Real Time Forecasting of Flows and Loads to WWTPs for Enhanced Hydraulic and Biological Capacity during Stormwater Events

Prédiction en temps réel de débit et de charge à la STEP pour améliorer les capacités hydraulique et biologique.

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RÉSUMÉ

Le contrôle avancé des systèmes intégrés d'assainissement des eaux urbaines peut constituer un moyen intelligent d'accroître la capacité de la station de traitement des eaux usées lors d'événements pluvieux. Nous présentons des outils permettant de prévoir débits et charges d'une station d'épuration (STEP), à partir de données en ligne : mesures d'ammonium à l'entrée de l'installation, prévisions radar immédiates et mesures de débit. Ces prévisions permettent de préparer et d'améliorer le traitement de la STEP de manière à minimiser le risque de rejet d'eaux insuffisamment traitées. La capacité de l'usine de traitement des eaux usées est ainsi accrue.

ABSTRACT

Advanced control of integrated urban drainage-wastewater systems can be a smart way to increase the capacity of wastewater treatment plants during stormwater events. We demonstrate tools to forecast flows and loads from the urban drainage system to a wastewater treatment plant based on online data in terms of ammonium measurements at the inflow to the plant, radar nowcasts and flow measurements. These forecasts make it possible to prepare and improve the treatment at the plant so that the risk of discharging insufficiently treated water is minimized. Hence the capacity of the wastewater treatment plant is increased.

KEYWORDS

Integrated control, Real time, Stochastic models, Stormwater, Water Quality

1 INTRODUCTION

Integrated Urban Drainage-Wastewater System (IUDWS) are designed to protect urban areas from health risks in dry weather (DW) and from flooding risks in wet weather (WW). IUDWS should also avoid health and environmental impacts due to wastewater discharges (in DW) and combined sewer overflows (in WW), i.e. they operate in two different operational domains, with different characteristics. DW operations can easily be handled by static controls, while the stochastic nature of rainfall makes it difficult, or maybe even impossible, to design a static system that always operates optimally.

A method that has gained increased scientific and practical attention within dynamic control of urban drainage systems is Model Predictive Control (MPC). This type of control optimizes future operations with respect to a model of the controlled system. In case of rain events, the MPC finds the best operation sequence that ensures optimal performance of the IUDWS for the event in question as evaluated by an objective function.

Different authors have suggested MPC for optimization of pumps and valves in urban drainage systems to improve the capacity and reduce the risk of overflow. However, the majority of studies only focus on the drainage system while disregarding the operation of the downstream WasteWater Treatment Plant (WWTP), which is often assumed to have a fixed maximum capacity.

This paper aims at demonstrating how an integrated MPC approach can improve the overall performance of an IUDWS by combining forecasts of the status of the upstream urban drainage system with information from the WWTP. Hence we present techniques for forecasting incoming flow and ammonium load from the upstream catchment to a WWTP, and on the basis of these data, how to optimize the performance and capacity of the WWTP.

2 METHODS AND EXAMPLES

2.1 Flow and ammonium load forecasts during stormwater events

Forecasts of flows in urban drainage systems must be driven by rainfall inputs. The appropriate type of rainfall data for a given case depends on the desired forecast horizon. If the transport time of water in the sewer system provides a delay that exceeds the required forecast horizon, then it will be sufficient to use real-time observations of rainfall from e.g. rain gauges and weather radars, whereas rainfall forecasts are needed if the system delay is shorter than the required horizon. The most common types of rainfall forecasts are based on radar extrapolation models (skillful 2-3 hours ahead) and Numerical Weather Predictions (NWP, skillful up to a few days ahead). Radar extrapolation forecasts are more skillful in the very near future than NWP and usually have higher spatial-temporal resolution. However, depending on the type of weather, e.g. convective rain events, the radar-based forecast skill can deteriorate quickly with lead time. NWP is necessary for forecast horizons longer than 3 hours ahead.

