diagnosis of faults remains problematic due to inherently large uncertainties in the model and sensor outputs.

In the case of flow restrictive devices, it should be ensured that there is no fail mechanism that can completely close the actuator in case of a failure mode. Such failures can lead to increased spills and flooding, even during DWF conditions. There have been no reports of these form of failures, but they remain a potential threat. Through deliberate retention of water in the system to avoid CSO events, the risk of flooding could increase (Garofalo *et al.* 2017). This flood risk can increase with the addition of more actuators, compensated by a decrease in CSO volume. Integration of this additional flood risk is an important part in the design of the RTC strategy. This risk might be exacerbated if changes in the system are not propagated into the RTC procedure.

Increased automation and information streams can make the UDS more vulnerable to cybersecurity incidents. WWTPs have been subject to such incidents with discharge of untreated wastewater as a result (Hassanzadeh *et al.* 2020). Actuators in the UDS, especially in the case of a centralised control architecture, could become vulnerable to cybersecurity threats. This is not to say that local control is immune to malicious attacks, as most manholes are easily accessible. Previously proven security measures should therefore always be an integral part in the application of RTC to real catchments.

Continued monitoring of the RTC performance can help in the mitigation of the risk, through early detection of malicious actors and sensor failing. Additional redundancy in the monitoring network (by adding multiple sensors at the same location) might mitigate against some forms of sensor failure, but will simultaneously increase the overall RTC costs. Methodologies to ensure risk mitigation, however, are limited to fault-tolerance in sensor and actuator performance. From the literature, it appears that this alone is not enough to ensure the long-term enhanced performance of RTC.

2.7. System changes and potential impacts

The interaction between RTC and the sewer system happens on different timescales (Mollerup *et al.* 2016a). However, over the longer timescales, the UDS will have undergone changes influencing the behaviour of the system. These changes can have an impact on the overall performance of the RTC strategy, and given that lack of cooperation between planning and operation departments has been highlighted as an impediment to RTC adoption (Lund *et al.* 2018), understanding how these changes affect the RTC performance can become an important step towards more ubiquitous adoption of more advance RTC procedures. Datasets such as presented by Pedersen *et al.* (2021) are an important tool in understanding the long-term performance of RTC, and they should ensure that the documentation of changes to the system is mapped out in such datasets (van Daal-Rombouts *et al.* 2017b). Here, we review the literature on what changes can be expected to happen to the UDS over the short- and long-term, and relate them to the performance potential of RTC. Gaps in knowledge are identified and expanded on.

Changes to the system can be divided into four main types: Contextual changes, large-impact configurational changes, small-impact configurational changes and temporary operational changes (Table 2). Their relative impacts on the UDS and thereby the RTC performance potential are discussed below.

2.7.1. Contextual changes

2.7.1.1. Legislation. Reduction of pollutants through the UDS is driven by increasingly stringent legislation. In the EU, the Urban Waste Water Treatment Directive of 1991 (Council Directive 91/271/EEC), specified the treatment targets and the Water Framework Directive (WFD) of 2000 (Council Directive 2000/60/EC) the targets for a good ecological, chemical and physical state of the natural water bodies. The WFD marks a trend towards impact-based approach to water policy although enforcement remains questionable (Kallis & Butler 2001). A new Urban Waste Water Treatment Directive is currently under public consultation, and is likely to include an additional target for micro-pollutants emitted from UDS and more restrictions on emission of untreated wastewater, arising from findings based on uncalibrated models that the current targets are not being met consistently in all member states (Pistocchi *et al.* 2019).

Legislation is bound to influence the objective functions set for the RTC strategy, influencing the performance potential. Some RTC procedures have been found to increase the frequency of CSO events whilst decreasing the overall volume (Cembellín *et al.* 2020). RTC as the basis for the environmental permitting could be a flexible and efficient way to implement legislation (Meng *et al.* 2020).

