Pollution based real time control of wastewater systems

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Abstract Wastewater systems are traditionally built as static systems to handle a design load. The real load varies, though, and hardly ever equals the design load. This implies that wastewater systems hardly ever operate in an optimum way, especially during wet weather. Real time control (RTC) of regulators can improve the operation by better fit of the system to the actual state and load. RTC based on pollutant concentrations together with hydraulic conditions (pollution based real time control, PBRTC) is investigated in this paper to assess the potential pollutant load reduction on receiving waters at wet weather without expansion of transport or storage capacity. Both CSOs and WWTP effluents contribute to the pollutant discharges to receiving waters and both are considered. Three cases are studied to assess the potential benefit of PBRTC. Giving priority to the most polluted wastewater for treatment and storage in branched interceptor systems can reduce CSO discharge loads by more than 20%. Biological WWTPs and especially activated sludge plants are more complex and less stable than chemical precipitation plants during and after high pollutant and hydraulic load. Biological plants can hence profit more from PBRTC than chemical precipitation plants. Receiving waters that are sensitive to acute effects caused by intermittent discharges can benefit more from PBRTC than receiving waters with problems connected to long-term accumulation of pollution.

Keywords Mathematical modelling; pollution; real time control; sewer network; urban hydrology; wastewater treatment

Introduction Wastewater systems are traditionally built as static systems to handle a hydraulic design load. But the real load of a wastewater system varies and hardly ever equals the design load. This implies that the wastewater system hardly ever operates in an optimum way during wet weather. Today, some wastewater systems use real time control (RTC) systems to improve performance by controlling regulators such as pumps, weirs and gates to fit the actual hydraulic load and utilise the available capacity better and, thus, reduce CSO volumes. However in most cases, it is not the hydraulic load that is important for the receiving waters, but the pollutant load. RTC based on pollutant concentrations in addition to the hydraulic conditions is investigated in this paper. Taking pollutant concentrations into account in addition to the hydraulic conditions, the pollution based real time control (PBRTC) gives the opportunity to assign priority between wastewater of different quality and thereby further reduce pollutant load on receiving waters at wet weather without expanding transport or storage capacities.

Spatially and temporally varying pollutant concentrations within the catchments together with the varying hydraulic conditions give a basis for PBRTC. The concentration variations are a product of the spatially and temporally varying load on the sewer network from households, industry, surface runoff and infiltration/inflow (I/I) and varying transport times from the loading points to the regulators. Both varying snowmelt and rain intensities causing surface runoff lead to varying dilution rates and thus pollutant concentration
differences in the sewer network. Hence, a dense network of precipitation gauges is important for assessing PBRTC benefits through a modelling study. Unfortunately, spatially distributed precipitation measurements with high temporal resolution are rarely available.

When computing pollutant discharges into receiving waters from combined sewer systems, contributions from both CSO discharges and wastewater treatment plant (WWTP) effluent have to be considered. Control actions in the sewer network can influence the WWTP effluent and vice versa. Hence, an integrated modelling tool that can simulate sewer network and wastewater treatment processes simultaneously is necessary for such an investigation contrary to traditional sequential simulation of sewer network and WWTP. A simulation tool on a MATLAB®/SIMULINK® platform was chosen for this project. The tool consists of three modules with PLASKI for wastewater production, SIMBA® sewer for wastewater transport and SIMBA® for wastewater treatment processes (Alex et al., 1999; ifak 1997 and 1998; Risholt, 2000). The simulation system provides flexibility to add water quality models and models for non-standard techniques such as integrated control based on pollutant concentrations and pollutant transport.

