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Coordinating Rule-Based and System-Wide Model Predictive Control Strategies to Reduce Storage Expansion of Combined Urban Drainage Systems: The Case Study of Lundtofte, Denmark

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Abstract: The environmental benefits of combining traditional infrastructure solutions for urban drainage (increasing storage volume) with real time control (RTC) strategies were investigated in the Lundofte catchment in Denmark, where an expensive traditional infrastructure expansion is planned to comply with environmental requirements. A coordinating, rule-based RTC strategy and a global, system-wide risk-based dynamic optimization strategy (model predictive control), were compared using a detailed hydrodynamic model. RTC allowed a reduction of the planned storage volume by 21% while improving the system performance in terms of combined sewer overflow (CSO) volumes, environmental impacts, and utility costs, which were reduced by up to 10%. The risk-based optimization strategy provided slightly better performance in terms of reducing CSO volumes, with evident improvements in environmental impacts and utility costs, due to its ability to prioritize among the environmental sensitivity of different recipients. A method for extrapolating annual statistics from a limited number of events over a time interval was developed and applied to estimate yearly performance, based on the simulation of 46 events over a five-year period. This study illustrates that including RTC during the planning stages reduces the infrastructural costs while offering better environmental protection, and that dynamic risk-based optimisation allows prioritising environmental impact reduction for particularly sensitive locations.

Keywords: combined sewer overflow (CSO); coordinating real time control (RTC); Dynamic Overflow Risk Assessment (DORA); environmental impact reduction; sensitivity of receiving waters

1. Introduction

The interest in online optimization of combined urban drainage systems (UDS) through real time control (RTC) strategies is increasing both among researchers and practitioners. Examples of this are presented in Schütze and Muschalla [1]. Increasingly, UDS are facing demands for better performance in terms of the reduction of environmental impacts and flood risk, while decreasing their costs and environmental footprint. Large-scale, static, infrastructural investments such as disconnecting impervious areas, increasing pipe capacity, and creating additional storage facilities, are often applied, but their costs can be extremely high, especially for older systems located in densely populated areas with high property values. Conversely, RTC has the ability to monitor and dynamically adapt UDS to the current situation to minimize combined sewer overflows (CSO) and optimize flows to the wastewater treatment plant (WWTP) [2]. Numerous practical applications have reported performance improvements and capital cost reductions by implementing RTC in sewer networks [3–9].

A variety of RTC strategies exist with different elements, such as forecasting, online models, optimization algorithms, etc., included in the implementation. System-wide RTC strategies can be divided in two groups: reactive systems or predictive systems [10]. The first are typically operated by predefined ruled-based control actions, and do not require complex features such as rainfall and runoff on-line forecasting models. Mollerup et al. [11,12] suggested distinguishing between a basic, regulatory, reactive control layer based on local control loops, and a more elaborate, coordinating, control layer where control loops may interact, and constraints on actuator capacities or water levels at key locations in the system may be handled. Predictive control systems are more complex, with several features, such as online models and weather forecasts, to estimate the future status of the UDS and react accordingly.

Typically, RTC has been compared against static infrastructural investments [13,14], but little information exists about combined approaches, where static and RTC approaches are complementary elements of the same solution, such as the expansion of storage volume in combination with RTC. As the cost of a RTC strategy mainly depends on the required equipment, including sensors, actuators, controllers, and telemetry, and the costs of operation and maintenance, a cost–benefit analysis should be performed to identify the most appropriate solution [13,15].

This study aimed to demonstrate the benefits of combining an infrastructural solution (basin expansion) with two alternative RTC approaches in the Lundtofte catchment in Denmark, where a storage expansion is being planned to comply with new and stricter legal requirements. We also considered the impact sensitivity in different sections of the receiving water body. The system performance was evaluated in terms of CSO volume reduction, environmental impact, and investment and operation costs. The two RTC approaches are (1) a reactive, coordinating RTC system based on a set of predefined "if–then–else" control rules; and (2) a model predictive control (MPC) system employing a risk-based optimization algorithm that considers flow forecast uncertainty and system-wide distributed CSO impact cost, called DORA (Dynamic Overflow Risk Assessment [16]). The comparison followed the procedure outlined in the M180 guidelines [15], and the catchment was simulated with a detailed hydrodynamic urban drainage model for 46 historical rain events recorded during a five-year period. Based on the results of the single event simulations, we developed a method to extrapolate annual statistics, and quantified the benefits on a yearly basis.

2. Materials and Methods

2.1. Study Area: The Lundtofte Catchment

The Lundtofte catchment (Figure 1) covers an impervious area of 584 ha with a residence time of approximately 7 h. The WWTP (Mølleåværket, in the northeast corner of the catchment) has a capacity of 132,000 PE, with an average daily load around 1000 m^3/h and a maximum capacity in wet weather of 1.5 m^3/s (5400 m^3/h). The catchment includes 16 storage basins with significant volumes for control, including one at the WWTP, and 47 CSO structures discharging to different sections of the Mølle Å river system. Among the potential control points, where placing an actuator is possible, 13 correspond to CSO structures, while four are located at other points in the system.

The combined UDS in the area collects both stormwater and wastewater from different municipalities (Gladsaxe, Lyngby-Taarbæk, and Rudersdal) and is operated by different water utility companies, resulting in the uncoordinated management of different parts of the system, with few exceptions. The main collectors and the WTTP are jointly managed. The Mølle Å river system is divided into four environmental sections (Figure 1a): Gladsaxe in the Gladsaxe municipality; Stades Krog, Brede, and Orholm in the Lyngby-Taarbæk municipality; and Nymølle and Aalebækken shared by the Lyngby-Taarbæk and Rudersdal municipalities. Each environmental section has different sensitivities and regulations, while being affected by CSO discharges caused by UDSs belonging to different utility companies.

