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

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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 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 combined sewer overflow (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 3-year rainfall time series. The 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 consequences of climate change and/or urbanisation.

Key words: CSO spill volume reduction, flow control device location, in-sewer storage, real-time control

HIGHLIGHTS

- Genetic algorithm (GA) method gives improved performance over volume approaches.
- A screening method is utilised to increase efficiency of the GA.
- The new optimisation-based methodology proved suitable for adaptive design.
- A local real-time control system is shown to reduce overflow spill volume.

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 (Butler *et al.* 2007; Berggren *et al.* 2012; Todeschini 2012; Miller & Hutchins 2017). 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 the operation and management of existing urban drainage assets by monitoring the state of the system and regulating flow conditions in real time (Schütze *et al.* 2008; Dirckx *et al.* 2011). RTC systems can be classified into local control systems, or system-wide control systems, based on their complexity level and control scope (Schütze *et al.* 2003; Environmental Protection Agency [EPA] 2006; García *et al.* 2015). 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 with 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 online 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 the strategy and implementation of local RTC (e.g. Carbone *et al.* 2014; Garofalo *et al.* 2016; Altobelli *et al.* 2020), compared with studies of global control systems (e.g. Fuchs & Beeneken 2005; Dirckx *et al.* 2011; Grum *et al.* 2011; Seggelke *et al.* 2013; Kroll *et al.* 2018; Lund *et al.* 2018; Meneses *et al.* 2018). CENTAUR is a local RTC system that utilises the existing in-sewer capacity to control stormwater volumes in sewer networks (Ostojin *et al.* 2017; Mounce *et al.* 2020). CENTAUR consists of autonomous flow control devices (FCDs) that are 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 the previous research (Abdel-Aal *et al.* 2016; Shepherd *et al.* 2016; Leitão *et al.* 2017; Shepherd *et al.* 2017; Sá Marques *et al.* 2018; 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 the 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).

The selection of optimal control locations for the reduction of urban flooding and 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 variations 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; Philippon *et al.* 2015; Kroll *et al.* 2018), 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 (GA) 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 32 GB 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.

METHODOLOGY

Case study network and FCDs

The case study network selected for this study is the Arendonk sewage system that is 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 contributing area of 479 ha, and consists of 1,513 nodes, 16 CSOs, and a total pipe length of 69.8 km (Kroll *et al.* 2018). Pipe slopes vary between −0.044 and 0.88 m/m (90% between 0 and 0.006 m/m), while pipe diameters range between 0.11 and 2 m. The sewer network is simulated with a calibrated EPA SWMM (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 RTC 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). The FCD opening degree is calculated by the Fuzzy Logic control algorithm through MatSWMM based on the water level in the CSO chamber and immediately upstream of the FCD location at a pre-defined time step (30 s). 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 min.

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 GA optimisation (*GA Method A*, *GA Method B*). The FCD 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 maximising the use of storage within the existing drainage infrastructure. When selecting FCD 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 Methods 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.

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 0 and 0.006 m/m) and the 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 FCD positioning method, found in several research studies for the design of RTC systems in sewer networks (Philippon *et al.* 2015; Kroll *et al.* 2018; Eulogi *et al.* 2021), allows the rapid assessment of a high number of potential FCD installation sites without the need for hydraulic simulations.

FCD location optimisation using the GA (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 the 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 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 the 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 the area of search, computational load, the rate of convergence, and the 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 as ‘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 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 the Intel E5-2637 processor and 32 GB 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).

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 h (storm event with a return frequency seven times per year), following the Flanders Environment Agency (VMM) design guidelines for sewer systems (Coördinatiecommissie Integraal Waterbeleid 2012a).