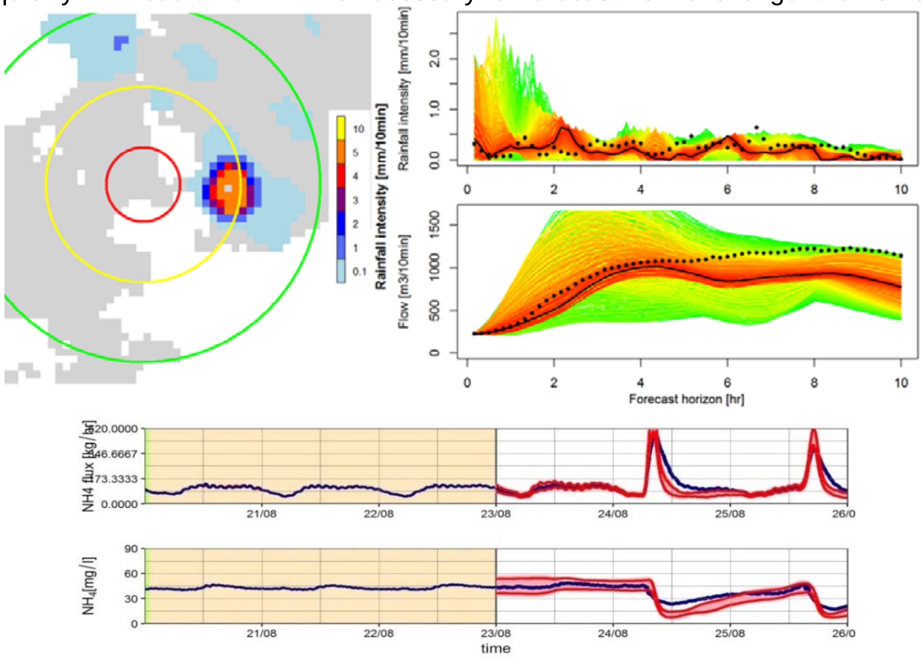

Figure 1: A single time step of a NWP-based rainfall forecast over Zealand and Southern Sweden (top, left). A time series of predicted average rainfall intensity over a sewer catchment in Copenhagen including spatial uncertainty colored by distance from the catchment (top-right-upper). A resulting ensemble flow forecast at the outlet of the sewer catchment (top-right-lower). Observed variables are indicated with black dots, while the colored lines are ensemble scenarios with red colors being rainfall (and resulting flow) predicted near the sewer catchment, while yellow and green colors are scenarios predicted to happen

further away. Example of NH4 concentration and load predictions (90% prediction bounds) based on a calibrated DW model (yellow background). Blue: measured; red: modelled (Bottom).

Urban runoff simulations are often based on detailed hydrodynamic models, but for real-time purposes we have to use conceptual or surrogate models that are computationally efficient. In combined sewer systems, the uncertainty related to flow at the WWTP inlet is dominated by the rainfall input. Uncertainty can be accounted for by conditioning stochastic terms in the runoff models on the forecasted rainfall, or by propagating an ensemble of rainfall scenarios through a model. Figure 1 shows an example of a short-range NWP forecast over Copenhagen developed by the Danish Meteorological Institute, as well as an ensemble flow forecast produced with a conceptual, bucket-type runoff model.
The existing WWTP influent generators are based on simple approaches, such as modelling of ammonia fluxes (expressed as NH4+) based on expected daily loads (listed as tabular values or approximated using Fourier series). When operating in online conditions, these models should account for stochastic variations and changes in the wastewater generation in the upstream catchment.
Figure 1 shows an example of an adaptive stochastic model for prediction of NH4+ operating at the Damhusaaen WWTP. The stochastic model utilizes available past measurements from a moving window, and it predicts the incoming NH4 in DW as well as in WW.

2.2 Hydraulic and biological capacity increase

Several operational strategies at the WWTP that use or will have the benefit of using forecasts of flow and load from the drainage system have been developed and are described below.

2.2.1 Aeration Tank Settling (ATS)

ATS is a real-time control strategy (RTC) that is activated before the increased flow arrives at the WWTP and hence the forecasted flow is used. The purpose of this is to increase the hydraulic capacity of the secondary settling tanks through a reduced solids load on the settling tanks. When activated the mode will pump sludge from the settling tanks to the aeration tanks. ATS operation will ensure that the nitrification and denitrification cycle in the process tanks will consist in a combination of permanent settling in some process tanks/sections, and alternating settling in other process tanks/sections (switch between no mixing, no aeration to nitrification/denitrification) and normal nitrification/denitrification in the remaining process tank/sections. The ATS is used for many different activated sludge plant configurations, such as the BIO-DENITRO® process (Munk-Nielsen, 2015) and the Pre-Denitrification process (Gernaey, 2004).

2.2.2 Return Activated Sludge (RAS)

Optimization with sludge blanket measurements ensures maximum utilization of the hydraulic capacity with compliant effluent WW quality and balanced with stable operation of return sludge pumping in DW (Önnerth, 2017). Önnerth, (2017) describes a case study where a RTC like this is developed and tested. The RTC has two control PID loops, one based on the sludge blanket level in the settling tanks and the other based on RAS MLSS (Return Activated Sludge Mixed Liquid Suspended Solids) in the return sludge. The RTC uses the forecast flow to start removing the sludge from the secondary settlers by increasing the return sludge flow. When the storm water flow arrives to the WWTP the return sludge flow is set to a minimum. This strategy reduces the risk of sludge escape and increases the hydraulic capacity of the plant. The RTC includes a flow distribution for equalization of the sludge blankets across secondary clarifiers and an adaptation feature that decides whether priority should be given to the hydraulic capacity in WW or to stable operation in DW. By using forecasted flow and forecasted load, time delays can be taken into account and utilizing more of the full hydraulic capacity.