**Methods**

**Case studies**

Three cases are studied to assess the potential benefit of PBRTC. Two cases are from Norway and one from Germany, see Figure 1. They are all combined sewer systems (CSSs) with interceptors in two or three branches. Both Norwegian study areas are located at river mouths by fjords with chemical precipitation WWTPs discharging into the fjords and combined sewer overflows (CSOs) discharging into the rivers and the fjords. The Ladehammeren catchment in Trondheim, Norway has a coastal climate with major CSO volumes due to snowmelt in winter and spring (Thorolfsson and Brandt, 1996). Fredrikstad in southern Norway has less precipitation during winter with some 50% snow and major volumes of rain in autumn and heavy rain storms during summer (Interconsult AS, 1992). The German case of Odenthal has an activated sludge plant with a river as receiving water. The Norwegian cases have very little or no storage volumes while the German case has some storage of the order of 25 m³/ha. Figure 1 shows the location of the study areas while Table 1 sums up some characteristics of the cases.

Total phosphorus concentration (tot-P) is the key pollutant in the discharge permit in Fredrikstad, while the WWTP at Ladehammeren has to remove 85% of suspended solids (SS). However, as the local receiving waters are fairly similar in both Fredrikstad and Trondheim with a river and a fjord, tot-P is chosen as key pollutant for both the Norwegian cases. Chemical oxygen demand (COD) is chosen as key pollutant for the Odenthal case to express the discharge of organic matter into the river. Ammonia is also a very important...
pollutant for rivers and it is included in the model for Odenthal. But, for simplicity at this first stage, it is not included in the PBRTC strategies.

Modelling

Wastewater production. Wastewater production is simulated with PLASKI. This is a water balance model for continuous or event-based simulation of rainfall-runoff from surfaces, snow accumulation and snowmelt, evapotranspiration, surface infiltration into pervious ground and infiltration/inflow (I/I) to the sewers (Risholt, 2000; Alex et al., 1999; Risholt et al., 1999). PLASKI routes runoff through linear reservoir models to model the runoff delay. Domestic and industrial discharges are modelled with weekly or diurnal variation curves. Subcatchments creating inflows to the interceptors are modelled with separate hydrological models. The complexities of the hydrological models are dependent on the available information on the subcatchments. For example, the impervious areas are divided into street and roof areas in the Fredrikstad model, while for Odenthal the only total impervious area, i.e. the sum of street and roof areas, were available. Runoff from different surface types and I/I are given constant, but different, pollutant concentrations. Hence, the resulting concentrations of the inflow to the interceptors are varying during runoff events as the ratios of the contributing sources are varying and as the domestic and industrial discharges are varying.

Wastewater transport. The hydraulic transport is modelled with SIMBA® sewer. SIMBA® sewer divides the sewers into a liquid phase upper layer over a sediment lower layer. Sewage flow is modelled with the diffusive wave approximation of the St.Venant equations. The approach underestimates the dynamic storage in the sewer system during runoff events with the highest error for the most variable events (Campisano et al., 2000). Models for sedimentation and erosion of solid fractions of pollutants are included. These are based on the flow velocity as key input to Monod on and off terms. In addition an equilibrium model for pH and alkalinity is included for the Fredrikstad case. Pump and CSO structures are included for the interceptors. Fredrikstad has some 150 pumping stations with emergency overflows and more than 50 CSOs which all are potential discharge points. To simplify the model, some of these constructions are lumped in the subcatchment models. The discharge from such a subcatchment model to the downstream interceptor is limited to the maximum discharge of the constructions, and excess water discharge directly form the subcatchment to the receiving waters as CSO.

Wastewater treatment. The Odenthal WWTP is modelled with the Activated Sludge Model No. 1 (Henze et al., 1987) included in SIMBA. The chemical precipitation WWTPs in Fredrikstad and Ladehammeren are modelled on the basis of chemical equilibrium for the precipitation, equilibrium between floc growth and break-up in the flocculation stage and a secondary clarification model based on discrete settling theory (Risholt, 2000). The precipitation and flocculation models are running in the SIMBA environment as user-defined models.
Control strategies. A control strategy is the time sequence of all regulator set points in a RTC system (Schilling, 1992). Advanced methods like mathematical optimisation and fuzzy logic exist to implement control strategies. For the three cases, it is however chosen to model the control strategies as heuristic decision trees based on measurements of flows, levels and concentrations.