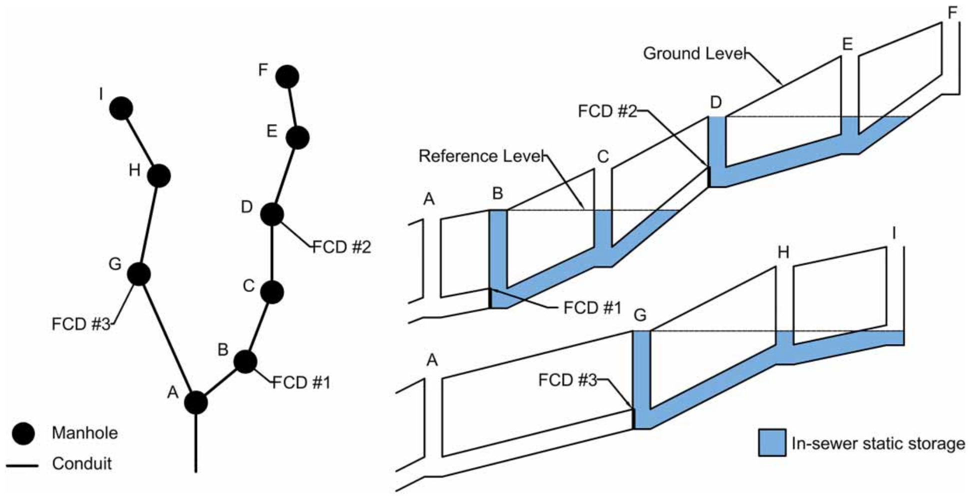


Figure 1 | Selection of potential FCD locations under GA Method B based on mobilised in-sewer storage capacity and FCD's position within the sewer network. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.085.

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). A total of 24 independent storms with duration between 100 and 1,268 min were selected from regional historical rainfall series recorded in the period 2004–2017, and three classes comprising of eight rainfall events are thus examined: storms with a return frequency of 10 times per year; storms with a return frequency of seven times per year; set of storms with the 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 min).

RESULTS

Spill volume reduction at a single CSO

The methodologies are utilised to define locations for the 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 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 the 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. 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 3. Overall, FCD 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 is also included within the 2-FCD and 3-FCD 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 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,