2.2.3 Maximum flow optimization

The purpose of the optimization is to be able to biologically treat as much water as possible. The maximum hydraulic capacity of the WWTP provides a threshold for the maximum flow to the WWTP based on online measurements of the sludge blanket in the secondary settlers, the outlet turbidity and optional treatment performance. The threshold gradually increases during storm water operation due to the operation of the ATS and it decreases if the sludge blanket in the secondary settling tanks or the turbidity out of the WWTP becomes too high or, lastly, if treatment performance is too poor. Conversely, the threshold increases if the sludge blankets in the secondary settling tanks or the turbidity out of the WWTP are improved. Currently the control is rule based and no delays in the system are taken into account. Hence by using forecasted flow and forecasted load, it is expected that time delays can be taken into account, thereby utilizing more of the full hydraulic capacity.

2.2.4 Model predictive control (MPC) using ammonium forecast

Future high incoming nutrient loads should lead to a preparation of the biological treatment in the WWTP to secure satisfactory effluent concentrations. Such preparation can be done by intensifying treatment in the period before the load. We suggest a MPC strategy for the biological nutrient removal which predicts the effect of different aeration control scenarios. The model is similar to what is described in Stentoft et al. (2018) but with an extension to include forecasted ammonium loads as an input to the model.

The optimal control is found by minimizing an objective function which considers the cost of discharging nutrients and the electricity costs related to aeration. Discharging nutrients above a certain threshold is penalized significantly compared to the other costs, and hence the optimization always aims at satisfying this soft constraint.
We optimize the aeration in the biological treatment 24 hours ahead with and without forecasts of incoming ammonium. This is shown in Figure 2, where an increased ammonium load (which is 10 times the normal DW flow) is predicted at 20:00-21:00.

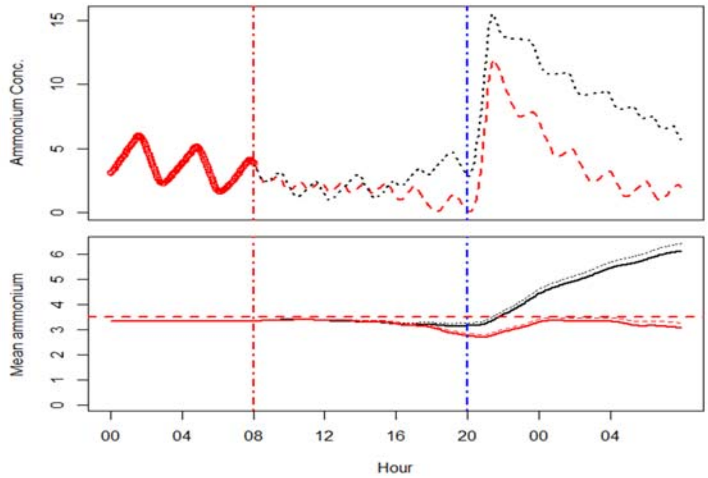

Figure 2: Control of effluent ammonium concentrations from a WWTP based on forecasts started at 08:00 (vertical red dotted line). A large incoming ammonium load is predicted at 20:00-21:00 (vertical blue dotted line), corresponding to a first-flush situation with 10 times more incoming ammonium compared to DW. The upper plot shows predicted effluent concentrations. The lower plot shows the 24-hour predicted mean of the concentrations (which are subject to regulatory constraints) with uncertainty. The dashed line is the effluent requirement of 3.5 mgN/l. Note that the black line (without weather forecast) performs worse in terms of treatment compared to the red line (with weather forecast).

3 CONCLUSION

We describe methods to forecast flow and ammonium concentrations coming to a WWTP from the urban drainage system and show examples of how these forecasts may be used to improve the performance of WWTPs during stormwater events. These methods provide reliable forecasts which perform well in describing the future flows and concentrations. The forecasts are used in different real-time control and model predictive control applications which optimize the overall performance of the integrated urban drainage-wastewater system. These applications increase the hydraulic capacity by modifying the internal sludge flows of the settler and the biological reactor. Furthermore, the biological capacity is increased by optimization of the future control of aeration given a forecasted large incoming ammonium load. These methods are useful for efficient control of WWTPs and urban drainage systems during wet-weather.

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