Table 2 | Different types of changes identified

Type of change	Description	Examples
Contextual changes	Non-physical changes which have impact on the UDS	Requirements set for UDS change; change in prevailing climate
Large-impact configurational change	Permanent physical changes to the UDS which significantly impact the objective function of an RTC strategy	Installation of new tank; expansion of pumping capacity
Small-impact configurational change	Permanent physical changes to the UDS which don't significantly impact the objective function on their own.	Local implementation of SUDS, relining of conduits
Temporary operational change	Temporary change in the operational capacity of the system	Pump capacity loss, data transmission loss

Legal requirements might also arise to reduce greenhouse gas (GHG) emissions from the urban water cycle. GHG emissions occur along the UDS, through power demand of pumps in the sewer system, to in-sewer processes generating GHGs. Mechanisms to include the estimation of GHG emissions in the formulation of UDS control strategies have been developed (Flores-Alsina *et al.* 2011) and a control strategy specifically to minimise energy consumption of the entire UDS without additional pollution was developed, noting that catchment-wide energy saving can only be done through investigation of both up- and downstream indicators (Kroll *et al.* 2018b). Co-optimisation of both CSO reduction and energy consumption was shown as promising for control (Bonamente *et al.* 2020), although the conceptual UDS used has little basis in reality. Despite this new emphasis on GHG emissions in UDS control strategies, the specific focus on climate and social sustainability of RTC for UDS is still in its early stages (Ashagre *et al.* 2020). Heat recovery from the UDS (Nagpal *et al.* 2021) might also add new demands to the functioning of the system, which could influence operator preferences and therefore RTC functionality.

Operational cost reductions due to a fluctuating abundance of renewable energy can be incorporated into an MPC system for WWTP (Ostojin *et al.* 2011; Stentoft *et al.* 2020). This mainly entailed pumping when energy prices were low. Uncertainties should be explicitly considered in these systems, however, as inaccurate model parameters, precipitation forecast and real-time data could cause additional overflows and reduce effluent quality. Furthermore, the purposeful storing of wastewater in a sewer, thereby increasing the hydraulic retention time, can lead to increase GHG emissions from the sewer (Kyung *et al.* 2017), increase in biofilm production (and thereby more GHG emission potential) and sewer-pipe corrosion (Jensen *et al.* 2016). Attempting to reduce GHG from the urban wastewater system should include estimations of in-sewer processes, although for accurate model results more research into the physical processes underpinning the emissions is necessary (Mannina *et al.* 2018).

Resource recovery from WWTPs (thereby becoming water resource recovery facilities (WRRFs)) is becoming more ubiquitous (van der Hoek *et al.* 2016; Solon *et al.* 2019). Resource recovery can benefit largely from a stable inflow of chemical content (Nowak *et al.* 2015), which has already been shown to be a possible RTC objective (Troutman *et al.* 2020). As the recovery of resources becomes a more important part of the WWTPs/WRRFs, this type of control is likely to become more prominently used in practice, providing the associated risks (see section 2.6) can be minimised. Using new data sources, like smart meters of water consumption, can generate a more detailed picture of the DWF in a system (Lund *et al.* 2021; Zhang *et al.* 2021), opening new possibilities for DWF based RTC. Research in the potential of integrating this new data source has not been reported.

The legislative drive to reduce both GHG emission and increase treatment of micro-pollutants are competing goals as the required treatment steps will be energy intensive (Jones *et al.* 2007). Adding additional treatment steps to the WWTP will also increase treatment cost, which can become problematic as the affordability of access to sanitation needs to be ensured following the United Nations Sustainability Development Goals. RTC's ability to ensure the minimisation of both the economic and carbon footprint of tertiary and quaternary treatment steps as well as resource recovery systems from an integrated WWTP and UDS point of view is unknown and remains an important research direction.

