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Real Time Control strategies to reduce expansion of urban drainage systems. Case study: Lyngby-Taarbæk

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REAL TIME CONTROL STRATEGIES TO REDUCE EXPANSION OF URBAN DRAINAGE SYSTEMS. CASE STUDY: LYNGBY-TAARBÆK

Contrôle en temps réel pour réduire l'expansion des réseaux d'assainissement urbain ; Etude de cas : le bassin versant de Lyngby-Taarbæk

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Abstract:

This article illustrates how real time control (RTCs) strategies can contribute to reduce the expansion of urban drainage infrastructures while maintaining the desired level of service. The Lyngby-Taarbæk catchment is used as case study: based on a static design, a storage expansion of 24,200m^3 has been planned to fulfil new environmental requirements. Two RTCs methods are implemented in order to maintain the same combined sewer network performance while reducing the planned basin expansion, and consequently reducing the investment cost. A state-of-the-art global control scheme using a 2-hour weather forecast (the Dynamic Risk Overflow Assessment - DORA) is tested. Also, a strategy involving predefined "if-then-else" control rules is developed and tested. The performances of both RTC strategies are compared and evaluated by analysing 46 historical rain events with various patterns. According to the simulation results, RTC succeeded in providing similar performance of the drainage system by maximizing use of the available storage. A storage reduction of 5,220 m^3 is accomplished (corresponding to 21% of the proposed basin expansion). The reduced system operated dynamically generates lower combined sewer overflow (CSO) discharges for small to medium rain events; while the desired performance of the system is achieved for big events. The rule-based strategy reduces significantly CSO, however DORA provides generally better results by using forecasting and risk-based approach. These results show that implementing RTC strategies during the design stages could reduce the elevated cost associated with UDS expansion while offering a similar or even better protection to the environment.

Key-words: real time control, optimization of storage capacity, combined sewage overflow

Résumé:

Cet article examine les avantages du contrôle en temps réel (CTR) en étudiant le cas du bassin versant de Lyngby-Taarbæk (Danemark). Pour répondre à des exigences environnementales, la capacité de stockage du système doit être augmentée. Deux stratégies de CTR sont testées pour réduire cette extension tout en maintenant la performance du réseau : d'une part, un algorithme complexe d'optimisation utilisant des prévisions météorologiques à 2 heures appelé DORA; et d'autre part, un algorithme simple composé d'une série de règles « si-alors-sinon ». Les performances du système sont comparées pour 46 pluies historiques. Les résultats montrent que l'instauration du CTR permet d'améliorer les performances du système en augmentant sa capacité de stockage et en offrant une gestion intégrée du réseau. Ainsi une réduction de 5200m^3 de l'extension initiale est possible. Le système ainsi réduit contrôlé dynamiquement génère nettement moins de rejets polluants pour les pluies faibles à moyennes alors que les rejets restent stables pour les fortes pluies. Le CTR améliore également la distribution géographique des rejets pour protéger les zones sensibles. Même si les règles de contrôle donnent de bons résultats compte-tenu de leur niveau de complexité, DORA permet d'obtenir les meilleurs résultats. Ainsi considérer le CTR dans la phase de conception permet de réduire une extension nécessaire du réseau tout en offrant une meilleure protection de l'environnement.

Mots-clefs : contrôle en temps réel, optimisation de la capacité de stockage, rejets polluants

I INTRODUCTION

Traditionally, large-scale construction programs such as sewer separated systems, conveyance pipes and storage facilities have been used as restoration strategies for sewer discharges and urban floods. Investments related to such programs are extremely high, especially for old systems located in densely populated areas with elevated land values. As a consequence, the interest in alternative solutions such as real time control (RTCs) strategies is increasing. RTCs approaches have the ability to manipulate and monitor urban drainage systems (UDS) to minimize Combined Sewer Overflows (CSO), to optimize flows into the waste water treatment plant, and to reduce floods in urban areas [Schütze et al., 2004]. Numerous practical applications have reported performance improvements and capital cost reductions by implementing RTCs in sewer networks [Dirckx et al., 2011]. These state-of-the-art techniques mainly aim at fully exploiting the existing storage capacity, balancing for example the effect of spatially distributed rains, and at reducing the impact on the receiving water bodies.