The Lyngby-Taarbæk utility company is planning to upgrade its UDS to minimize CSO discharges and to fulfil legal requirements. A proposed river restoration plan involves a 24,200 m^3 expansion of the detention storage, distributed amongst four key locations (Figure 1b).

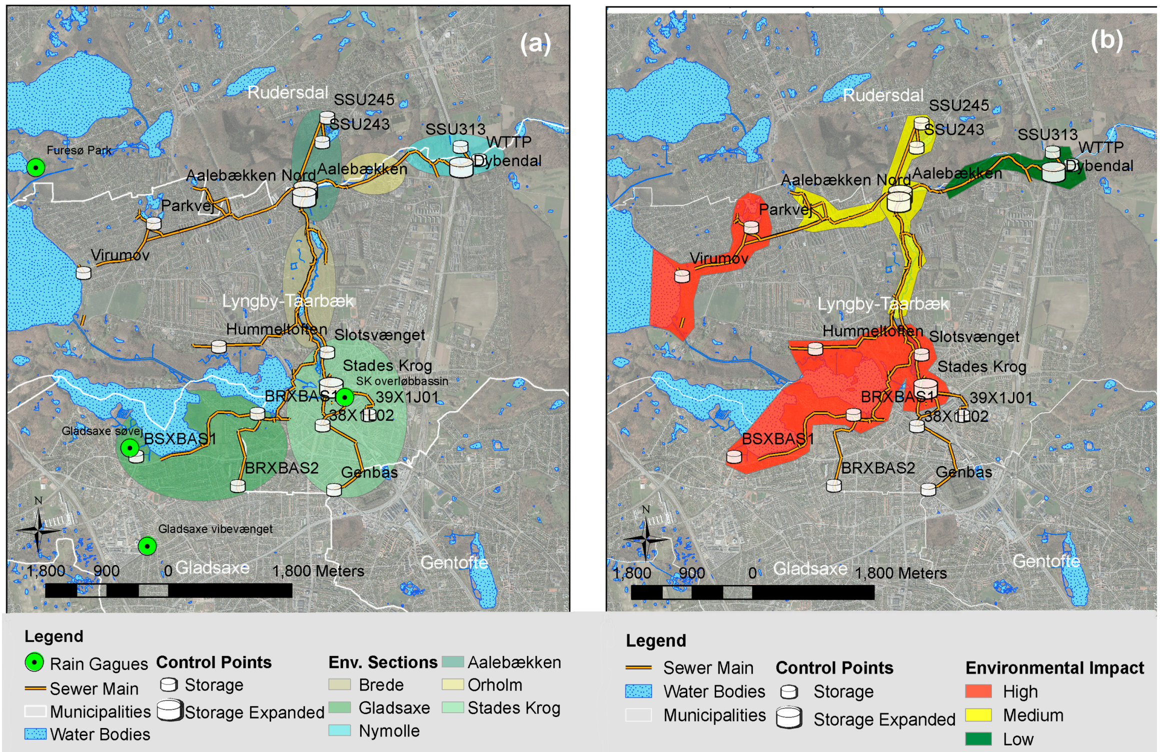

Figure 1. Overview of the Mølle Å river system, the urban drainage system (UDS), and storage volumes in the Lundtofte catchment: (**a**) location of the rain gauges and regulated environmental sections; and (**b**) potential impact of overflows river sections, also referred as environmental impact areas (see Appendix B for more details).

2.2. Model and Input Data

The system performance was simulated using an existing high-fidelity (HiFi) model, a detailed hydrodynamic model consisting of 612 nodes and 614 links, which was implemented in MIKE URBAN (MU; www.mikebydhi.com).

Historical precipitation data were retrieved from the Danish Water Pollution Committee network operated by the Danish Meteorological Institute [17]. Rain series from four stations (Figure 1a) were selected to represent the spatial rainfall distribution in the catchment over a five-year period from February 2008 to February 2013, when all four rain gauges were in service.

The use of complex HiFi models, like MU, is recommended when assessing RTC potentials due to their ability to simulate backwater effects [10], but these models have high computational requirements, making long-term simulations impractical and unfeasible. Therefore, 46 rain events were selected to represent the annual variation in rainfall in terms of rainfall depth and duration. This selection included the 15 largest rain events occurring during the observation period, and 31 additional events, which represent more frequently occurring medium- and small-sized rain events. Additionally, two 14-year rainfall time series were used to establish a relationship between the magnitude of the 46 CSO events and their return period (Section 2.5).

2.3. Development of RTC Strategies

This study followed the steps outlined in the M180 guideline document prepared by the German Association for Water, Wastewater, and Waste [15].

2.3.1. Preliminary Analysis of Control Potential and Design of Reactive Control Loops

Across the 17 locations with control potential, a preliminary analysis showed that the existing storage was seldom used. The implementation of both RTC strategies was simulated by adding actuators at these sites in the form of moveable gates in the MU model. The actuators were set to maximize the storage volume while avoiding the creation of additional problems up or downstream. For example, high storage volumes were found in pipes with relatively flat slopes; their inclusion in the RTC improved the system performance without storage expansion. Moreover, a static solution was included in the model by enlarging a short pipe stretch of 250 m located in a rural area in the Rudersdal municipality, which was identified as a bottleneck in the system.

Specific measures were implemented to avoid flooding as a result of the introduction of RTC. For example, if the water level rose above a surcharge threshold, the RTC set-points were overwritten, allowing the maximum possible discharge.