2.7.1.2. Climate Change. Anthropogenic climate change is projected to alter the rainfall patterns over the coming decades, although the climate models are difficult to downscale to a small time- and space-scale needed for UDS modelling, meaning the assessment of hydrological impacts remains problematic (Willems *et al.* 2012). Results of downscaling are also found to be non-transferable, meaning in some catchments climate extremes with regard to rainfall might be exacerbated. For Flanders and the Netherlands a standardised time-series tool was developed to aid in decision-making concerning climate adaptive cities (Bakker & Bessembinder 2012). As CSO should only occur when the full UDS capacity is reached, a non-linear increase in CSO volume under different climate scenarios due to increased rainfall intensity is expected and has been reported for cities in Norway and Canada (Nie *et al.* 2009; Nilsen *et al.* 2011; Gooré Bi *et al.* 2015).

The implication of increased rainfall intensity on the functioning of a heuristic VB-RTC system showed a decrease in relative reduction of CSO volume by the RTC for a catchment in Flanders (Dirckx *et al.* 2018). The implementation of RTC was considered a 'no-regret' measure, however, as it still managed to reduce the total overflow volume. Using a PB-RTC or IB-RTC strategy instead might become more interesting, as changes in concentrations might be controlled, even when volumetric capacity is reached (Sun *et al.* 2020a). This was concluded after only simulating four rainfall events, therefore the validity of this conclusion needs further investigation.

The larger effect of climate change, however, will not be increased frequency of intense rainfall events, but rather the changes that will be made to the urban environment and UDS to mitigate these effects (Kourtis & Tsihrintzis 2021). When the awareness of water issues inevitably results in wide-spread adoption of what is known in China as 'Sponge Cities' (Jiang *et al.* 2018), RTC of combined sewer systems is unlikely to remain a major factor in CSO pollution reduction.

Although the RTC and UDS literature as a whole has investigated the potential impacts of physical effects of climate change (increased rainfall intensity and higher temperatures), there is no research on the impacts of greener cities on the performance of RTC. To ensure that RTC truly is a 'no-regret' solution to CSOs, further research into this area is necessary.

2.7.2. Configurational changes

Transitional modelling attempts to identify pathways which can occur for a given UDS (Zischg *et al.* 2019), but long-term changes are always subject to deep uncertainty making prediction and long-term planning challenging (Babovic *et al.* 2018). Changes of the system will affect the efficacy of RTC and might require an overhaul of the implemented strategy or procedure depending on the effects. Here we discuss likely changes that can occur to a UDS and examine the potential impacts they might have on the functioning of an RTC strategy.

2.7.2.1. Green-blue-grey solutions. To ensure legal compliance and reduce ecological and economic damages from overloading the UDS, green-blue-grey solutions are often implemented. These measures are specifically designed to reduce urban flooding or pollution and should therefore have an effect on the flow rates throughout the UDS, potentially affecting the optimal settings in the case of a heuristic RTC strategy and the validity of the internal MPC model in the case of an optimisation-based RTC strategy. These changes include both small-impact and large-impact configuration changes (Table 2).

The optimisation of rehabilitation of sewer networks can reduce construction costs of grey solutions if the effective gains cannot be achieved through RTC (Vojinovic *et al.* 2014; Baek *et al.* 2015). Optimisation of green-blue-grey (GBG) solutions for urban flooding can give insights into the multiple benefits and co-benefits within each solution (Alves *et al.* 2020). The quantification of co-benefits for green-blue (GB) solutions in particular remains a central issue to the optimisation of their implementation.

Considering GB solutions, the spatial distribution and type of solution are a key influence on their potential for CSO reduction, but the location of CSO structures is equally important (Joshi *et al.* 2021). GB solutions rely mainly on the (temporal) attenuation of urban runoff, thereby either flattening the peak load to the sewer or reducing the runoff altogether (Fletcher *et al.* 2015). This would be a beneficial change to the UDS for RTC performance, as the runoff response of larger storm events decreases in intensity, and falls within the range in which RTC is most effective (Vezarro 2021). This is not explicitly investigated and cannot be generalised, as the relative potential of RTC has been reported to decrease with the implementation of GB solutions (Altobelli *et al.* 2020). If GB solutions become so prevalent that all urban runoff is completely infiltrated, RTC can remain relevant by shifting its focus to the application within GB solutions (Xu *et al.* 2021). Stability of the WWTP inflow and pollution dynamics also becomes more dominant.