This study aims at demonstrating the benefits of integrating RTCs (computer aided management of sewer networks) when considering improvement of the UDS performance. The Lyngby-Taarbæk catchment (Denmark) is used as case study. Here, the local utility has planned an expansion of the UDS storage capacity to reduce CSO discharges due to recent legal requirements. Control strategies are assessed in this study as a complementary solution to basin expansion, showing how RTC combined with smaller basins can achieve a similar (or better) level of service than the planned basins. The performance of a proposed approach (calculated based on 46 historical rain events, occurring over a 5-years period) is compared against the expanded UDS under static operation. Two real time control methods are implemented and compared: (i) a model predictive control using a two-hour weather forecast (the Dynamic Overflow Risk Assessment – DORA [Vezzaro and Grum, 2012]) and (ii) a simple algorithm composed by a set of predefined "if-then-else" control rules.

II CASE-STUDY: LYNGBY-TAARBÆK CATCHMENT

The Lyngby-Taarbæk UDS serves 34 000 inhabitants with an estimated dry weather flow of 100 l/s. During wet weather conditions, the waste water treatment plant (WTTP) can raise the capacity to 1,340 l/s. There are 21 storage basins with significant volumes for control and 47 CSO structures discharging to four water bodies with different sensitivities.

The UDS collects both storm and wastewater from different municipalities: Lyngby, Søllerød, and Gladsaxe. These municipalities/utility companies operate and handle expenses independently, resulting in a not coordinated management of different parts of the UDS. Furthermore, some elements of the UDS (such as the WTTP and main trunks) are managed jointly. Environmental regulations control the CSO on a per-section basis, defining different requirements for each section (also called environmental section) of the receiving water body (the Mølle Å stream). Each environmental section includes multiple CSO discharge points, which can involve several utility companies. The main environmental sections are: Stades Krog pertaining to the Lyngby-Taarbæk jurisdiction; Gladsaxe belonging to the Gladsaxe Commune; and the Nymølle and Aalebaekken sections shared by Lyngby-Taarbæk and Søllerød.

The Lyngby-Taarbæk utility is investigating various UDS management alternatives in order to minimize CSO discharges and to fulfil legal requirements. A restoration plan has been proposed involving an expansion of 24,200 m^3 of storage capacity distributed between four key locations: Stades Krog 1, Aalebækken Nord, Aalebækken and Dybendal (Figure 1). The cost of such expansions would be handled only by Lyngby-Taarbæk utility since it falls within its jurisdiction, while all the involved municipalities will benefit from the planned expansion of the system.

III METHODS

III.1 Material and data

The performance of the investigated RTCs approaches are evaluated by using a MIKE URBAN (MU – www.mikebydhi.com) model of the study area (recently updated by Krüger A/S). MU is a full hydrodynamic modelling tool widely accepted by the Danish authorities. It uses Saint-Venant equations to estimate the hydraulics in sewer systems, a recommended feature when assessing RTC, as it allows the simulation of back water effects [USEPA, 2006].

The RTCs strategies are assessed based on a water quantity approach (CSO volume), thus no assessment on the water quality (CSO pollution) is considered. In order to consider the different sensitivity of the receiving water body, different impact costs (expressed in monetary terms per volume of discharged CSO) are applied according to the location of the CSO structure. In the absence of sensitivity studies for the area, impact costs are estimated based on traditional assumptions and perceptions regarding protection of the environment, population health, and property values. Prioritization is given to high populated areas and recreational values provided by water bodies. It is assumed that lakes have higher recreational values than rivers. Also, the city centre (located south of Figure 1) has higher overflow cost than rural areas.

