

Using ensemble weather forecast in a risk based real time optimization of urban drainage systems

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ABSTRACT. – Global Real Time Control (RTC) of urban drainage system is increasingly seen as cost-effective solution in order to respond to increasing performance demand (e.g. reduction of Combined Sewer Overflow, protection of sensitive areas as bathing water etc.). The Dynamic Overflow Risk Assessment (DORA) strategy was developed to operate Urban Drainage Systems (UDS) in order to minimize the expected overflow risk by considering the water volume presently stored in the drainage network, the expected runoff volume based on a 2-hours radar forecast model and an estimated uncertainty of the runoff forecast. However, such temporal horizon (1-2 hours) is relatively short when used for the operation of large storage facilities, which may require a few days to be emptied. This limits the performance of the optimization and control in reducing combined sewer overflow and in preparing for possible flooding. Based on DORA's approach, this study investigated the implementation of long forecast horizon using an ensemble forecast from a Numerical Weather Prediction (NWP) model. The uncertainty of the prediction is characterized by an ensemble of 25 forecast scenarios. According to the status of the UDS and the forecasted runoff volumes, the objectives for the control strategies might vary from optimization of water volumes to reduction of CSO risk. Thus different modes are implemented in DORA-LF (Long Forecast) in order to adjust the control strategies to the situations. In order to handle the long forecast, the horizon is divided into multiple and variable time step. This new approach was tested on selected rain events and shows an improvement in the protection of sensitive areas during long or/and coupled events by allowing anticipated CSO in low sensitivity areas.

Key-words: Overflows risk, Model Predictive Control, Urban water management, Numerical Weather Prediction model

Utilisation de prévisions météorologiques longue durée pour améliorer la gestion dynamique du réseau d'assainissement

RÉSUMÉ. – La gestion en temps réel des réseaux d'assainissement représente une solution économique pour répondre à la recherche croissante de performance (e.g. réduction des rejets de réseaux unitaires, protection des milieux aquatiques etc.). La stratégie DORA (Dynamic Overflow Risk Assessment) a été développée pour contrôler les réseaux d'assainissement dans le but de réduire les rejets d'eau usée en opérant le système de façon à utiliser sa capacité de stockage totale. Pour ce faire DORA prend en considération le volume d'eau initialement présent dans le système et les prévisions de ruissellement basées sur 2 heures de prévisions météorologiques provenant de radars. L'incertitude des prévisions météorologiques est prise en compte dans l'optimisation via une distribution gamma. Pour chaque plan d'eau, le volume d'eau usée rejeté est associé à un coût par mètre cube représentant sa vulnérabilité. Cependant, une période de prévision de 2 heures est relativement courte lorsqu'utilisée pour la gestion de grands bassins de rétention pouvant nécessiter plusieurs jours à vider. Cette étude a pour objectif de développer l'utilisation de prévisions météorologiques de longues durées en se basant sur la stratégie de DORA. Pour ce faire, un ensemble de 25 scénarios de 55 heures provenant d'un modèle de Prévision Numérique du Temps (PNT) est utilisé. Plusieurs stratégies de gestions sont utilisées, elles varient en fonction des conditions du réseau d'assainissement et des prévisions météorologiques. Ainsi, 3 différentes configurations ont été créées dans DORA-LF pour ajuster les objectifs de contrôle en fonction des données (« Dry », « No CSO » et « CSO »). Afin de simuler les variations temporelles des contrôles lors de l'optimisation, l'horizon temporel est divisé en intervalles de temps de durées variables. Cette nouvelle approche a été testée sur un exemple théorique inspiré du bassin versant d'Amager, Copenhague, Danemark. Sur le panel d'événements pluvieux testés, l'utilisation de longues prévisions météorologiques ne permet pas de réduire les volumes de rejets liés aux événements de courtes durées avec une forte intensité. Par contre lors d'événements de longues durées et/ou couplés, l'utilisation de longues prévisions météorologiques permet, grâce à des rejets anticipés dans des zones peu vulnérables, d'améliorer la protection de zones sensibles.