If heuristic rules have been used to set up the RTC procedure, and significant investments are made into GB solutions, the re-evaluation of the rules will have to happen. The shift in the system loading, especially when the changes are spatially heterogeneous, can cause the rules not only to be sub-optimal, but possibly exacerbating CSO events. Development of methodologies that provide a robust way of assessing the continued functionality of RTC strategy under model-uncertainty should become a research priority to ensure long-term functioning of the RTC strategies. An MPC procedure will also need frequent updates of the underlying model to ensure that the automated procedures remain optimal. Adjustment of the underlying detailed model (digital twin) should be relatively straightforward, though the control-oriented model might be more difficult, thus raising the overall cost of maintenance. Understanding RTC efficacy decrease over time and the trade-off between model maintenance and RTC performance is a key factor in ensuring the longevity of RTC strategies.

To ensure optimal functioning of the UDS, consideration should be taken to the existing RTC during the planning phase of the GB solutions to ensure that the optimal effects of the GB solutions are achieved, as was previously shown to be important for grey infrastructure implementations in controlled catchments (Fradet *et al.* 2011). Integration of the co-benefits of GB solutions could prove too reliant on operational preferences to formalise for inter-catchment use. Integrated modelling of the entire UDS, including receiving water bodies, should be considered for the optimised rehabilitation as it gives a better insight into the impact of measures on all the relevant facets (Benedetti *et al.* 2013). Explicit research into formal optimisation of these directions has not been reported but should become an important research direction as both GB solutions and RTC become more widely adopted in urban areas.

Grey solutions (implementation of storm water settling tanks, creation of separate sewer systems, enlarging the drainage pipes and increasing pump capacity) will have a more profound effect on the hydraulics within the UDS itself rather than the inflow amount. In combination with actuator addition, this could lead to more latent storage. Indeed, Altobelli *et al.* (2020) reported a relative increase in RTC efficacy with the implementation of settling tanks in their hydrodynamic model, improving the CSO volume reduction from 34 to 41% compared to their statically controlled counterparts, with the investigated sizes of possible tanks not playing a significant role in this. From this, a co-optimisation of UDS rehabilitation (as presented in Vojinovic *et al.* 2014) and RTC could prove an interesting area of research, although the double optimisation function might become too computationally expensive. Release of retained water by stormwater settling tanks (SSTs) in the system can increase the removal efficacy of the suspended solids, particularly the smaller fraction (Muschalla *et al.* 2014), making the potential for PB-RTC in UDS a more interesting option. The addition of grey infrastructure can lead to new dynamics in the system, which can be exploited through RTC.

The above statements are particularly relevant to retrofitted RTC strategies: strategies applied to pre-existing UDS. Although the relevance of this type of RTC might decrease due to the UDS changes outlined before, rapid urbanisation in developing countries where UDS have to be designed can take full advantage of the benefits of RTC within the design phase. Attention in literature should therefore go not only to the optimisation of design of sewer systems, or RTC optimisation of existing infrastructure, but to the dual optimisation of design and operation. Methodologies to automate the generation of fast models necessary for RTC development can play a major role in this and have been proposed (Kroll *et al.* 2017) but should be tested further and expanded upon to ensure their validity.