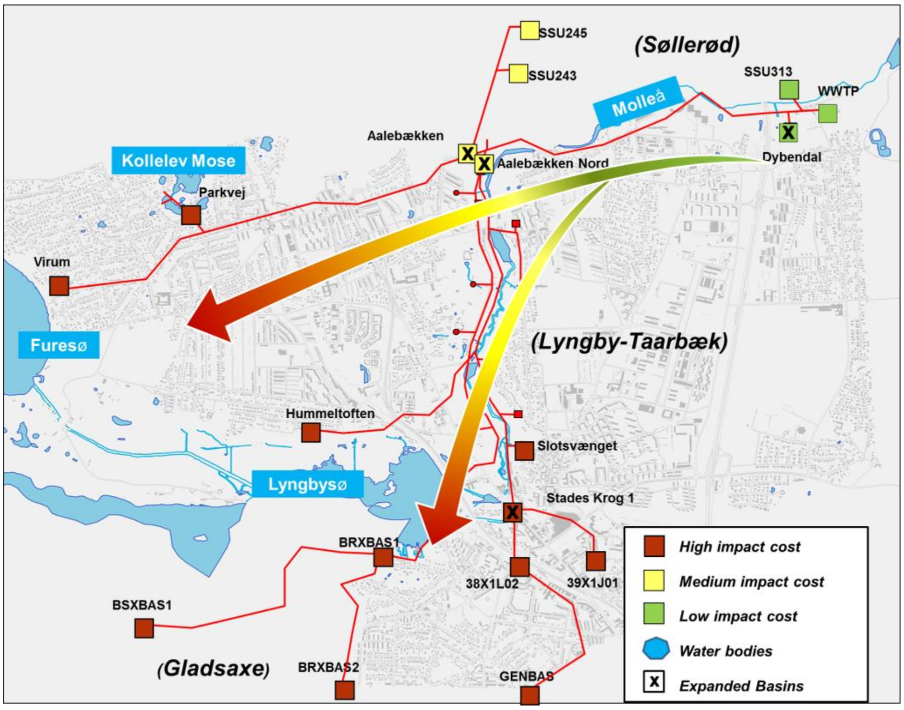

Figure 1 Impact costs associated with combined sewer overflow structures based on the sensitivity of the receiving water bodies. Also, it shows the location of the expanded basins.

Due to the lack of numerical values, the impact costs are chosen and defined as:

- High impact cost 15 €/m^3 (High density areas; High flood risk; Lakes)
- Medium impact cost 10 €/m^3 (Medium density; Upstream parts of the river)
- Low impact cost 3 €/m^3 (Low density areas; Downstream river) and 2 €/m^3 at WWTP

To get an approximate representation of real spatial rain distributions, four rain gauges are used to prepare the surface runoffs for all simulations. The historical precipitation data are provided by the Danish Meteorological Institute (DMI) and the Water Pollution Committee of The Society of Danish Engineers (SVK). The chosen observation period is from February 2008 to February 2013, covering a period when all the four rain gauges were in service. Due to high computational time required by MIKE URBAN, a continuous simulation over the five years of data available is not feasible. Thus, a selection of 46 rain events is made to consider an accurate overview of rains occurring annually with various patterns in terms of rainfall depth and duration. This selection includes the 15 biggest rains occurring during the observation period. Additional 31 events are added to consider frequently occurring medium and small rain events. Moreover, rain data is checked to avoid offline periods from the rain gauges.

III.2 RTC implementation

The implementation of RTC in this study follows the steps detailed in the framework of the M180 guideline document prepared by the German Association for Water, Wastewater and Waste [Schütze et al, 2008].

III.2.1 Step 1 Preliminary analysis:

After specifying the RTC objectives, a crude estimation for control potential is estimated by gathering all physical characteristics (basin and pipe volumes, actuators, etc.) and hydraulic data (filling degrees, CSO frequency, etc.) of the UDS. The RTC potential is calculated following the PASST guidelines, resulting in a medium to high potential with 33 points [Schütze et al, 2008].