2.3.2. Rule Based Real Time Control (RBC)

The reactive, rule based approach operates based only on the present state of the system, i.e., information on current flows and water levels. The RBC approach applies several pre-defined "if–then–else" rules for all possible states of the system to fully utilize the storage capacity, and reduces the CSO volumes and impacts. The RBC was optimized based on a trial and error procedure, based on the MU results. Basically, outflow set-points from controlled points were modified depending on the filling degree of the local and neighboring basins. In case of unavoidable overflows, the RBC strategy was designed to protect the most sensitive receiving waters.

2.3.3. Model Predictive Control (MPC)

This predictive approach applies a global, system-wide risk-based optimization strategy, called Dynamic Overflow Risk Assessment (DORA) [16], which combines actual measurements from the system (in this case, states were simulated with the MU model), rainfall–runoff forecasts, and the uncertainty of these forecasts. DORA minimizes a global risk function, which is calculated as:

$$\text{Risk function} = \sum_{i=1}^{N_{basins}} \left(R_{Cr,i} + R_{F,i} - R_{hor,i}\right) \tag{1}$$

where R_{Cr} is the expected cost of overflows due to the runoff already in the UDS; R_F is the expected cost of overflow volume generated by the rainfall occurring within the forecast horizon, set to 2 h; and R_{hor} optimizes the available storage volume beyond the forecast horizon by mainly controlling the emptying of basins.

The expected cost of CSO due to forecasted runoff R_F for each controlled point (i) includes forecast uncertainty and is calculated as:

$$R_{F,i} = R_i \cdot \int_{V_{critical}}^{\infty} V_{F,i} \cdot p(V_{F,i}) \mathrm{d}V_{F,i} \tag{2}$$

where R_i is the risk factor for the ith basin (expressed in monetary units, e.g., EUR/m^3); $V_{critical}$ is the available storage capacity (i.e., when the forecasted runoff is greater than $V_{critical}$, overflow will occur); $V_{F,i}$ is the forecasted runoff to the ith basin; and $p(V_{F,i})$ is the probability associated with the forecasted runoff volume. DORA aims to reduce the overflow risk across the entire catchment, as calculated by Equation (1), by adjusting the flows between the controlled points. Optimal average flows over the next 2 h are identified at each time step of 2 min, which is every time new measurements of water levels and flows are available, by using a genetic algorithm, as initially proposed by Rauch and Harremoës [18]. In this study "perfect rainfall forecasts" are used, which generate predicted runoff volumes that correspond to the actual inflows to the controlled points. DORA allows for the prioritization of the controlled points through the risk factor R_i: higher values of R_i are assigned to the most sensitive points, resulting in higher CSO risk than at less sensitive points. In this case, the monetary value of overflow, expressed by the risk factor R_i, was defined as an arbitrary value, reflecting the different sensitivity of the different discharge points (see Section 2.4.2). A constant forecast uncertainty was assumed, allowing the calculation of the CSO risk with an analytical solution, as in Vezzaro and Grum [16].

2.3.4. Simulated Scenarios

In this study three scenarios were simulated:

1. The baseline scenario represented the traditional approach, where only static solutions are implemented, which included the 24,200 m^3 basin volume expansion at four locations (Figure 1 and Table 1), without RTC.
2. The RBC scenario included the new actuators mentioned in Section 2.3.1 and basin volume expansions of 18,980 m^3 (Table 1). The sizes of these basins were defined according to an iterative process, where the RBC scenario was simulated in MU for the 46 events, along with gradually smaller basin storage volumes, until the total CSO volume was equal to the one obtained in the baseline scenario, i.e., the legal requirement for CSO volume discharge. The RBC scenario required a storage volume that was 5220 m^3 (21%) lower than in the baseline scenario to obtain similar performance in terms of CSO volume reduction.
3. The MPC scenario used the same actuators and storage as the RBC scenario, but the system was globally controlled by DORA, which aimed to minimize the CSO risk by using the forecasted runoff as described in Equation (1).

Table 1. Increased storage volumes for the simulated scenarios at relevant basin locations.

Location	Baseline Scenario (m^3)	RBC and MPC Scenarios (m^3)	Saved Volume (m^3)
Dybendal	500	0	500
Aalebækken	7800	6700	1100
Aalebækken Nord	3500	2400	1100
Stades Krog 1	12,400	9880	2520
Total	24,200	18,980	5220

2.4. Indicators of Scenario Performance

The three scenarios were compared by looking at CSO volume, environmental impact risk points, and utility cost. These outputs were calculated both on a global, system-wide scale and on a per-environmental section basis.

2.4.1. Combined Sewer Overflow Volume

The CSO volume is the most straightforward output for assessing RTC strategies. This variable is also commonly used by legislation [8], but does not fully evaluate the environmental effects on the receiving water body [19–21].

2.4.2. Environmental Impact Risk Points (EIRP)

To better assess the environmental impacts of CSOs, the environmental impact risk point (EIRP) indicator was calculated. This indicator was obtained for each CSO structure as the product of the CSO volume and the unit EIRP, defined as a number of points given per m^3 of overflow. High EIRP values indicate that considerable adverse impacts on the environment are expected. The unit EIRP depends on the location of each CSO structure, and considers both the local conditions and the sensitivity of the receiving water bodies. EIRP is equivalent, but not identical, to the risk factor R_i used by the MPC scenario using DORA. In this study, the risk factor R_i was defined by simply dividing the EIRP value by 10 (Appendix B).

As no in situ studies on the sensitivity of the Mølle Å stream are available, unit EIRPs were assigned by using the U.S. Environmental Protection Agency (EPA) method for CSO ranking [10]. This method prioritizes CSO structures by considering, among others, (1) the direct risk to public health; (2) the characteristics of the receiving water bodies (lakes with low turbulence and mixing degree are assigned a higher score than rivers); (3) the composition of wastewater (urban areas with high traffic loads, highly impervious areas, and commercial or industrial activities are assigned higher scores than residential or rural areas); and (4) estimates of flow contributions (a high score is assigned where a high proportion exists between CSO flows and recipient water flow).