Mots-clés : Contrôle en Temps Réel, Prévision Numérique du Temps (PNT), Commande Prédictive, Rejets polluants

I. INTRODUCTION

Real Time Control (RTC) can be used to optimize the operation of the Urban Drainage System (UDS) and hence leads to a better performance. Therefore, RTC offers a relevant alternative to the construction of expensive storage facilities by optimizing the use of current available storage.

Weather radar nowcasts can provide information about the future evolution of rainfall, enabling RTC strategies to optimize the UDS based on the expected runoff volumes. For example, the Dynamic Overflow Risk Assessment (DORA) approach [Vezzaro and Grum, 2012] includes a two hour radar-based rainfall forecasts, along with their estimated uncertainty in the UDS optimization process. DORA is under implementation in two Danish urban catchments in the city centre of Aarhus and Copenhagen (see [Grum *et al.* 2011]) and it represents the most recent example of integration of radar-nowcasts into schemes.

However, the temporal horizon of radar-based predictions (1-2 hours) used in DORA is relatively short when used for the operation of large storage facilities, which may require longer time intervals (up to days) to be emptied. This limits the performance of the RTC in reducing combined sewer overflow and in preparing for possible flooding.

The objective of this study is to develop a control strategy based on long forecasts and assess its potential with respect to mitigation of Combined Sewer Overflow (CSO). This is achieved by incorporating long forecasts (up to 55 hours) from a Numerical Weather Prediction (NWP) model into an integrated control scheme for the UDS. The NWP forecasts (an ensemble of model simulations developed by the Danish Meteorological Institute) are integrated in the existing radar-based DORA control scheme. This new control strategy, DORA-LF (Long Forecast), was implemented in Matlab according to the scheme outline in Figure 1. DORA-LF identifies the optimal flows between the storage basins by using (i) the NWP forecast processed by a runoff model

(upper part of Figure 1), and (ii) the current measurements from the UDS (lower part of Figure 1)

This proposed new control strategy, DORA-LF, was tested on a semi-hypothetical catchment, inspired by a sub-catchment in Copenhagen, Denmark. The catchment was simulated by using a deterministic hydraulic model (MIKE URBAN – www.mikebydhi.com) which was connected with a Matlab implementation of DORA. The results of this study provide the basis for a full integration of NWP models into global RTC strategies, contributing to a further improvement of the performance of UDS systems.

II. METHODOLOGY

II.1. Dynamic Overflow Risk Assessment (DORA)

The Dynamic Overflow Risk Assessment (DORA) strategy (see [Vezzaro and Grum, 2012] for further details) aims at reducing the risk of overflow (quantified as the product of overflow cost and its probability) by minimizing a global cost function through an optimization routine. The global cost function considers:

- The current water volume stored in the entire system, allowing for a better usage of the storage capacity across the entire drainage network. This information is provided by online measurements from the system (water levels in the storage basins).
- The expected runoff volume in each sub-catchment in the near future (2 hr), thus allocating greater storage in the system where needed. Radar-based runoff nowcasts [Thorndahl *et al.*, 2012], which are updated every 10 minutes, are used for this purpose.
- The uncertainty in the runoff volume nowcasts, which is used to estimate the overflow risk at each basin. Currently, uncertainty is described by a fixed gamma distribution, but a dynamic description based on grey-box models is currently in the testing phase (see for example [Vezzaro *et al.*, 2013]).