Based on the system performances and characteristics, a control scheme is built including 15 control points distributed between all the utility companies. A total of 24 actuators are controlled: 9 already present in the UDS and 15 are added compared to the original system. In some cases, multiple actuators are used under the same control point depending on the hydraulic complexity and storage structures considered. Actuators are added in order to activate unused or rarely used storage for different rain events. For example, high storage volumes are found in pipes with relatively flat slopes. The control of these points is achieved by implementing moveable gates or pumps to control outflows and consequently water levels at each control point. These actuators are added to fully exploit the unused capacity upstream from the basins that are intended for expansion. Thanks to this approach, important reductions in the planned storage basins are possible. Implementation of actuators is conducted after a detailed hydraulic analysis, aiming at avoiding flood caused by storage in pipes. In order to avoid flood caused by RTC, specific control rules are implemented, prioritizing the protection of surface surcharges. Moreover, a 250 m long pipe located in a rural area is enlarged since it constitutes to a bottleneck of the system.

III.2.2 Step 2 control strategies:

Two types of real time control strategies are implemented and compared. Both procedures aim at improving the environmental performance of the system, though by using different objective functions.

- *Real time control (RTC)*

RTC actions are based on the present state of the system without any forecast of the incoming flows to the UDS. It operates based on several pre-defined and simple “if-then-else” rules for all possible states of the system. In principle, it manipulates throttle outflows depending on the filling degree of the local and neighbour basins. In case of unavoidable overflows, it protects the most sensitive structures. This control scheme is built within MIKE URBAN and it was developed for this specific case. The objective function of this strategy aims at optimizing the storage capacity and reducing the CSO volume

- *Model predictive control (MPC)*

MPC employs a global control strategy (the Dynamic Overflow Risk Assessment – DORA [Vezzaro and Grum, 2013]), which combines (i) actual measurements, (ii) rainfall-runoff forecasts, and (iii) the uncertainty of these forecasts. DORA is a risk-based strategy which minimizes a global cost function, which is calculated as:

$$Cost\ function = \sum_{i=1}^{N_{basins}} (C_{Cr,i} + C_{F,i} - C_{hor,i}) \qquad \textbf{(1)}$$

where the first term (C_{Cr}) is the cost of overflow volume created by the runoff that already entered the UDS; the second term (C_F) is the expected overflow volume generated by the rainfall occurring during the forecast horizon (defined as the time when the uncertainty in runoff predictions becomes too significant to allow a confident use of the predictions); and the third term (C_{hor}) is a factor considering the available storage volume beyond the forecast horizon. The expected cost of CSO due to forecasted runoff (C_F) is calculated as:

$$C_{f,i} = \int_{V_{critical}}^{\infty} c_i \cdot V_{F,i} \cdot p(V_{F,i}) dV_{F,i} \qquad \textbf{(2)}$$

where $V_{critical}$ is the available storage capacity (i.e. the forecasted runoff equals $V_{critical}$ overflow will occur), c_i is the impact cost for the i-th basin, $V_{F,i}$ is the forecasted runoff the i-th basin, and p($V_{F,i}$) is the probability associated to the runoff forecasts. DORA optimizes the future evolution of the system based on a two-hour rainfall forecast. The objective function of this strategy thus aims at reducing the impact due to CSO events.

III.3 Scenarios investigated

Table 1 Proposed basin expansions investigated for the different scenarios at the locations of interest.

	Baseline scenario (m^3)	**RTCs** scenarios (m^3)	Volume difference (m^3)
Dybendal	500	0	500
Aalebækken	7 800	6 700	1 100
Aalebækken Nord	3 500	2400	1 100
Stades Krog 1	12 400	9 880	2 520
Total	24 200	18 980	5 220

Three scenarios are simulated: the “*baseline*” scenario has the aforementioned expansion of 24,200 m^3 at four locations. This baseline scenario results are used to assess the performance of the RTC strategies. The *RTC* and *MPC* scenarios differ from the baseline scenario for their ability to react dynamically (through the actuators mentioned in section III.2.1) and for the smaller basin volumes at the locations listed in Table 1.The basin volume reductions applied, in the RTC and MPC scenarios, are based on the results obtained from the control strategies operated in the fully expanded system. The CSO saving achieved enabled to reduce by 5 220 m^3 the system capacity (equivalent to 21% of the planned expansion) while maintaining similar performance.