No direct risk to public health was assumed in the Lundtofte catchment since bathing activities are limited and no significant public health impacts have been reported. The U.S. EPA method allowed the identification of three main groups of CSO structures (Figure 1b):

1. CSO structures likely to generate a low impact with scores of 30 points or less, located downstream along the river and mainly in residential or rural areas with low population density.
2. CSO structures likely to generate medium impact with scores between 30 and 100 points, located midstream and mainly in residential areas with medium population density.
3. CSO structures likely to have a high impact with scores between 100 and 150 points, located upstream, near lakes, and mainly in urban areas with higher density.

2.4.3. Utility Costs

The materials and construction costs for all scenarios presented in this study were estimated according to Dirckx et al. [13]. Other costs, such as subscription to rainfall forecast services, operation and maintenance (O & M), and troubleshooting services, were estimated based on the METSAM project in Copenhagen [22]. A detailed description of the utility costs used in this study is available in Appendix A. The yearly expenses for the different services were included in the total utility costs as estimated net present values (NVP):

$$\text{NPV}\ (i) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{3}$$

where i is the discount rate; N is the project lifetime; and R_t is the yearly cost. A typical discount rate and the utility life of sewer systems of 3% and 50 years were used, respectively.

2.5. Extrapolation of Annual Statistics

The 46 simulated events (Section 2.2) have different magnitudes and return periods. To extrapolate yearly statistics from this set of discrete events, expected annual CSO volumes and EIRPs were calculated using an approach inspired by a method applied in flood risk management [23].

The CSO density curve f_{CSO} (Figure 2) was estimated by multiplying the CSO volume for each event with the event's frequency. These event frequencies were determined based on long-term statistics, performed on the baseline scenario for a period of 14 years. The frequencies were assigned based on the total CSO volumes generated per event. The expected relative change in yearly CSO volume for scenario A ($\Delta\text{CSO}_\text{A}$) was then calculated as (Figure 2):

$$\Delta\text{CSO}_\text{A} = 1 - \frac{\int_0^{t=1\ \text{yr}} f_{\text{CSO,A}}\ (t)\text{d}t}{\int_0^{t=1\ \text{yr}} f_{\text{CSO, baseline}}(t)\text{d}t} \tag{4}$$

where $f_{\mathrm{CSO,baseline}}(t)$ (m^3/year) is the CSO density curve for the baseline scenario and $f_{\mathrm{CSO,A}}(t)$ (m^3/year) is the CSO density curve for scenario A.

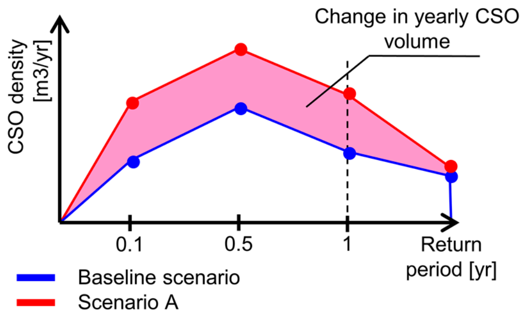

Figure 2. Illustration of method used to extrapolate annual statistics from discrete events with different return periods. The hatched area corresponds to the difference between two investigated scenarios.

3. Results and Discussion

3.1. Preliminary Results of Control Potential Based on the M180 Guidelines

A crude estimation of the control potential in the catchment was performed by gathering all physical characteristics (basin and pipe volumes, actuators, etc.) and hydraulic data (filling degrees, CSO frequency, etc.) of the studied UDS. According to the point system listed in the M180 guideline, [15] Lyngby-Taarbæk scored 33 points, corresponding to a medium–high potential for RTC.

The utility cost (Table 2) for the baseline scenario was solely due to the storage expansion of 24,200 m^3. For both RTC scenarios, the storage expansion volume of 18,900 m^3 (Table 1) plus the expanded pipe was estimated to 21.1 million Euros (€), representing 95% (RBC) and 93% (MPC) of the total utility costs for these scenarios. The additional installation of the sluice gate components, central supervisory control and data acquisition (SCADA) unit, and the NPV of operation and maintenance (O & M) costs were estimated to be around 1.03 million € for both RTC control schemes. The costs for services only required for MPC, including radar rainfall, forecast, and debugging, were estimated to a NPV of 430,000 €, which corresponds to less than 1% of the total project utility costs, and caused the MPC scenario to be slightly more expensive than the RBC scenario.

Table 2. Total combined sewer overflow (CSO) volume, environmental impact risk points (EIRP), and total utility cost for the three scenarios.

Scenarios	Total CSO Volume (m^3) (In Thousands)	EIRP (In Millions)	Utility Cost (€) (In Millions)
Baseline	1475	151	25.2
RBC	1371	146	22.3
MPC	1362	142	22.7

3.2. Event Results Summarized at the Catchment Level

Figure 3 compares the total CSO volumes for the baseline scenario (horizontal axis) against the corresponding CSO volume for the RTC scenarios (vertical axis) for the 46 simulated events. When an event was below the identity line, the RTC scenario (RBC or MPC) decreased the CSO volume compared to the baseline scenario.