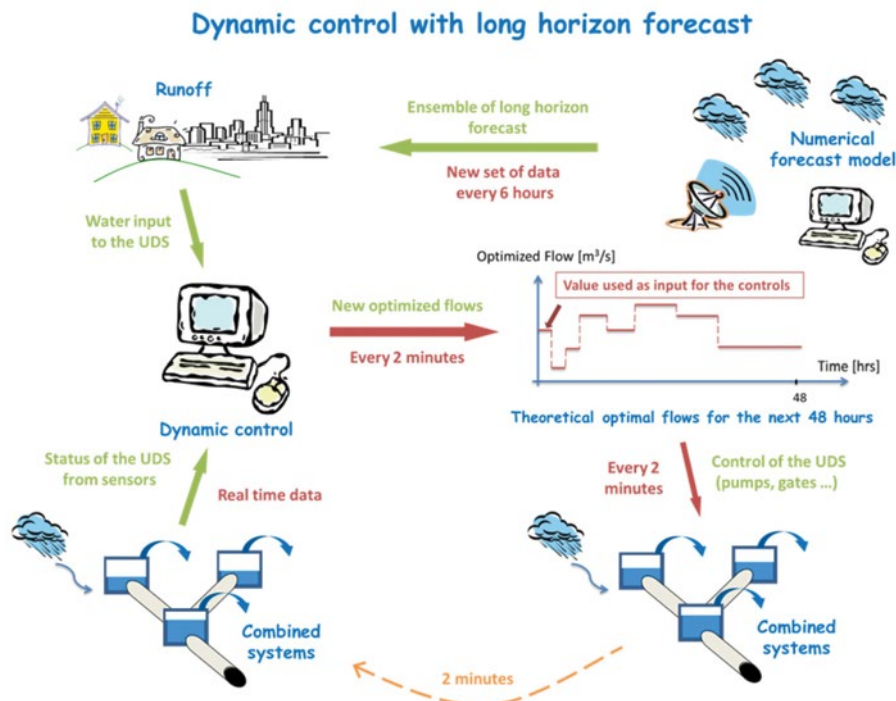


Figure 1: Schematic of dynamic control process with long forecast horizon.

- The sensitivity of the receiving water body is expressed for each basin by the cost in [€/m³], which is linearly proportional to the overflow volume. Higher prices are assigned to sensitive points (such as bathing areas in summertime), while lower prices are used at less sensitive points, such as bypass of Wastewater Treatment Plant (WWTP).

The optimization routine is run every 2 minutes, i.e. every time new measurements from the drainage network are available. The algorithm thus estimates the optimal average flows for next 2 hours between the retention basins that ensure the minimum overflow risk across the entire catchment.

II.2. Numerical Weather Prediction model

The main input of the proposed new control strategy consists of 25 scenarios generated by the HIRLAM model, developed by the Danish Meteorological Institute (for more details see [Du, 2007]). Model results are generated on a 5 km² grid, with a forecast horizon up to 55 hours. New forecasts are generated every 6 hours, as shown in Figure 2 (where the combination of the 25 ensembles is expressed as quantiles).

For simulation purpose the first 6 hours are used as input to the MIKE URBAN model, while the 48 hours forecasts are used as input to the Model Predictive Control (MPC).

II.3. New control strategy

The proposed approach (DORA Long Forecast – DORA-LF) extends the optimization horizon of DORA by using the 25 scenarios ensemble from the NWP model. DORA-LF schematized the controlled system into a simple model which only includes the available storage units. As mention in section II.1, a sensitivity cost, (linearly dependant to the CSO volume), is associated to each basin to reflect the vulnerability of the receiving water. In the current version, transport time between basins is neglected. The runoff generated in each sub-catchment during each time step is directly connected to the basin and a water balance in done between each time step, as schematised in Figure 3.

It has been found necessary to differentiate between three different modes of operation that each has a different objective function: “dry”, “No CSO” or “CSO”.

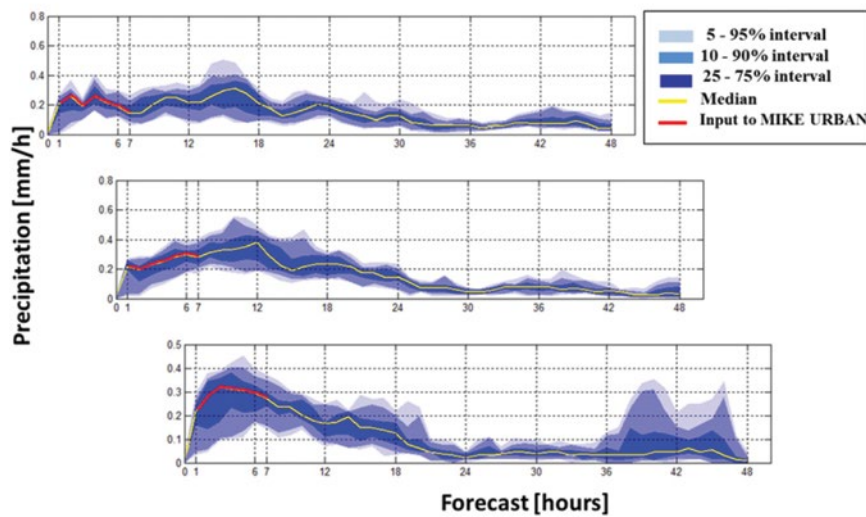


Figure 2: Quantiles distribution of the 25 scenarios ensemble from the NWP forecast model renewed every 6 hours.