III.4 Assessment of system performance

To maintain the same "environmental performance" for the reduced system, it is necessary to assess the results for the total catchment and for each section. The total catchment scale indicates full impact of the UDS into the environment: these performances are estimated by adding, for all events tested, the overflow volumes, or associated impact costs, from all CSO structures independently from their given jurisdiction. The per-section scale is bound to the legal requirements where the CSO volume indicator is measured based on the sections mentioned in Section II.2. Thus, a reduced system which worsens at any of these two scales would not be an acceptable substitute strategy of the baseline scenario. Safety is ensured through the recommendations given by Schütze et al. [2004] which stand that the worst case scenario should at least provide an equivalent system performance before RTCs are implemented.

IV RESULTS AND DISCUSSION

The first assessed indicator is the total overflow volume generated at the catchment scale (sum of all overflows). In Figure 2, the x-axis is the total overflow volume discharged in the baseline scenario while the y-axis represents the CSO volume generated by the reduced system operated with RTC (squares) and with MPC (triangles). Each square or triangle represents one of the 46 rain events simulated. When a point falls on the identity line, the same performance is reached compared to the baseline scenario. If it falls above, the total overflow volume discharged is increased, and if it falls below, the total overflow volume is reduced.

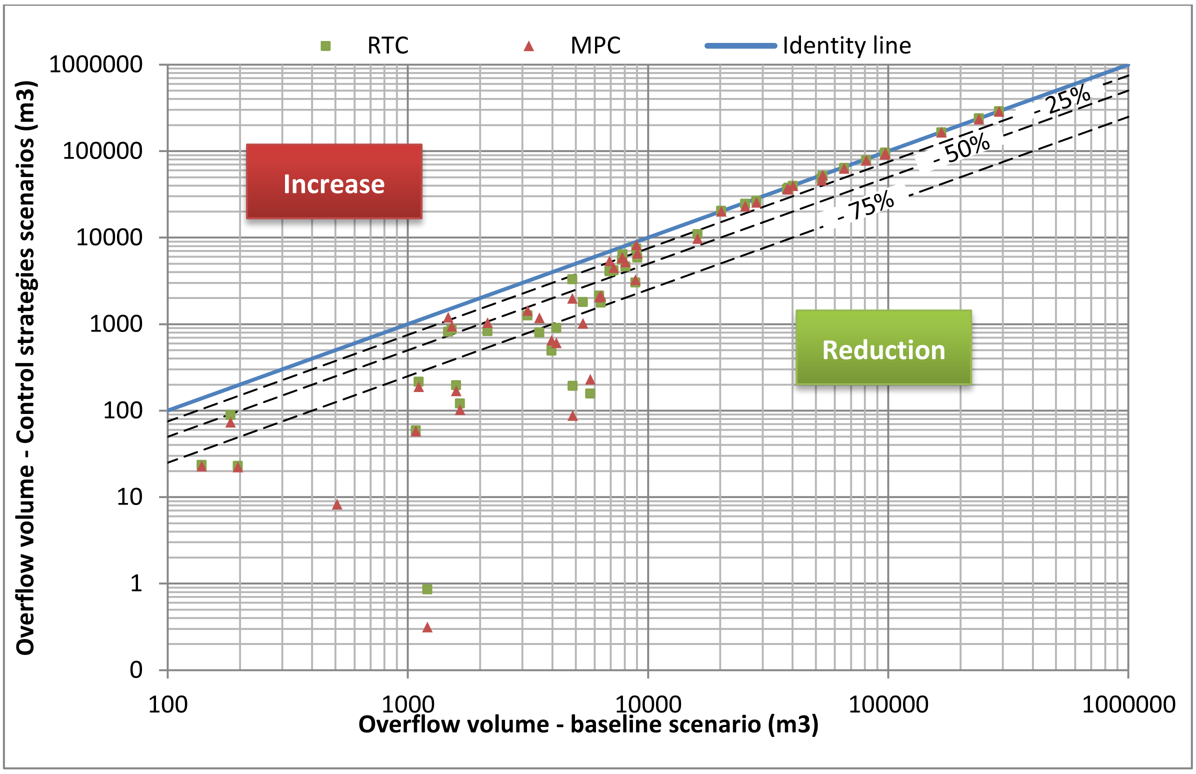

Figure 2 Comparison of the overflow volume discharged at the catchment scale for the three scenarios. In dotted lines the percentile reductions.