Calibration
The models are calibrated by comparing simulation results with measured flows and water quality measurements at pumping stations, CSOs, and inflow and outflow of the WWTPs. Unfortunately, no wet weather water quality data are available for the Odenthal case and only few water quality measurements at wet weather are available for the Fredrikstad and the Ladehammeren cases.

Wastewater flows fit fairly well for all cases for dry-weather conditions and summer wet weather. Discharge caused by snowmelt or combined rain and snowmelt during winter and spring are more difficult to simulate correctly. This is due to the increased complexity of the runoff process under such conditions. Comparisons of simulated water quality values to corresponding values from analyses of wastewater samples show the same trend as for the flow simulations. The wastewater quality simulation during summer wet weather is more inaccurate than the flow simulation.

Simulated periods
Table 2 shows the simulated periods for the three cases. The first period for the Fredrikstad has input data from two precipitation gauges with 27 minutes sampling time, while data from only one of the gauges with one-hour sampling time was available for the second period.

Results and discussion
Introduction
The three wastewater systems have different characteristics with respect to storage volumes, transport capacities, WWTP and receiving waters. Hydrological conditions are also different. These aspects of the cases are the basis for an attempt to generalise the results. All case studies suffer from lack of calibration data, especially for wet weather conditions. Thus, the results expressed in absolute numbers are not very reliable for the cases themselves. But as the models are realistic in principle, relative comparisons of the simulations are used as a basis for generalisation even though they do not give exact answers.

A real wastewater system with PBRTC does not act as ideally as a simulation model. Uncertainty in measurements and operational limitations of regulators will reduce the potential benefit of PBRTC as compared to derivations from computer simulations. Rohlfing (1993) investigates such aspects for volume based RTC with mathematical optimisation including model predictive control and forecasting of inflows. Rohlfing finds for two cases that the suboptimal operational behaviour can reduce CSO reduction potential up to 30% and 50% from the optimum value found by computer simulations. The uncertainty of forecasts is not relevant for the results of the cases in this study. But for PBRTC, the uncertainty

<table>
<thead>
<tr>
<th>Case</th>
<th>Period I</th>
<th>Period II</th>
<th>Period III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odenthal</td>
<td>3 Sept.–8 Dec. 1997</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
of measurements or calculations of pollutant concentrations will lead to a reduction of the simulated optimum benefit compared to the reduction from the optimum benefit for classical RTC under otherwise equal conditions. This implies that the “real” benefit of PBRTC might be up to 50% lower than the simulation shows.

On the other hand, the models for the case studies had to be based on a number of simplifying assumptions such as diurnal sanitary sewage flows and concentrations curves and spatially homogeneous rainfall and temperature. As the real processes show more variation than the model assumptions the benefit of PBRTC is thus underestimated. Without comprehensive measurements in implemented cases it is very difficult to estimate whether the real benefit of PBRTC is larger or smaller than the estimated benefit.

**Input data for modelling**

The Fredrikstad case is simulated with input from both one and two precipitation gauges for the 70 days calibration period. PBRTC simulation with precipitation input from two gauges gives a load reduction in the range of two times the load reduction with only one gauge. This result shows the importance of representative input data with thorough and detailed measurements of spatial and temporal variability of precipitation. The maximum temporal resolution used in the Fredrikstad case was one value per 27 minutes. This is not good enough to find the real potential benefit of PBRTC. The measurement time-step for CSO modelling must not be longer than the time of concentration for the catchments upstream of the CSOs. In most cases this would require a time-step of less than 10 minutes. The Ladehammeren case with two minutes time-step has a good temporal resolution while the 15 minutes time-step of the Odenthal case is slightly too long. When old monitoring systems were built, data storage was expensive, and this is one reason for the low temporal resolution of precipitation measurements. Today, data storage is much cheaper and it should be possible to store high-resolution data for longer periods of time.