2.7.2.2. Actuators Addition. Several studies do investigate the potential of RTC in combination with addition of actuators, or increasing the static or pumping capacity as part of the RTC strategy. The attribution of the performance to the real-time procedure of the strategy is not always separately investigated. Cembrano *et al.* (2004) added a reservoir to the Barcelona case study in conjunction with an RTC system. The RTC strategy was able to improve the system performance, but in a very limited way (<1% for total CSO volume). Interestingly, the RTC worked better for heavy rain episodes to alleviate flooding (5% decrease in flooding volume, 9000 m^3 vs. 6000 m^3 for CSO volume), due to the location of the installed reservoir, showing the effect of the location of actuators on the RTC procedure potential. With a second tank installed, the MPC system could achieve a 17% total CSO volume reduction for small events compared to a static reservoir, and 28% reduction of flooding volume for larger upstream events (Puig *et al.* 2009; Ocampo-Martinez *et al.* 2013).

Optimisation of the location and number of actuators is a key part in an RTC strategy that includes actuator placement. In larger UDS, this problem can become computationally too expensive if all manholes (or nodes in a model context) can be considered as a potential actuator location (Leitão *et al.* 2018). For VB-RTC, the in-sewer storage potential can be calculated to determine the optimal positioning of flow control devices, allowing a reduction in complexity of the optimisation problem (Eulogi *et al.*, 2021). Full package options (actuators, relevant software and hardware) are becoming commercially available (e.g. CENTAUR project, Shepherd *et al.*, 2016), which might lead to a more widespread adoption of RTC. Co-optimisation of added actuators and other GBG-solutions has not been investigated. The potential of this co-optimisation should be studied in relation to other changes outlined above.

2.7.3. Temporary operational changes

Short-term changes frequently occur in UDS. Pump failure, pump capacity loss, maintenance works and WWTP capacity reduction unavoidably happen and have an impact on the UDS. Failure events have been found to be responsible for a significant number of CSO events (Korving & Clemens 2005). If a system is rebalanced through RTC procedures, the impact of decreased pumping capacity could lead to worse performance of the UDS compared to a baseline. Similar observations were made for an integrated control, with different defects in the WWTP showing a lower robustness of the control strategies compared to the status-quo control (Vanrolleghem *et al.* 2005). Assumptions that the control actions can be carried out by actuators and downstream pumps as a non-variate boundary condition therefore do not hold, and the impact of such assumptions should be studied in the context of the different control architectures. These impacts will be more pronounced in systems reliant on pumps for the conveyance of the water.

Explicit encoding of operational variables that can be considered by optimisation functions could therefore be an important factor in ensuring the resilience of RTC strategy, though the impacts and solutions have not been given attention in the literature. Using data-driven models or deep reinforcement learning agents (e.g. Darsono & Labadie 2007) can be particularly vulnerable to these temporary changes if not used in the training data, with decreased efficacy as a result (Saliba *et al.* 2020). The black-box nature of reinforcement agents can make it harder for posterior analysis of why decision were made and addition of safety control can be harder (Bowes *et al.*, 2021). Methods should be developed to consider these factors in data-driven techniques as well.

2.8. Gaps in knowledge

Despite the scientific maturity of RTC applied to UDS, the long-term functioning of these systems has not been given sufficient attention in the scientific literature. This is likely to be one of the contributing factors to the lack of adoption of RTC in practice. Based on the review, we highlight four main areas in the literature where gaps in the knowledge are most pressing:

- **Performance, potential assessment and benchmarking of RTC strategies**. A precise definition of the performance of an RTC system, in terms of the baseline and rainfall events necessary, is still to be provided. For this reason, inter-catchment studies to understand the RTC performance potential and the ability to understand what characteristics of UDS influence the RTC potential remain unknown. Benchmarking efforts have been made, but are limited to a single, conceptual catchment. The potential for benchmarking in RTC has therefore not been fully investigated, as multiple full-hydrodynamic models available to all researchers are necessary for this.
- **RTC goal and procedure selection.** The inclusion of the wastewater treatment plant into the control strategy leads to a trade-off between pollutants from the UDS and WWTP. Methods to identify the most optimal settings from an ecological point of view are necessary for the widespread adoption of WWTP inclusion in sewer system RTC. Furthermore, whether (and when) the potential increased performance of integrated or optimisation-based control outweighs the additional efforts (modelling, monitoring and more complex control problems) required remains an open question. The effect of uncertain and erroneous rainfall forecasts in the RTC strategy have also had limited attention in the literature.
- **Architecture of RTC.** The benefits and drawbacks of the different architectures have been analysed in various papers, but validations of the conclusions have not been performed. Pathways from low complexity control to more complex control have not been identified and could be an important step for the adoption of complex RTC system architectures. The risks inherent in each architecture regarding cybersecurity and unforeseen failure events have not been mapped and tested adequately, which can have a major impact on the implementation of each architecture.
- **Adaptability of RTC systems to uncertain future changes.** The continuous functioning of RTC systems over longer time periods, whereby significant changes occur to both the urban drainage system itself and the context in which it functions, has not been assessed in literature. How different types of changes influence the RTC efficacy over a longer time period remains unknown. No papers have been found assessing the adaptability of RTC strategies to new situations nor has any research been published investigating the sensitivity of the performance of different RTC strategies to such new situations.

The above knowledge gaps are both practical and theoretical in nature and therefore form a barrier to widespread implementation of RTC. Within these, there are several more specific underlying gaps, which have been highlighted in sections 2.2–2.7.

3. FUTURE RESEARCH DIRECTIONS

Real-time control of UDS has been described in the literature for decades. Over the years, more complex control algorithms have been shown to outperform more simple control strategies (with respect to the criteria used) and an abundance of research on the computational efficacy and theoretical performance of RTC strategies has been published. Given the availability of these systems and the knowledge gaps outlined in Section 2.8, we believe that the future research on the subject of RTC should focus on the following:

To address the first gap shown above, a comprehensive set of case studies should be developed and made freely available for researchers to function as a benchmark for RTC research. Drawing together case studies that have extensive monitoring data and models available and varying in their characteristics will allow for the validation of conclusions that have been drawn from single, often oversimplified case studies. This set of case studies should include a full hydrodynamic model of each system and where possible additional integration of receiving water bodies' dynamics, quality parameters and a model of the wastewater treatment plant. The catchments included in the set should encompass a variety of sizes of catchments, climates, and configurations with respect to actuators, storage tanks and WWTP layout. For this reason, an international collaborative effort should be made.

Potential outcomes from such a benchmarking set can update tools that identify the feasibility of RTC for a particular UDS *a priori*. Ensuring that these tools give reliable approximations by comparing the given ratings to objective and comparable results can help in the further adoption of RTC by giving more confidence to operators about the validity of the tool recommendations.

Development of methodologies aimed towards the gradual implementation of more complex algorithms with optimal local control as a starting point should be a priority to address the second knowledge gap mentioned in section 2.8. This can help ensure ubiquitous implementation of more complex RTC strategies in practice, resulting in the ability of the research field to assess the real functioning of more complex RTC strategies. Data fed back from implemented case studies can subsequently form the basis to validate the theoretical results currently dominating the scientific literature. Further research should focus on understanding the impact of the model, forecast and system state uncertainties on the real performance potential of different RTC strategies. Using realistic forecast data, historic actuator performance, and uncertain initial conditions for optimisation models all represent the real implemented context and should therefore be explored more.

Similarly, testing when the pollution-based and impact-based RTC outperform traditional volume-based RTC enough to justify the additional efforts needed should be done. Integrating new objectives, thereby transitioning from a single to a multi-objective problem, and understanding how the behaviour of the controller changes can bring better insights into the trade-offs between these objectives.

More emphasis should be placed on the development of new RTC objectives in line with new requirements of WWTPs and WRRFs. Net zero greenhouse gas emissions targets will have big impacts on the urban wastewater system and will require overhauls of current infrastructure. Research into how RTC can play a significant role in ensuring this transition to happen smoothly should be encouraged.