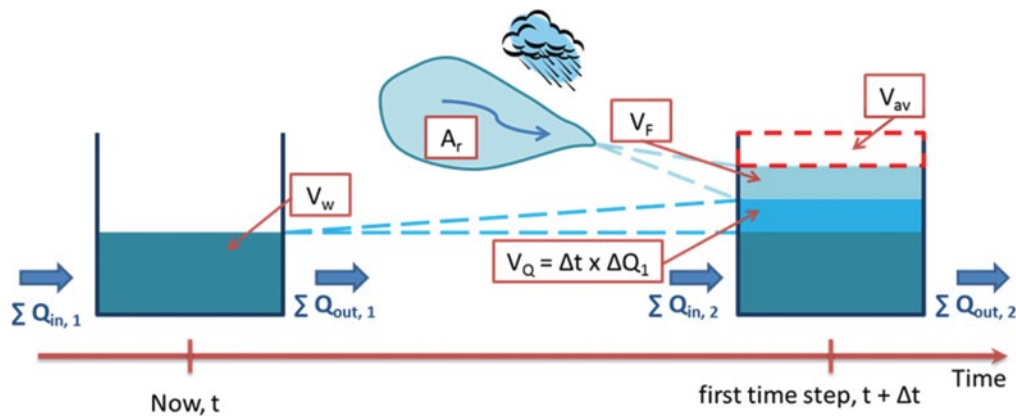


Figure 3: Schematic diagram of a detention basin and its evolution after one time step. The optimization variables for this first time step are $Q_{out,1}$ and $Q_{in,1}$. Where V_w is the initial volume of water in the basin, V_Q is the variation of volume from the sewage inflow and outflow, V_F is the volume of runoff from the reduced area A_r and V_{av} is the volume available for storage.

Based on the current status of the UDS and the forecasted precipitation, the control algorithm chooses which of the modes of operation, and thus objective function, is most appropriate for the current situation, as described in Figure 4. The criteria to switch between the different operational modes were adjusted to avoid instability.

II.3.1. Dry Mode

The Dry Mode covers 2 situations: (i) When no risk of overflows are forecasted (ii) When the possibility of CSO events are forecasted, but there is no anticipation capacity at the present time (e.g. the forecast suggest an intense events, basins are empty and there is no stored volume to optimize). In both situations, there is either no need or no degrees of freedom for CSO mitigation;

II.3.2. No CSO Mode

The “No CSO Mode” is used when a basin reaches a certain degree of filling or when the number of scenario leading to CSO events is too low to deem it to base the control strategy on CSO volume. The purpose of this control strategy is to optimise the distribution of the relative storage capacity throughout the sewer system according to the vulnerability of the receiving water body (and thus prepare the system in an optimal way in case CSO events become likely). As displayed in equation (1), the relative capacity of a basin is defined as the relationship between its current available capacity (V_{av}) in relation to the size of the reduced area connected (A_r) to it.

$$Relative\ Capacity = \frac{V_{av}}{A_r} \quad (1)$$

This optimization strategy is mainly based on the current status of the UDS and hence does not require long forecast data input. Furthermore in order to minimise the computation time the algorithm is based on one time step horizon of 2 hours.

Two cost functions are minimized: the first one (equation (2)) aims at emptying the UDS towards the WWTP as fast as possible, while the second (equation (3)), aims at reducing the risk of CSO due to coupled rain events by optimizing the distribution of the available storage capacity. The degree of filling is used to represent the potential for optimising a basin. Indeed the relative capacity of an empty basin cannot be improved.

$$Risk_Cost_1 = k_{empty} * \sum_{i=1}^{Nb\ re\ b} V_{W_i} \quad (2)$$

$$Risk_Cost_2 = \sum_{i=1}^{Nb\ re\ b} f(Degree\ of\ filling_i) * \frac{Average\ Relative\ Capacity}{Relative\ Capacity_i} * \frac{Sensitivity\ Cost_i}{Average\ Sensitivity\ cost} \quad (3)$$

As displayed above, this mode has 2 cost functions to be optimized. The emptying of the UDS towards the

WWTP should be prioritized over water distribution; this is done through the weighting factor K_{empty} .