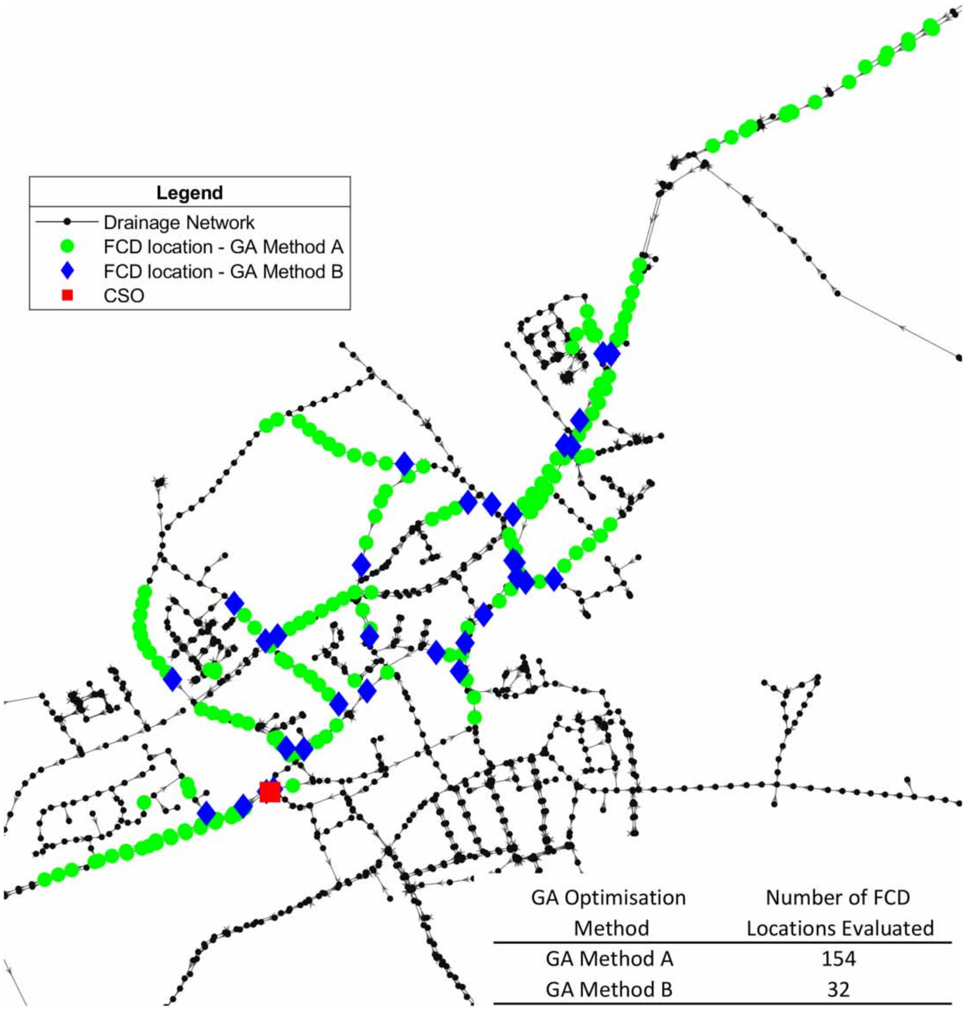
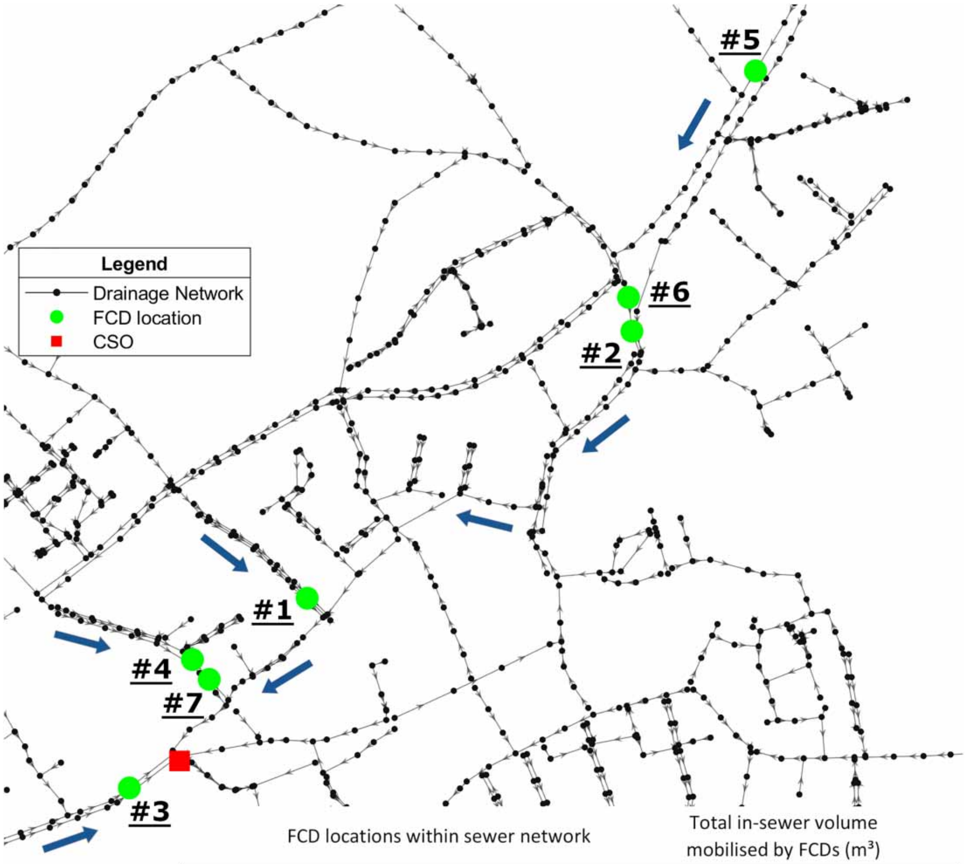


Figure 2 | Potential FCD locations evaluated using GA Method A and GA Method B for the composite design storm event *f7* (spill volume reduction at single CSO). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.085.