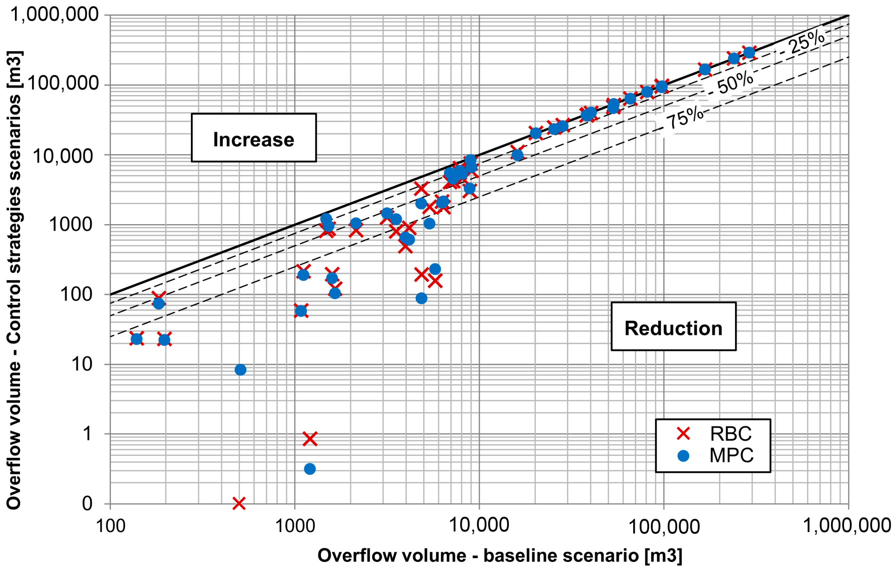

Figure 3. Event overflow volumes discharged at the catchment scale for the rule-based real time control (RBC) and model predictive control (MPC) scenarios compared to the corresponding baseline scenario results. The dotted lines represent percentile reductions.

Figure 3 reveals a threshold for events with overflow volumes around 20,000 m^3 in the baseline scenario. Below this threshold, both the RBC and MPC scenarios reduced the CSO event volumes compared to the baseline scenario. The RTC scenarios reduced the CSO volume by more than 50% for 21 of the 46 events modelled. However, above this threshold all scenarios performed similarly. A similar pattern in RTC performance was found in other studies [16,24]. This underlines how the best performance for RTC is obtained for relatively frequent rain events. In this case study, the return period was estimated to be around 0.3–0.4 years. These events typically have a magnitude smaller than the available storage capacity of the system, often causing CSO in a limited number of overflow structures. Therefore, it is possible to obtain a high reduction in CSO volumes of up to 100%, which means complete avoidance of some CSO events, by optimizing the water storage across the entire UDS. Notably, in this case study, RTC is capable of obtaining such performance in combination with a reduced storage implementation of about 21%, or about 5200 m^3 (Table 1), sufficiently maintaining the effect for large events to compensate the saved storage implementation.

When examining the sum of CSO volumes for the 46 events (Table 2), both RTC scenarios reduced the total CSO volume compared to the baseline scenario (1,475,000 m^3), with MPC having a small advantage over RBC, with reductions of 112,000 m^3 (approximately 8%) and 104,000 m^3 (approximately 7%), respectively. Similarly, the reduction in EIRP compared to the baseline scenario (EIRP 151 million) was 3.3% for RBC (EIRP 5.0 million) and 6.1% for MPC (EIRP 9.2 million). For total utility cost, the reduction compared to the baseline scenario (25.2 million €) was 11% for RBC (2.9 million €) and 10% for MPC (2.5 million €). The reduction of 5200 m^3 in storage volume for the RBC and MPC scenarios more than sufficiently compensated for the costs of implementing, operating, and maintaining the RTC systems.

3.3. Results at the Environmental Section Level

Figure 4 compares the total CSO volumes discharged to the different environmental sections of the Mølle Å stream. As mentioned earlier, both RTC strategies reduced the total overflow volumes compared to the baseline scenario, even with a 21% lower storage capacity; however, the spatial overflow distribution varied depending on the strategy tested. For example, a considerable reduction was observed in the Nymølle section, which is shared by both Lyngby and Rudersdal utilities, due to the removal of the bottleneck in the Rudersdal jurisdiction (Section 2.3.1). This demonstrates the benefit of integrated management beyond the jurisdiction of the different water utilities. The Nymølle environmental section has low sensitivity, whereas Aalebækken, Stades Krog, and Gladsaxe have high to medium sensitivities, explaining why the MPC scenario yields higher total CSO volumes in Nymølle than the RBC scenario.

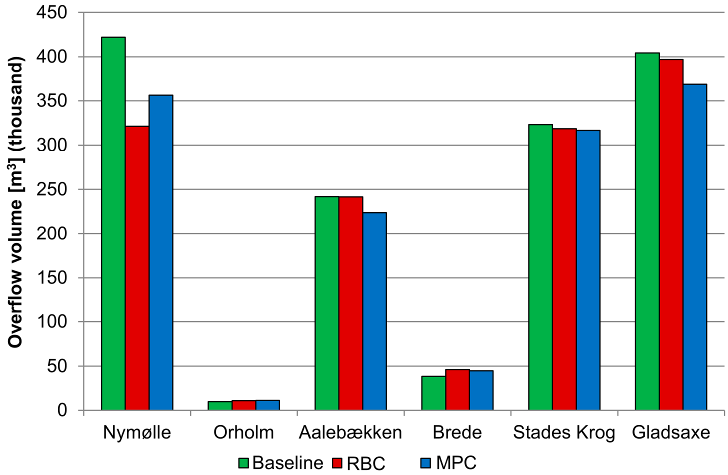

Figure 4. Distribution of the total overflow volume per environmental section for the three scenarios.