II.3.3. CSO Mode

The DORA-LF control scheme switches to the “CSO mode” if at least 3 scenarios of the NWP ensemble (corresponding to a probability higher than 12%) lead to forecasted CSO events. Compared to the “No CSO” mode (optimizing volumes), the optimization algorithm here aims at reducing the CSO risk. To do so, the “CSO mode” utilizes the forecasted CSO volume, along with the sensitivity of the receiving water, as displayed in equation (4). The uncertainty of the forecast is calculated over the full range of the ensemble; the water balance for each basin is calculated for each time step (ts) and for all the 25 NWP scenarios. The risk-cost is subsequently calculated by multiplying the estimated CSO volumes ($V_{CSO_{i,j,k}}$) by the cost of the individual overflow locations ($Cost_k$). The algorithm optimises the flows rate between the basins in order to minimize this risk-cost.

$$Risk_Cost = \sum_{i=1}^{Scenarios} \sum_{j=1}^{Nb\ re\ ts} \sum_{k=1}^{Nb\ re\ b} V_{CSO_{i,j,k}} * Cost_k * \left(1 - k_{horizon} * \frac{j-1}{Nb\ re\ ts} \right) \quad (4)$$

If the cost of an overflow is considered constant over the predicted horizon, a possible solution to the optimisation could be to allow excessive CSO volume in a low sensitive basin in order to protect a sensitive basin from an uncertain CSO event. In order to avoid this and balance CSO events

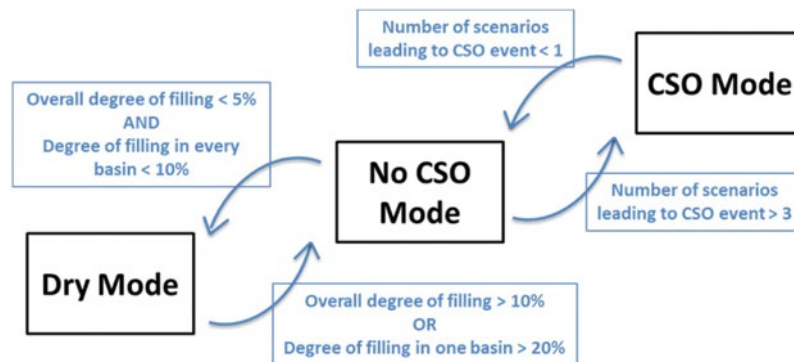


Figure 4: Decisions tree for switches between control strategies modes.

taking place in the near, more certain future (1-2 hours) with CSO events forecasted in the distant, less certain, future (up to 48 hours) a horizon discount function, $k_{horizon}$, is applied to the equation. $k_{horizon}$ can then be adjusted according to the balance one wishes to obtain.

Both the relative cost between basins and the horizon discount can impact significantly the optimization and they must be assessed carefully according to the objectives of the control strategy.

III. STUDY CASE - EVALUATION OF THE PERFORMANCE

III.1. Simplified Kløvermarken catchment

The performance of DORA-LF control strategy is evaluated on a semi-hypothetical model inspired by the Kløvermarken catchment (Figure 5), located in Southern Copenhagen. The total reduced area is estimated to be 16.6 km², which is subdivided into 4 sub-catchments (Table 1). There are 4 detention basins with a total storage capacity of about 86,150 m³. The catchment discharge to Lynetten WWTP, which has a maximum biological treatment capacity of 6.4 m³/s.

The CSO structures discharge to water bodies with different vulnerability. Thus, different costs are assigned to each overflow structure according to the sensitivity of the recipient.