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.

For each FCD positioning method, the simulated spill volume reduction resulting from the implemented CENTAUR control system is shown in Figure 4. FCD placement schemes optimised by the GA provide higher CSO spill volume reduction compared with 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 with the baseline system with no intervention and when implementing the third flow controller compared with the 2-FCD 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 FCDs. The manual relocation of FCDs is also found to



Number of FCDs	FCD locations within sewer network: Static Storage Method	GA Method A	GA Method B	Total in-sewer volume mobilised by FCDs (m³): 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 3 | FCD locations selected by the Static Storage Method, GA Method A, and GA Method B for the composite design storm event *f7* (spill volume reduction at single CSO). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.085.

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 7–10% higher than solutions found by GA Method B. No CSO spills occur for the design storm event under a 3-FCD 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 with GA Method A. The computational time needed by the GA to identify near-optimal solutions is reduced from 5 to 4 h with two FCDs implemented, and from 9 to 6 h with three FCDs implemented (Windows10 computer with the Intel E5-2637 processor and 32 GB of RAM).

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

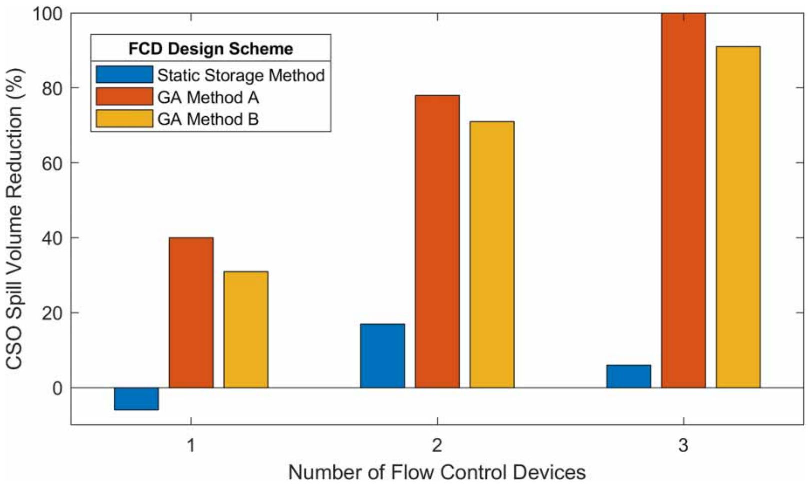


Figure 4 | Spill volume reduction at single CSO for composite design storm event *f7* obtained by placing FCDs using the Static Storage Method, GA Method A, and GA Method B. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.085.

5. Within the unregulated network, a total predicted spill volume of 1,955 m^3 is discharged at the 16 CSOs under the *f7* design storm event.