Figure 5 compares the total CSO volumes discharged to recipients with high, medium, and low sensitivities. For areas with a high impact cost or more sensitive areas (Figure 1b), MPC reduced the total CSO volume by 33,000 m^3 (4.3%), whereas RBC only reduced the volume by 10,000 m^3 (1.3%) compared to the baseline scenario (Figure 5a). For the lowest impact cost areas, RBC resulted in higher CSO reductions with 100,000 m^3 (21%), whereas MPC reduced CSO by only 67,000 m^3 (14%). Again, these results are due to the different objective functions applied by RBC and MPC. Both strategies tend to move the overflows from the most sensitive to the least sensitive areas, but the risk-based approach used in the MPC strategy has greater flexibility in defining the optimal set-points, and thus obtains lower environmental impacts (Table 3).

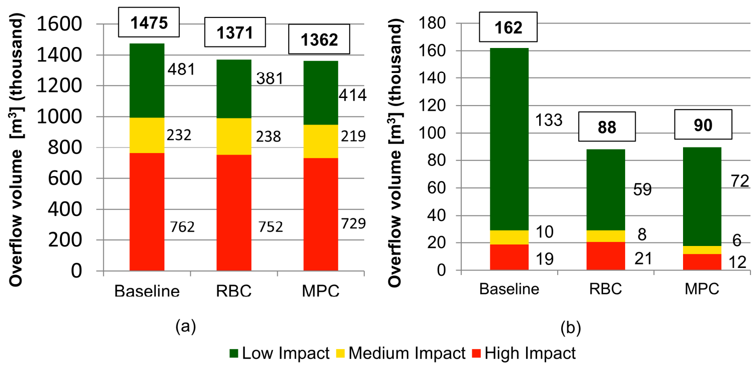

Figure 5. Overflow volumes for the three scenarios depending on the sensitivity of the recipient. The white rectangle above each column shows the total overflow volume for all sensitivity classes. (**a**) All 46 simulated events; (**b**) Events only included with less than 20,000 m^3 of CSO in the baseline scenario.

Table 3. Simulated environmental impact risk point (EIRP) values expressed as millions for different environmental impact areas and their relative reduction.

Scenarios	Low Impact	Medium Impact	High Impact	Total
Baseline	13.7	23.2	114	151
RBC	9.62 (−30%)	23.8 (+2.8%)	113 (−1.3%)	146 (−3.3%)
MPC	10.7 (−22%)	21.9 (−5.5%)	110 (−4.3%)	142 (−6.1%)

Looking at the events that caused less than 20,000 m^3 CSO in the baseline scenario, which were the events where control fully expressed its potential for using the available storage volume, the RBC scenario obtained slightly higher overall CSO volume reductions compared to the MPC scenario. However, when looking at the most sensitive recipients in the high impact category, the MPC scenario obtained better results (Figure 5b). MPC reduced the CSOs in the areas with high sensitivity by 36%, from 19,000 to 12,000 m^3, whereas the RBC strategy increased the overflows by 10%, from 19,000 to 21,000 m^3. This is explained by the objective function used in DORA, where different discharge locations are prioritized according to the value of R_i. In some cases, a lower environmental impact could be achieved by overloading less sensitive points to protect more sensitive sections.

3.4. Estimated Yearly Performance

All scenarios performed similarly for events with return periods beyond two years, as well as for some individual events with lower return periods. The CSO density curve shown in Figure 6 displays this result. However, for most events corresponding to return periods shorter than two years, such as for medium–small events, below the 20,000 m^3 threshold described in Section 3.2, the two RTC scenarios performed better than the baseline scenario. When extrapolating the yearly CSO volumes using Equation (4), the reduction for the RBC scenario compared to the baseline was estimated to be 6900 m^3 per year (10.8%), whereas the MPC scenario reduced the CSO volume by 7100 m^3 per year (11.2%). Similarly, we estimated that the environmental impacts generated by CSOs over one year were reduced by 5.5% with RBC and 9.9% with MPC.

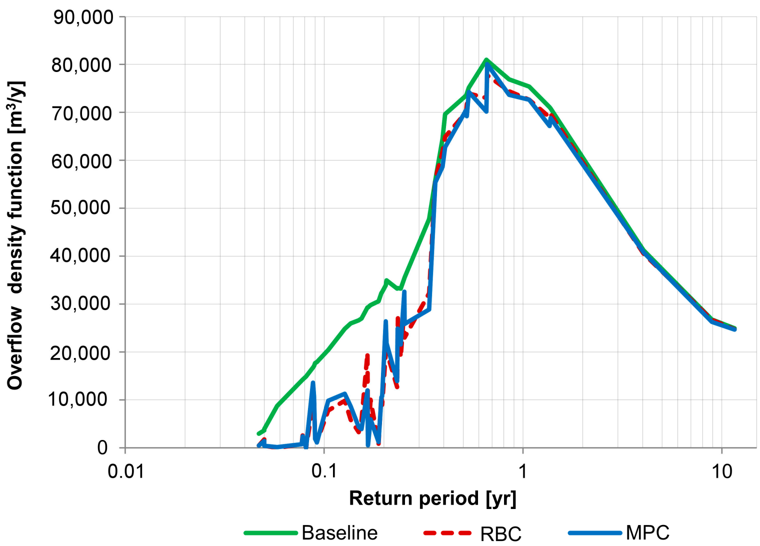

Figure 6. Extrapolated yearly overflow volumes saved by both RTC methods illustrated by the area between the CSO density curves for the baseline scenario curve (solid green line) and the RTC scenarios (RBC in dotted brown line and MPC in solid blue line).

4. Discussion

Both the investigated RTC strategies enable important CSO reductions depending on the magnitude of the overflow, with greater relative improvements obtained for events with magnitudes comparable to or lower than the available storage capacity. Conversely, no improvements were observed for events exceeding the available storage capacity, implying that for extreme events, such as those that cause flooding, more drastic solutions are required to create the necessary storage capacity. These solutions could involve carefully using public spaces such as parks or parking lots to store water. This is the classic behavior of a RTC system, which optimizes the usage of the available storage volume in the UDS, but cannot avoid CSO when this capacity is exceeded, which was reflected in our findings.