Lei (1996) investigates influence of spatial resolution of rainfall measurements for rainfall-runoff modelling by making simulations of runoff volumes for varying numbers of precipitation gauges for three urban catchments with key numbers as shown in Table 3.

Lei finds that two or three precipitation gauges in a catchment should be sufficient to derive reliable runoff statistics for a typical size urban catchment. But as all simulations with input from less than maximum number of precipitation gauges deviate from the best resolution input, Lei finds that it is practically impossible to guarantee precise recordings of spatial measurements by simply increasing the number of precipitation gauges. For PBRTC it is not runoff statistics for several events at the catchment outflow that is important, but the spatial distribution of runoff intensity within the catchment creating flows of different pollutant concentrations during each single event. This implies that simulations for PBRTC evaluation need higher spatial resolution for precipitation measurements than for deriving catchment runoff statistics. In Fredrikstad there are four precipitation gauges connected to the monitoring system. But poor quality of the data limits the use of all of them. If all the four gauges in Fredrikstad were measuring and recording properly, the gauge density would be reasonable for controlling the downstream part of the wastewater system.

**Table 3** Catchment areas, number of events and precipitation gauge densities in a study by Lei (1996)

<table>
<thead>
<tr>
<th>Case</th>
<th>Total area [ha]</th>
<th>Number of precipitation gauges</th>
<th>Area/gauge [ha]</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essen</td>
<td>3,200</td>
<td>17</td>
<td>188</td>
<td>85</td>
</tr>
<tr>
<td>Schwamendingen</td>
<td>40</td>
<td>7</td>
<td>6</td>
<td>55</td>
</tr>
<tr>
<td>Fehraltorf</td>
<td>2,000</td>
<td>7</td>
<td>286</td>
<td>25</td>
</tr>
</tbody>
</table>
The transport capacities in the downstream end of the interceptors in Ladehammeren are so limited that the WWTP can handle total inflow. Thus, when using data from only one precipitation gauge as input, the lack of information on the spatial distribution of precipitation is of only minor importance since PBRTC can not give any significant load reduction for the wastewater system considered. Spatial homogenous rain intensity is also used for the Odenthal case. The catchment with its total area of 4.3 km² is located within a circle with 7 km diameter, and it is clear that simulations with spatial variation of rainfall would lead to more varying pollutant concentrations between the three branches than shown in the results. Consequently PBRTC will perform better in reality than shown by the simulations for the Odenthal case.

**Runoff event characteristics**

As described above, spatial runoff variation increases the potential benefit of PBRTC. This is illustrated by the difference in results for a period simulated with precipitation input from both one and from two gauges in the Fredrikstad case. The one gauge alternative uses input from a western gauge with one-hour time-step while the two gauges alternative uses input from the same western gauge and an eastern one, both with 26.7 minutes time-step. The simulated P load reduction from the controlled structures is 29% with input from two gauges and 13% with input from only one gauge. Some of the difference is due to the reduced temporal resolution of the latter. But the simulated runoff from subcatchments using input from the eastern gauge only for both alternatives, have only small runoff differences compared to subcatchments changing input from the western to the eastern gauge. The spatial resolution of precipitation can thus be more important for PBRTC than the temporal resolution as long as the temporal resolution is not all too low.

For the Odenthal case, making a priority of most polluted wastewater for treatment has highest efficiency for low rain intensities and small event depths, see Figure 2. The efficiency is lower for rain events of both high intensity and depth but does not approach zero for the major event as concentration differences for the wastewater flows remain for making a priority for treatment when the storage volumes are filled up. During the simulation period in Odenthal there was one major event (38.7 mm rain in 17 hours). For this event the COD load reduction was 18% which equals 2 tons of COD.