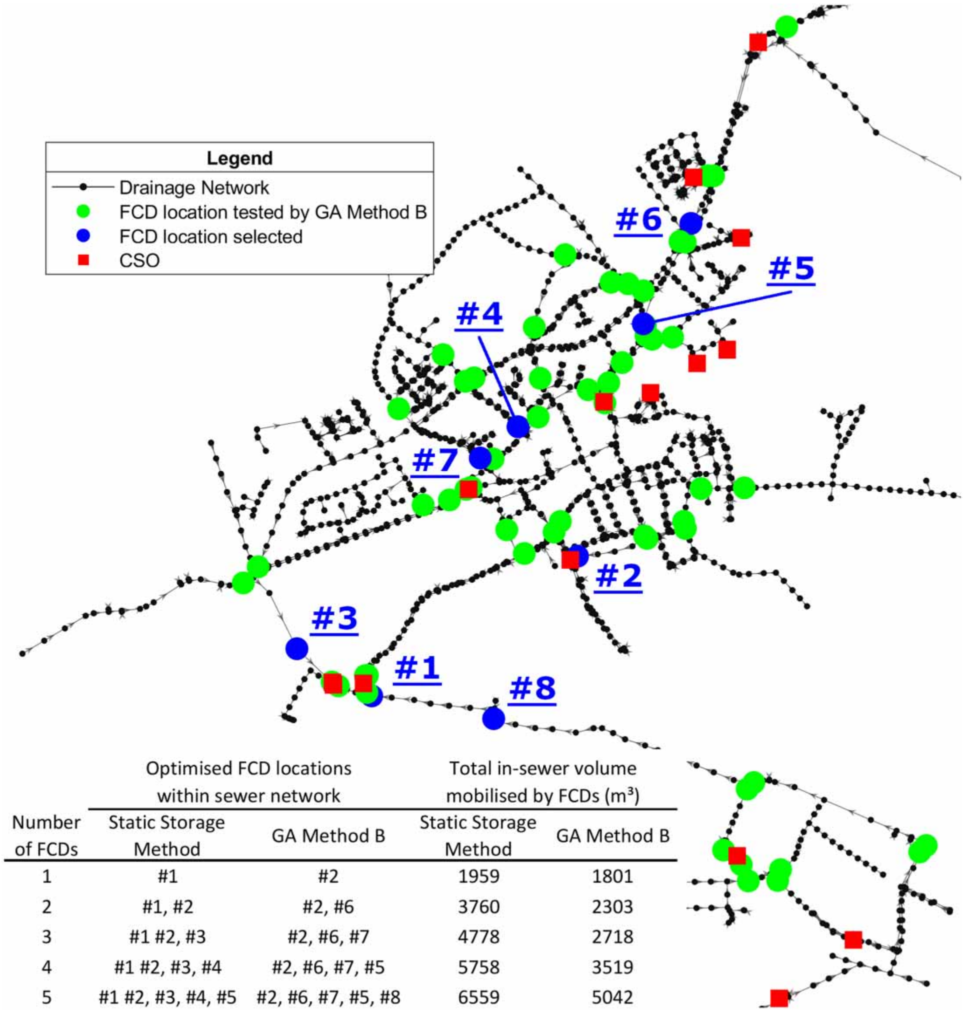
In this case, the implementation of GA Method A for overflow volume reduction is neglected due to the computational burden required for simulating spill at 16 CSOs. The capability of the GA solver in selecting near-optimal solutions in a feasible time frame is found to be limited by the simulation runtime required to run hydraulic analysis and the number of combinations between potential FCD locations and the 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 1,002 to 63 (V_0 equal to 100 m^3), and this resulted in a computational time between 9 h (two FCDs) and 16 h (five FCDs).

As shown in Figure 5, two FCD locations obtained by the Static Storage Method (#2 and #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 and 1,960 m^3 for the Static Storage Method, and between 500 and 1,800 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% (one FCD implemented) and 76% (three FCDs implemented). Overall, inclusive sets of FCD 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 6. GA-based installation sites always result in a larger CSO volume reduction, with a total CSO spill volume reduction of 37% when implementing one FCD and 90% when implementing five 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.

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)).



Number of FCDs	Optimised FCD locations within sewer network: Static Storage Method	Optimised FCD locations within sewer network: GA Method B	Total in-sewer volume mobilised by FCDs (m³): Static Storage Method	Total in-sewer volume mobilised by FCDs (m³): 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 | FCD locations selected by the Static Storage Method and GA Method B for the composite design storm *f7* (spill volume reduction at 16 CSOs). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.085