Figure 2 shows a threshold for rain events creating overflows between 10,000 m^3 – 20,000 m^3 in the baseline scenario. Above this threshold, large CSO events (worst-case scenarios) generate similar CSO volumes for the baseline scenario as for the systems with reduced basin volumes (RTC and MPC). The baseline UDS shows an inadequate use of the total systems capacity; showing how the implementation of actuators (RTC and MPC) has activated unused or rarely used capacity in basins or storage pipes for different rain events. These enable both control strategies to achieve the same performance by exploiting all the capacity with a 5,220 m^3 smaller storage volume.

For all rain events below the threshold, both control strategies discharge less CSO than the baseline scenario. Figure 2 shows that both control strategies reduced the overflow volumes for 21 out of 46 events by more than fifty percent. For the 46 individual rain events, RTC and MPC achieved a total CSO reductions of 103,000 m^3 (7%) and 113,000 m^3 (8%), respectively. The performances of RTC and MPC show high interevent variations, but the general trend from the 46 rains shows that both methods provide similar performances regarding total CSO volume discharged.

For some individual events (Figure 2), RTC achieves higher CSO volume reductions than MPC. However, in those events, MPC achieves lower impact cost (which is the goal of DORA). In fact, in some cases DORA's goal can be achieved by overloading less sensitive points in order to protect more sensitive sections. Looking at the estimated impact cost caused by the CSO events (CSO volume * CSO cost), cost reductions are 6% for MPC and 3% for RTC compared to the baseline scenario for all 46 events tested. The total impact cost generated by MPC is significantly lower (half) than RTC.

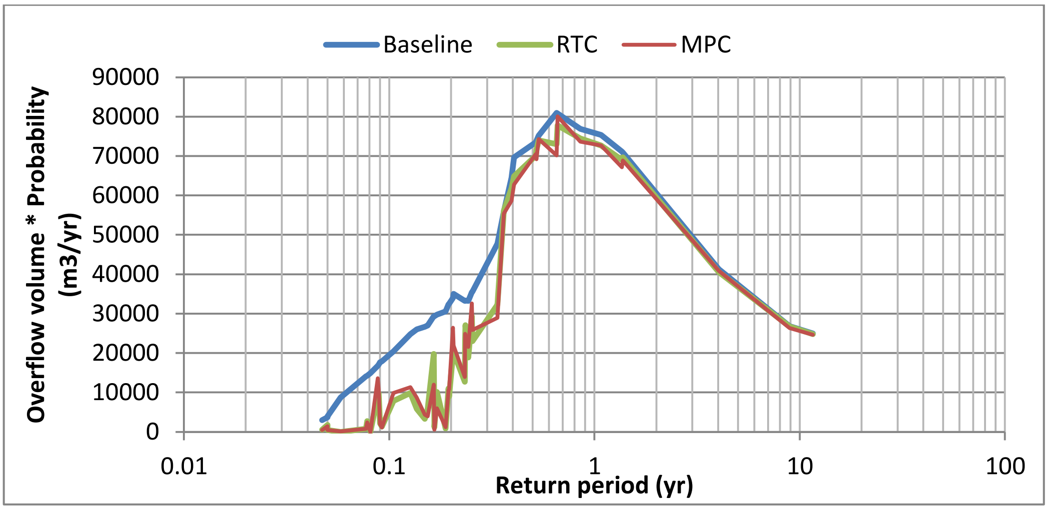

Figure 3 Overflow volumes saved per year by both RTC methods illustrated by the area between the baseline scenario curve (blue) and the RTCs scenarios curves (RTC in green and MPC in red)

As previously shown, RTC and MPC provides important benefits for smaller rain events which tend to occur frequently; thus, estimating the yearly performance of the system is particularly relevant. Weights are assigned to each rain event depending on its return period. Then, the product of the probability of exceedance (defined as the inverse of the return period) by the overflow volume generated is plotted over the return period of the rain (Figure 3). The numerical integration of the curves between the lowest return period observed and 1 year gives an estimation of the yearly CSO volume discharged.