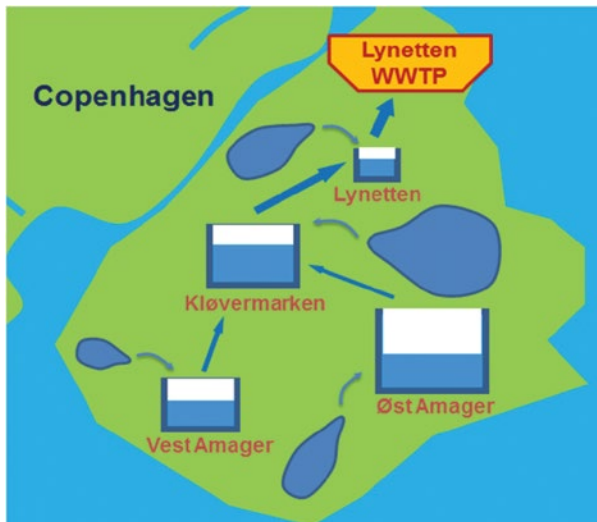


Figure 5: Scheme of the simplified Kløvermarken catchment.

Amager Strandpark (Amager Beach Park), a bathing area, is located at the east coast of Amager and Kalvebod Fælled, a park under the Natura 2000-scheme as an EU-recognized bird protection area, is located in the western part of Amager. Thus the two Amager basins are characterized by a high CSO cost, while bypass of the biological treatment at the Lynetten WWTP has a low CSO cost.

III.2. Results

The performance of DORA-LF was assessed based on two setups: (i) a short horizon of 2 hours divided in 2 time steps of 1 hour each; and (ii) a long horizon of 13 hours divided on 7 time steps of 1, 1, 1, 2, 2, 3 and 3 hours, respectively. These two set up were tested on long and coupled rain events. The CSO discharges resulting from an 11 hours coupled event are displayed in Figure 6.

Figure 6 shows that in the early stage of the rain event both setups lead to the same CSO. Indeed, the control could not operate because the UDS was in dry conditions. After this first pick of rain intensity, the short forecast management operate the UDS in order to minimize the short term CSO in Lynette (red circle) while the long forecast management maintain a high CSO discharge in order to protect more sensitive basin and decrease the CSO risk in those points (green circle). As displayed in Table 2, the long forecast strategy increase the total CSO volume by 1.4%, while reducing the risk-cost, which represents the impact to the environment, by 11%. This shows that the long forecast considerably improved the protection of sensitive waters, as overflows are avoided in Øst Amager and mitigated by 87% in Vest Amager.

IV. DISCUSSION

The implementation of long forecast in DORA-LF enhances the UDS management by improving the protection of sensitive areas in relation to long and/or coupled rain events. Nevertheless, the information provided by the long forecast does not improve significantly the CSO mitigation of short and intense events as cloudburst in comparison to short forecast. Indeed if the UDS is already empty there is not early preventive action available to reduce the future CSO volume.

IV.1. Limitations

The potential benefit of using a long forecast horizon in addition to radar-based nowcast with respect to CSO reduction, is depending on the UDS characteristics and the type of rain event. The larger the UDS is, the higher the potential.

Table 1: Key data of Kløvermarken catchment used in the study.

	CSO	Volume	Reduce area	Relative capacity		Maximal pumping	Minimal	
	Sensitivity	[m ³]	[ha]	[m ³ /ha]	[mm/m ²]	capacity [m ³ /s]	emptying time	
Vest A.	High	13 490	97	139.07	13.91	1.0	3.7	hours
Øst A.	High	44 400	228	194.85	19.48	0.7	17.6	hours
Kløver.	Medium	27 500	777	35.39	3.54	7.5	1.0	hours
Lynetten	Low	760	564	1.35	0.13	6.4	2	minutes