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 (eight storms per class): storms with a return frequency of 10 times per year, storms with a return frequency of seven times per year, and storms with a return period between 1 and 3 years. The FCD location selection procedure is repeated to reduce spill volumes at a single CSO (three FCDs implemented) and reduce the total overflow volume spilled at all 16 CSOs within the network (five FCDs implemented). Table 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 the 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 seven times per year and storms with the 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 three classes of storms tested. FCD 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 seven 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

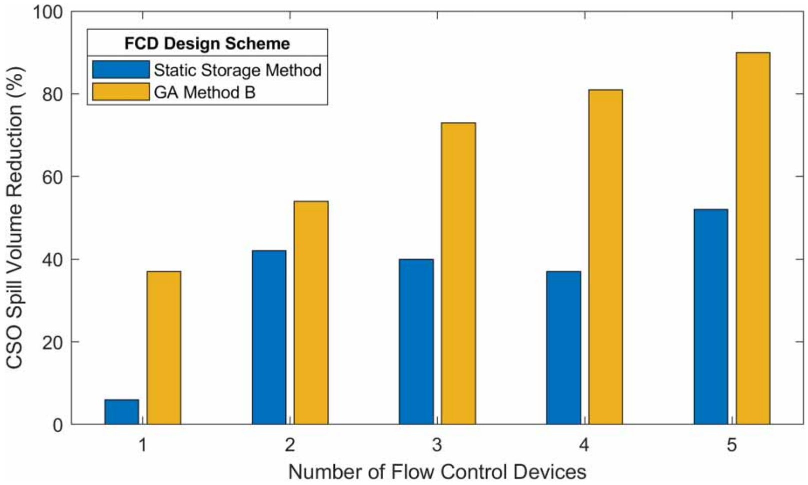


Figure 6 | Total spill volume reduction at all CSOs within the sewer network for the composite design storm *f7* obtained by placing FCDs using the Static Storage Method and GA Method B. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.085

Table 1 | Overflow spill volume reduction achieved by the RTC system for the series of 24 historical rainfall events, based on the number of CSOs regulated and the FCD placement strategy tested

Number of CSOs	Number of FCDs	FCD positioning method	Storm events return period (years) 1/10	1/7	1–3	Storm events return period (years) 1/10	1/7	1–3	Total spill volume reduction compared with baseline network over all rainfall events (%)
			Spill volume baseline network (m^3)			Spill volume reduction compared with baseline network (%)			
1	3	Static Storage	1,658	5,607	26,370	−3	25	15	16
		GA Method A				100	80	19	33
		GA Method B				100	73	17	30
16	5	Static Storage	3,365	11,846	78,946	41	45	20	24
		GA Method B				80	68	21	29

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 the 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.

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 the 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 seven times per year. Comparable CSO volume reduction is achieved during storms with the return period between 1 and 3 years (20% for Static Storage Method solution and 21% for GA Method B solution).

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 2 based on the number of CSOs regulated by the RTC system and the FCD placement strategy tested.

Table 2 | Overflow spill volume reduction achieved by the RTC system for the 3-year rainfall series, based on the number of CSOs regulated and the 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	86,230	15
		GA Method A		36
		GA Method B		33
16	5	Static Storage	242,070	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 by optimising the control locations with GA: 36% by placing FCDs using GA Method A and 33% using GA Method B. When five 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 with 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.

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 the 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 the 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 the 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 with 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% (three FCDs implemented) and 23% (one FCD implemented) compared with results obtained by GA Method A.

Overall, GA Method B enables a good trade-off between the 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 the optimal use of existing drainage infrastructure, rather than the 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 FCD locations are advantageous during the adaptive design of an RTC system, as then FCDs could be gradually added and a design implemented in stages 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 the GA in systems featuring different slopes or distributions of available in-sewer storage capacity within the catchment.

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 RTC system in reducing CSO spill volume. A novel GA pre-screening method was developed that allows the 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 capable of mitigating spill volumes over a wide range of rainfall inputs, and preventing CSO spills during frequent storms. In the case study evaluated, FCD 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 that 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 target 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.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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