According to this estimation, a total CSO reduction of 6,900 m^3 per year (10.8%) is achieved by RTC, while MPC saves 7,100 m^3 per year (11.2%) compared to the baseline scenario. The reductions for both control strategies are increased compared to the results with individual rains since higher weights are assigned to frequently occurring events (where the potential of RTC and MPC is higher).

The location of overflows is of particular interest in this study. Overflow discharges have different impacts depending on the recipient water bodies. Moreover, the environmental requirements must be fulfilled in a per section basis. Figure 4 and 5 illustrate the CSO distributions throughout the UDS.

Figure 4 compares the different CSO volumes based on the recipient's sensitivity for all tested events. The red (high), yellow (medium), and green (low) rectangles shows the sum of all overflows for each sensitivity area. As mentioned before, both control strategies reduce the total overflow volumes compared to the baseline scenario; but the spatial overflow distribution varies depending on the strategy tested. For areas with a higher impact cost or most sensible areas, MPC significantly reduces the CSO by 33,000 m^3 (4.3%) where RTC only reduces by 6,000 m^3 (0.8%) compared to the baseline scenario. For the lowest impact cost areas, RTC gained higher CSO reductions with 104,000 m^3 (21.6%) while MCP reduces 67,000 m^3(14.0%). Again, these results should be evaluated based on the different objective functions applied by RTC and MPC. Both strategies tend to shift the overflows from the most sensitive to the less sensitive areas, but the risk-based approach used by MPC achieves higher impact cost savings.

Considering the per-section scale, Figure 5 shows the overflows generated at the relevant environmental sections. Results show that the performances are maintained or even improved for all main environmental sections when control strategies are implemented, even though basins volumes are reduced by 21%. As mentioned in Table 1, a 5,220 m^3 storage volume is removed from the RTC and MPC scenarios distributed between three sections: 490 m^3 in Nymølle section, 2 210 m^3 in Aalebækken section, and 2 520 m^3 in Stades Krog section. At these sections, further CSO discharge reductions are achieved compared to the baseline scenario due to the robust control scheme.

For example, the great reduction observed in Nymølle section shared by both Lyngby and Søllerød utilities (Figure 5) is the result of a bottleneck removal replaced by an actuator in the Søllerød jurisdiction. Thus, a control measure located in one municipality may affect positively other municipalities. Both RTC strategies manage to exploit available storage capacity in all parts of the system located under different utilities jurisdiction. Thereby, this integrated management of the UDS generates benefits for the three municipalities involved as well as for the environment.

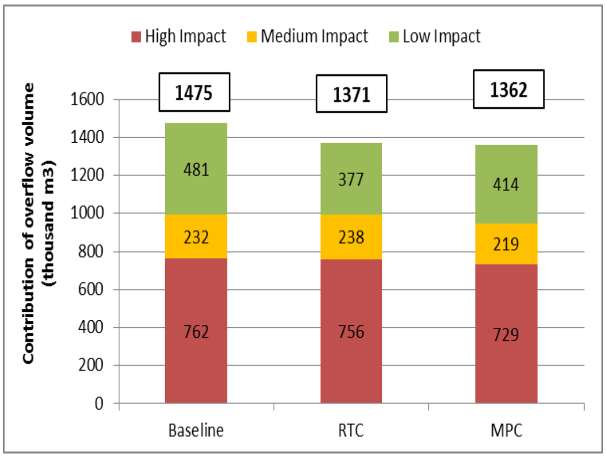

Figure 4 Spatial distribution of overflow volumes for the three scenarios depending on the level of sensitivity: The white rectangle above each column shows the total overflow volume.