The control methods tested in this study involve different levels of complexity. The complex risk-based optimization MPC approach, including weather forecasts and uncertainty (MPC scenario), generated better overall results for the overflow distribution. This was expected, since the optimization routine has a global, system-wide overview of the current and future status with a two-hour forecast of the sewer network, allowing a continuous redistribution of water volumes across the system to reduce the environmental impacts. In this specific case study, the simple "if–then–else" control rules applied in the coordinating control approach (RBC scenario) was simpler and faster to implement than MPC, showing reasonably good results considering the total overflow volume. However, rule-based control struggles to adapt to other objectives than CSO volume reduction, such as water-quality based control strategies [24], where the pollution at each controlled point and the sensitivity of the receiving bodies change in time and cannot be described by "if–then–else" rules. Similarly, the risk factor R_i (expressed in monetary units) can be linked to actual pollution levels at the discharge point if a CSO price is defined. For example, tariffs are defined for pollutant loads discharged by WWTPs in Denmark.

The full potential of the DORA algorithm has not yet been fully explored. As shown by Löwe et al. [25], a dynamic estimation of the forecast uncertainty can lead to significant improvements in the MPC performance compared to the use of the constant uncertainty description adopted in this study.

This simulation study only provides an estimate of the RTC potential in the Lundtofte catchment. The MU model used is a simplification of the real system, and dynamics are often more complex in reality. Also, the simulations were run offline, considering perfect weather forecasts. For online applications, real-time radar data and forecasts would be used instead of data from the four rain gauges used here, leading to a potentially better description of the spatial rainfall distribution but increasing the input and forecast uncertainty. The actual performance of the MPC strategy may thus be lower than in this study, even though uncertainty was considered and integrated into the optimization algorithm. Further investigations are therefore needed to fully document the expected effects of the considered MPC strategy.

5. Conclusions

This study showed how the combination of real time control (RTC) of urban drainage systems (UDS) with investment in static solutions can potentially reduce the need for infrastructure expansion investments while maintaining or improving the level of service. Based on simulations with a detailed hydrodynamic model, two RTC scenarios were investigated using spatially distributed rainfall as the input: a coordinating rule-based control strategy aimed at reducing CSO discharge volumes while avoiding flooding (RBC), and a model predictive control strategy (MPC) that employs a risk-based optimization algorithm considering flow forecast uncertainty two hours in advance and system-wide distributed CSO impact cost (utility). We furthermore developed a method to extrapolate annual statistics based on limited historical data (46 events from a five year period) and quantified the benefits in terms of CSO volume reduction, environmental impact reduction, and total utility cost, of including the two RTC strategies when planning the expansion and improvement of existing drainage networks.

The Lundtofte urban drainage system (UDS) offers an interesting opportunity to implement RTC, as both the investigated RTC strategies resulted in improvements compared to the baseline scenario based only on static infrastructure expansion. Several specific conclusions were obtained:

- Both RTC strategies reduced the storage volume expansion otherwise needed to fulfill the environmental regulations for CSO discharge by 5220 m^3 (21%).
- Both RTC strategies yielded reductions in CSO volumes, environmental impact risk points (EIRP), and total utility cost for the catchment as a whole, and for the individual environmental sections.
- RTC reduced the overflow volumes for frequently occurring events of magnitudes up to the total storage volume available in the system, which in this system corresponds to estimated event return periods lower than 0.4 years. For medium to large events, with a return period greater than about 1–2 years, RTC did not change the performance of the system.
- RTC optimally exploited the storage capacity across all involved municipalities, resulting in lower CSO volumes and impacts on sensitive receiving waters.

Comparing the control strategies, the MPC strategy had more benefits in terms of CSO impacts to sensitive recipients than the RBC strategy. Also, yearly statistics for the MPC strategy suggested a reduction in CSO volume of 11.2% and 9.9% in EIRP. Despite its simplicity, the RBC strategy achieved important reductions of 10.2% in CSO volume and 5.5% in EIRP on a yearly basis. Different RTC approaches can be implemented and significantly contribute to the improvement in the performance of UDS in a practical situation. Different strategies could complement each other in a robust hierarchical system. The simple RBC strategy can be used as a fallback strategy when problems occur in the complex MPC strategy, for example due to missing forecast data. Therefore, we recommend testing different control strategies to find the best suitable solutions for each specific case or catchment.

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Appendix A

The central unit of supervision control and data acquisition (SCADA unit) is an element to ensure the coordination, data gathering, and processing for RTC operation. This SCADA unit costs approximately 30,000 € per unit [13]. At the location of the sluice gates, four types of elements manage the in-situ coordination. These elements include: movable gates which are the physical objects that control the flows in the sewer; hydraulic engines that provide mobility to the gates; programmable logic controllers (PLCs); and power supplies, which in many cases are not readily available at the site. The total cost for a remote RTC set-up was estimated to be 35,000 € at each location where an actuator was placed [13]. Detailed costs can be found in Table A1. The costs were estimated for sluice gates, since most of the actuators used for the RTC scenarios were modelled or described as sludge gates.

The basin and pipe expansions were estimated at 802 €/m^3 and 250 €/m, respectively [13]. All the scenarios included some sort of basin expansion; therefore, this price was applied depending on the expansion volume. A pipe expansion cost was applied only to the MPC and RTC scenarios (250 m).