To address the third knowledge gap identified in section 2.8, research validating the benefits and drawbacks of the existing RTC system architectures should be undertaken as a key first step in understanding when the trade-offs favour one or another architecture. The current literature offers sufficient exploratory conclusions, which have to be validated through other studies. A key characteristic, which should be on the forefront of this discussion, is the fault-tolerant properties and susceptibility of RTC systems to increasingly frequent cyber-attacks. Hybrid architectures, leveraging the qualities of different architectures, could be developed to further advance the field.

Trends in low-cost albeit unreliable sensors, able to significantly extend the monitoring capabilities in UDS, should be followed and integrated in RTC strategies. How these information streams can be integrated in RTC strategies has not been explored, meaning research opportunities exist in this area. Other information streams are currently being tested in the UDS context and could provide further robustness to the RTC strategies.

A deeper understanding of the flexibility and requirements for different RTC strategies with respect to future changes should be developed to address the final knowledge gap identified in section 2.8. Firstly, the impact of potential changes to the UDS and its requirements on the RTC performance potential should be better understood. This should include long-term changes (e.g. stepwise implementation of SUDS, separation of the sewer network), temporary changes (e.g. influence of pump failure) and configurational changes (addition of storage tanks, upgrading of pumping stations/WWTP). Assimilation methods based on the continuous monitoring of the RTC strategy's efficacy under model and monitoring uncertainty should be developed to understand when updates to the RTC system are necessary.

Optimisation methods that include both RTC and configuration changes to the UDS have the potential to reduce investment in rehabilitation of these systems. This potential co-optimisation requires methods to reduce the computational penalty of having to optimise both the dynamic operation and static layout of a UDS. Generic model simplification methods are key to reducing the computational time needed for these methods. Furthermore, structured methodologies for the inclusion of RTC in the planning phase of new UDS (for rapidly expanding urban areas, particularly in developing nations) has not been investigated sufficiently, and can have a major impact in making sanitation more affordable for these regions. These methods should be ensured to be robust and sustainable to future changes.

Case studies detailing the transitions and changes of the UDS and their respective effects on the RTC system should be published as an initial step towards understanding how the RTC can be made to remain effective over longer periods. These case studies can form a test example on which the adaptability of the RTC strategies and procedures can be tested.

4. CONCLUSION

This paper presents a comprehensive review of the scientific literature for real-time control (RTC) of urban drainage systems, including factors affecting the performance of different RTC strategies. Additionally, to assess the longevity of RTC strategies, changes likely to happen to urban drainage systems were assessed and their implications to RTC set out. Based on this review, the main conclusions can be summarised as follows:

1. The decades of research into RTC have produced a plethora of different optimisation algorithms, control architecture and objectives. An overview of the benefits and drawbacks reported in literature for each was compiled, but validation of these trade-offs could not be done due to the variety in case study characteristics. The best suited control algorithm for a catchment will depend on operator preference regarding RTC performance, cost, in-house maintenance capabilities and current system configuration. These trade-offs, however, remains under-explored in the literature.
2. Urban drainage systems are rapidly changing with respect to their configuration and the requirements they need to meet. RTC can function in two ways with these future changes: (1) a central role in these transformations can be assigned to RTC as a cost-saving method. The RTC strategy therefore influences the decisions about the changes made to the UDS. This approach will require an integrated form of working between the operational and design/planning side of the UDS. This has been reported in the literature but no formal methodology has been presented so far; (2) An RTC strategy can be designed on an existing 'static UDS', meaning changes will influence the efficacy if the RTC is not updated. The RTC strategy thereby has a 'best-before' expiry date. Methods to identify this limit and adjust accordingly are a key step towards the long term implementation of RTC.
3. New control objectives and information streams are emerging, expanding RTC to not just address (the impacts of) flooding, sewer overflow or wastewater treatment plant overloading but also resource recovery and energy savings. Given the projected changes to the UDS and probable new legislations, these new objectives will become increasingly prominent. Therefore, hybrid control objectives, with shifting priorities during different states of the system, will become a key element in future RTC design.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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