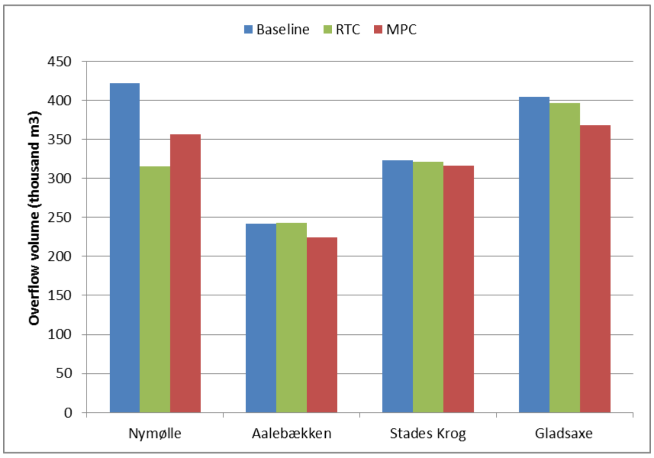

Figure 5 Spatial distribution of the overflow volume per environmental section for the three scenarios. Nymølle is the lowest sensitive area, while Aalebækken, Stades Krog and Gladsaxe have high to medium sensitivities.

According to the 46 rain events tested, even with a reduction of 21% of the UDS capacity, a better management of the storage capacity is achieved with the control strategies. Dynamic control implementation not only maintains the system performances but also provides higher gains in terms of CSO reductions, impact cost minimization, and per-sections requirements. The control methods tested in this study involve different levels of complexity. As expected, the complex risk optimization approach including weather forecast in MPC generates better overall results. Nevertheless, the simple “if-then-else” control rules applied in RTC, which is simpler and faster to implement than MPC in this specific study case, shows significant good results considering its level of complexity.

. Although the rain data is limited, from 2008 to 2013, the control implementations showed significant reductions depending on the size of the overflow. Specifically, control strategies provided an improvement in the performance of the system for small to medium size overflows (according to the UDS size).

This study, based on model simulations only, represents an indication of the RTC potential for this UDS. The MIKE URBAN model is a simplification of the real system and dynamics in reality are often more complex. Also, the simulations are run offline, considering perfect weather forecast. For online applications, real time radar data would be used instead of the four rain gauges data; leading to a potentially better spatial distribution but including uncertainty. The performance of MPC strategy may be lowered, even though such uncertainty is considered and integrated in the optimisation algorithm. Thus, further investigations should be conducted before any implementation in real life to assess the model errors and the consequences of an online operation of RTC on the system performance.

V CONCLUSIONS

This study shows how the integration of RTCs, computer assisted management of wastewater networks, during the planning and designing of urban drainage systems can potentially reduce the need for infrastructures while maintaining the same level of service. Two RTCs methods were tested and compared for several historical rain events: a rule-based control RTC and optimisation algorithm involving weather forecast MPC.

The Lyngby-Taarbæk catchment offers an interesting opportunity to implement computer aided management of its sewer network. Considering the proposed expansion "baseline scenario", the control strategies not only enabled to reduce 5,220 m^3 in storage volume which represents 21% of the total planned volume; but also, it maintained or improved the UDS performance. For frequently occurring events, RTCs systems significantly reduced overflow volumes, highlighting the benefits of a dynamically controlled system. For medium to large events, the control strategies maintain the performance of the system by utilizing the all infrastructure in the system. For the municipalities involved, the construction of a robust control scheme increases the UDS performance. Through time and space during a rain event, the dynamic control uses the storage available in all municipalities enabling to further reduce CSO which will benefit the different areas and the entire catchment.

Regarding the control strategies, MPC (DORA) achieved greater benefits considering the different sensitivities and total CSO discharges compared to RTC. The model predictive controls not only achieve higher CSO reductions but it also doubled the impact cost compared to the RTC for the 46 historical events. Also, MPC yearly results indicated that 11.2% CSO volume can be further reduced with a smaller expansion of the system. For the RTC's level of complexity, the strategy showed significant reductions, 10.2% CSO volume in yearly estimations. This highlights the potential and diversity of different tools that can be implemented. Therefore, it is recommended to test different control strategies to find the best suitable solutions for each specific case or catchment.

Even though RTCs showed important results in a fully hydrodynamic model (MIKE URBAN), further aspects should be investigated before implementation on the field. This study demonstrates a high potential for RTC on the Lyngby-Taarbæk catchment. Generally, it shows that implementing RTC can help reducing sewer networks expansion by using existing capacity while providing a better protection to the environment.

VI ACKNOWLEDGEMENTS

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