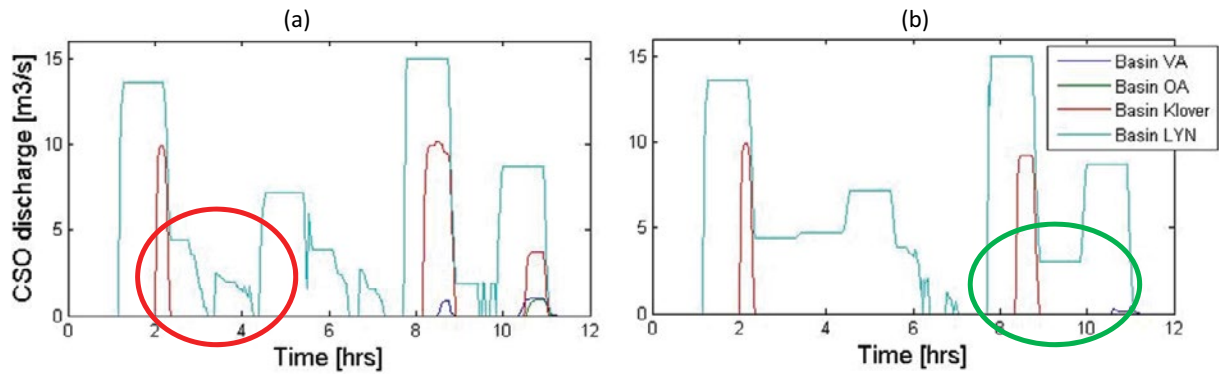


Figure 6: CSO discharge in the different basin with short horizon forecast management (a) and with long horizon forecast (b).

Table 2: Results of the short and long forecast horizon strategies.

	CSO Volume [m³]		Mitigation	
	Short horizon simulation	Long horizon simulation	[%]	Sensitivity
VA	2 930	380	-87%	High
OA	1 500	0 - 97 % filling	-100%	High
Klover	37 680	23 870	-37%	Medium
Lyn	209 360	230 860	+10%	Low
TOTAL CSO	251 470	254 920	+1.4%	
Risk-Cost	340 190	303 030	-11%	

Nevertheless the transportation time between the basins increases with the UDS scale, therefore neglecting it can be an issue for large systems.

The worse scenarios from the NWP ensemble lead to a high risk-cost and thus have a higher impact on the control strategy, which results to an overprotection of the sensitive areas. According to the UDS management objective, this tendency can be balance by weighting the scenarios.

IV.2. Future outlook

This study focuses on CSO mitigation, but long a forecast can also improve the UDS management during dry weather periods. Indeed by knowing when no overflows are expected across the UDS, the control strategy can be used to optimise the inflow to the WWTP or to reduce power cost by using the pumps during periods with low electricity costs.

Furthermore, knowing in advance if there is a risk of overflow can allow a better management of the WWTP, if the WWTP has a possibility for adjusting the operation to allow a larger flow of water through the plant during wet weather. In that case the forecast can also be used at the WWTP to switch between wet and dry mode according to the forecasted inflow (as illustrated with radar-based prediction in [Heinonen *et al.*, 2013]).

A long forecast horizon has also potential for flooding mitigation, as the forecasted CSO volume can be used for issuing warnings to the authorities. Furthermore, a control strategy can be implemented in regards to flood event. For example by using a different set of overflow costs in order to protect human properties instead of bathing areas.

V. CONCLUSION

A centralised model predictive control application (DORA-LF), using long ensemble forecast data from NWP model in order to improve the performance of urban drainage system, was presented in this study. Based on long forecasts (up to 48 hours) DORA-LF choose an appropriate control scheme (“Dry”, “No CSO” or “CSO”) according to the current status of the UDS and the forecasted runoff. Then optimal flows between the basins are calculated in order to minimize the associated cost function.

Apart for in the decision of switching between the different operational modes, the entire forecast horizon is used in the CSO mode. In the CSO mode the optimisation considers multiple and variable time steps. A water balance is done for each basin for each of those time step and for the 25 scenarios of the ensemble; thereby the CSO is estimated at all localization over the entire horizon and full ensemble. The different sensitivities of the receiving water bodies are taken into account as a cost per volume of CSO.

The rain events tested with DORA-LF suggest that the implementation of a long forecast improves the protection of sensitive areas by allowing preventive CSO events in low sensitive areas and thus mitigate the CSO threat in vulnerable areas.

The implementation of an ensemble forecast from a NWP model opens many other possibilities for the UDS management from flood events mitigation to dry weather period management. Furthermore, using an ensemble of scenarios allows to quantified and handle the uncertainty of the forecast.

VI. AKNOWLEGMENT

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