In the Ladehammeren case a simulation period with less runoff and CSO discharge volume has a higher nominal load reduction by PBRTC than another event with almost twice the CSO discharge volume. Both simulation periods have spatially homogenous rainfall as input. The minor volume period has two CSO events occurring in the evening when the domestic wastewater production is high and the DWF is highly polluted. The one CSO event during the large volume period occurs in the early morning when domestic wastewater production is low and the inflows to the CSOs are highly diluted. This implies that PBRTC

![Figure 2](https://iwaponline.com/wst/article-pdf/45/3/219/425125/219.pdf)
works better for runoff events when domestic wastewater production is high. Pollutant concentrations are higher and the nominal differences between different flows are higher than for an identical runoff event when domestic wastewater production is low. This effect applies to runoff caused by snowmelt that has a diurnal pattern with high rates during daytime when air temperature and short wave radiation are at their maxima.

**Sewer system**

To reduce CSO discharge loads by PBRTC, there must be some flexibility in the transport system or storage volumes for making a priority for most polluted wastewater. Different pollutant concentrations between branches give a basis for making priority. Figure 3 shows simulation results for the three branches in Odenthal. It is clear that no general statement can be made on which branch is most polluted.

The Ladehammeren wastewater system does not have excess transport capacity towards the WWTP or storage volumes and thus has nothing to gain from PBRTC in the downstream part of the wastewater system. One branch of the Ladehammeren interceptor system along the Nidelva river has two in-line CSOs and one inlet with an upstream CSO. It is possible to reconstruct the CSOs to make a priority for the most polluted wastewater between the subcatchment inflow and the wastewater already present in the interceptor. This local PBRTC of the CSOs gives a pollutant load reduction between 9 and 23% for the three simulated periods. It might be possible to improve this result by introducing a global PBRTC strategy to also make priorities between the CSO structures. This would especially improve the performance for events with spatially varying rainfall. As the Ladehammeren case has only one precipitation gauge, this control alternative is not investigated any further.

The Fredrikstad case shows that local success of PBRTC is useless as long as there are other uncontrolled discharges of the same magnitude. As long as the efficiency of PBRTC is of the magnitude of 20% load reduction, it is necessary that all the wastewater flows are controlled to keep a level of significance. Otherwise, measures like removing small CSO structures at upstream small creeks can be more efficient from an overall environmental point of view.

The Odenthal case with some storage volume shows a higher load reduction for PBRTC than the Fredrikstad case with precipitation input from two gauges in spite of using homogeneous rain input in the Odenthal case. This is due to the temporal variation of the wastewater quality and the possibility to retain the most polluted wastewater at the beginning of runoff events.

![Figure 3](https://iwaponline.com/wst/article-pdf/45/3/219/425125/219.pdf)

**Figure 3** COD concentration in the 3 inflow in Odenthal during a rain event
**Wastewater treatment plant**

Increased inflow at the beginning of wet weather leads to dry weather wastewater being pushed out of the grit chamber. This can lead to bypass of highly polluted wastewater if secondary treatment capacity is lower than the primary treatment capacity. Inflow control at the beginning of runoff events for flows exceeding the secondary treatment capacity to avoid bypass of dry-weather wastewater from the grit chamber is tested in the Fredrikstad case. The control strategy to create CSO at the WWTP inflow if it is less polluted than the outflow of the primary treatment stage gives no significant reduction in pollutant discharge load. At the beginning of the runoff events, the WWTP inflow consists of a wave of dry-weather wastewater being pushed towards the WWTP by the incoming surface runoff, and the WWTP inflow is thus not significantly less polluted than the wastewater present in the primary treatment stage.