Preliminary RTC analysis in the sewer network indicated that by increasing the pipe capacity at this location, major CSO reductions could be achieved with dynamic control. The removal of this bottleneck enabled the discharge of higher amounts of combined sewage to the treatment plant when the system was not under high loading.

O & M expenses are difficult to estimate and vary widely depending on the location affecting the distance travelled by the technical staff involved, size, and depth of the actuator. Moreover, O & M costs may be significantly reduced if a set contract with a service contractor is in place. The estimated O & M costs were 600–1200 € per year based on costs in the nearby city of Copenhagen, including two to three visits per year for lubrication of the equipment and a general check-up. Other extra costs considered for the MPC strategy were the access to radar data (raw rain images), modelled forecast data, and troubleshooting and debugging services. From experiences in on-going RTC projects in the city of Copenhagen, the prices of the aforementioned services were set to 5400 €/year for each service.

Table A1. Unit utility cost descriptions for all scenarios tested. A cross (X) means that the item is included in the given scenario.

Item	Unit	Cost	Baseline	RBC	MPC
Storage	€/m^3	802	X	X	X
Pipe	€/m	250		X	X
SCADA	€	30,000		X	X
Sluice gate	€	5000		X	X
Hydraulic Engine	€	10,000		X	X
PLC *	€	15,000		X	X
EI **	€	5000		X	X
O & M ***	€/year/unit	600–1200		X	X
Radar rain data	€/year	5400			X
Forecast rain data	€/year	5400			X
Debug service	€/year	5400			X

* PLC: Programmable logical controller; ** EI: Electrical installation; *** O & M: Operation and maintenance.

Appendix B

Table A1. List of the 47 CSO structures in the Lundofte catchment, along with the responsible municipality, Environmental Sections, EIRP with the corresponding is the risk factor R_i in brackets, and Environmental Impact.

CSO Structure	Municipality	Environmental Section	EIRP (R_i)	Environmental Impact
39X1J01w1	Lyngby	Stades Krog	150 (15)	High
43XO1_3w1	Lyngby	Not assigned	150 (15)	High
Aabrinkenw1	Lyngby	Aalebækken	100 (10)	Medium
Aalebaekken_nordw1	Lyngby	Aalebækken	100 (10)	Medium
Aalebaekken_sydw1	Lyngby	Aalebækken	100 (10)	Medium
Aalebaekkenw1	Lyngby	Aalebækken	100 (10)	Medium
Aastraede_Pstw1	Lyngby	Stades Krog	150 (15)	High
Aastraede_Pstw2	Lyngby	Stades Krog	150 (15)	High
Arnes_Markw1	Lyngby	Nymolle	30 (3)	Low
Borrebakkenw1	Lyngby	Brede	100 (10)	Medium
Brede_Stationw1	Lyngby	Brede	100 (10)	Medium
Brovaengetw1	Lyngby	Not assigned	150 (15)	High
Brovaengetw2	Lyngby	Not assigned	150 (15)	High
BRXBAS1w1	Gladsaxe	Gladsaxe	150 (15)	High
BRXBAS1w2	Gladsaxe	Gladsaxe	150 (15)	High
BSXBAS1w1	Gladsaxe	Gladsaxe	150 (15)	High
Dybendalw1	Lyngby	Nymolle	30 (3)	Low
Frederiksdal_Pstw1	Lyngby	Not assigned	150 (15)	High

Table A1. *Cont.*

CSO Structure	Municipality	Environmental Section	EIRP (R_i)	Environmental Impact
Frilandsmuseetw1	Lyngby	Brede	100 (10)	Medium
GENBASw1	Gladsaxe	Stades Krog	150 (15)	High
Gl_Skolew1	Lyngby	Brede	100 (10)	Medium
Hummeltoftenw1	Lyngby	Not assigned	150 (15)	High
Hummeltoftenw2	Lyngby	Not assigned	150 (15)	High
Kulsviervejw1	Lyngby	Nymolle	30 (3)	Low
Lottenborgw1	Lyngby	Stades Krog	150 (15)	High
Lundtoft_renseanlaegw1	Lyngby	Nymolle	30 (2)	Low
Lykkens_Gavew1	Lyngby	Brede	100 (10)	Medium
Mosebakkenw1	Lyngby	Not assigned	150 (15)	High
Nymolle_pstw1	Lyngby	Nymolle	30 (3)	Low
Orholm_pstw1	Lyngby	Orholm	30 (3)	Low
Orholm_Stw1	Lyngby	Orholm	30 (3)	Low
Overløb_fra_00LY120	Lyngby	Brede	100 (10)	Medium
Overløb_fra_00LY130	Lyngby	Brede	100 (10)	Medium
Overløb_fra_00LY144	Lyngby	Brede	150 (15)	High
Overløb_fra_00LY999	Lyngby	Brede	100 (10)	Medium
Overløb_fra_0MLY153	Lyngby	Stades Krog	150 (15)	High
OVVIRw1	Rudersdal	Aalebækken	30 (3)	Low
Parkvej_Pstw1	Lyngby	Not assigned	150 (15)	High
Slotsparkenw1	Lyngby	Stades Krog	150 (15)	High
Slotsvaengetw1	Lyngby	Stades Krog	150 (15)	High
Sorgenfri_Slotw1	Lyngby	Stades Krog	150 (15)	High
Sorte_Mosew1	Lyngby	Not assigned	100 (10)	Medium
SSU243w1	Rudersdal	Aalebækken	30 (3)	Low
SSU245w1	Rudersdal	Aalebækken	30 (3)	Low
SSU313w1	Rudersdal	Nymolle	30 (3)	Low
Stades_Krogw1	Lyngby	Stades Krog	150 (15)	High
Virum_Overdrevw1	Lyngby	Not assigned	150 (15)	High

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