The simulation results of the Odenthal case show that it is possible to reduce pollutant discharge loads by allowing higher inflow to the WWTP at the beginning of runoff events and then reduce the inflow if the rising sludge blanket leads to high solids concentration in the WWTP effluent. The load reduction is mainly caused by reduced CSO volume due to higher WWTP inflow. Simultaneously, the WWTP effluent load increases. Such a strategy has its best effect for small and medium sized rain events. For major events, the CSO reduction is insignificant and the disturbance of the secondary settler through the high inflow at the beginning of the event can lead to an overall negative effect both through higher flow and poorer quality of the effluent. Thus, the increase of the inflow rate has to be limited to avoid severe pollutant discharge from the WWTP effluent. Also the initial state of the secondary settler is important and, thereby, the length of the period since previous runoff events. For large events there might be no load reduction, but rather load increase. Inflow control did not improve the performance of the Odenthal wastewater system for the highest rain depth event in Figure 2, and the total COD load was increased for the following event. But for other events, inflow control based on sludge blanket level of the secondary clarifier shows improvements by up to 39% COD load reduction. This result however, has to be regarded with caution due to the use of a one-dimensional layer model of the secondary settler. Such a model cannot take into account the unfavourable secondary currents that will reduce the effluent quality at high hydraulic loads. Increased inflow did not create problems for the nitrification in the activated sludge tank.

Activated sludge plants with return sludge pumping and recycling are more complex than chemical precipitation plants. They are also more sensitive to high pollutant and hydraulic loads. Chemical precipitation plants do not suffer after a sludge loss like an activated sludge plant to re-establish a stable treatment effect after the event. Thus, activated sludge plants offer more options (and also have higher need) for control than chemical precipitation plants.

Models are not much used in connection with chemical precipitation plants, while several models exist for activated sludge plants. IAWPRC established a task group of international experts to promote the development and facilitate the application of practical models to the design and operation of biological wastewater treatment systems (Henze et al., 1987). No such effort has been done for chemical precipitation plants due to both their stable operation and the less frequent use of such plants for wastewater treatment. The lack of adequate models for chemical precipitation plants also disfavours the development of control systems for such plants.

**Receiving waters**

The WWTP effluent in Fredrikstad creates an accumulated P load that is much higher than the accumulated load from the CSOs in the sewer system. This reduces the PBRTC
efficiency on P discharge from the CSOs into the receiving river mouth to practically nothing with respect to the long-term P load. For the Odenthal case the main receiving water is a river that is more sensitive to acute effects of oxygen depletion caused by high loads of NH₄-N and COD. Here, the single event load is more important and PBRTC can give a significant reduction for each event. PBRTC is thus more efficient for wastewater systems where discharges of pollutants can lead to acute effects in receiving waters during runoff events. PBRTC can however be an efficient measure for accumulative problems if the intermittent CSO discharges are a major source of load on the receiving waters of the pollutant considered. For the Odenthal case the CSO discharges are a major source and the overall load reduction for the 88 days simulation period was 32% for COD. NH₄-N was not included in the control strategy, but as there is high correlation between concentrations of COD and NH₄-N, the results show 22% reduction of NH₄-N discharge to the river.

Conclusions
The analyses show that PBRTC is more beneficial for runoff events caused by relatively low rain depths and pronounced first-flush effects creating large pollutant concentration variations. Giving priority for the most polluted wastewater for treatment and storage in branched interceptor systems can reduce CSO discharge loads by more than 20%. The relative benefit is lower for events with high intensity and depth. However, the pollutant discharges from major events can still be reduced, as concentration differences between the flows remain to make a priority for treatment when all storage is filled. Giving priority for most polluted wastewater by local control at sequential CSOs in one interceptor can reduce pollutant loads on receiving waters by an order of 10% or more, even if no storage is available.

Biological WWTPs and especially activated sludge plants are more complex than chemical precipitation plants that are more stable, both, during and after high pollutant and hydraulic load. Thus, wastewater systems with biological WWTPs can benefit more from PBRTC than systems with chemical precipitation plants. PBRTC can reduce pollutant loads on receiving waters during intermittent wet weather events. Receiving waters where acute effects caused by the intermittent wet-weather discharges from combined sewer systems are predominant can benefit more from PBRTC than receiving waters with problems connected to long-term accumulation of pollutants. Thus, PBRTC as a measure to reduce wet-weather pollutant discharges is strongly dependent on wastewater system characteristics and actual pollutant problem.

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