Integrated control of sewer and WWTP based on the assessment of treatment capacity

Gestion intégrée du réseau et de la station d'épuration basée sur l'évaluation de la capacité d'épuration

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RESUME

Une condition préalable à une gestion intégrée du réseau d'assainissement et de la station d'épuration est une commande du débit à l'entrée de la station d'épuration contrôlé par sa capacité. Cela nécessite des informations fiables sur l'état actuel de la station d'épuration et sa réaction aux varitions hydrauliques, des COD et des substances nutritives. Actuellement, la plupart des stratégies de commande proposées sont fondées sur des études de modèles hypothétiques. Dans cette communication, la réaction de trois grandes stations d'épuration aux charges élevés par temps de pluie est analysée, fondée sur les valeurs mesurées en ligne sur une période des plusieurs années. Dans tous les cas, les facteurs limitants une augmentation de la charge ont été les procédés de la décantation secondaires et la capacité de la nitrification. Dans une étude de cas, des stratégies de contrôle prédictif ont été développées d'après ces procédés qui sont soutenus par un contrôle d'effluents. Des tests avec un modèle intégré du réseau et de la station d'épuration montrent que l'efficacité d'une commande du débit sur l'émission varie de manière significative avec l'intensité de la pluie.

ABSTRACT

A prerequisite for an integrated control of sewer and wastewater treatment plant (WWTP) is a capacity driven inflow control to WWTP. This requires reliable information about the current status of WWTP operation and its behaviour on varying hydraulic, COD and nutrient loads. So far most of the proposed control strategies are based on hypothetical modelling studies. In this paper the behaviour of three large WWTPs on increased storm water loads is analysed based on online measurements of several years. In all cases the main limiting factors for an increase of load were the sedimentation processes in the secondary clarifier and the nitrification capacity. In one case study predictive control strategies have been developed observing these processes which are backboned by effluent control. Test using an integrated model of sewer and WWTP demonstrate that efficiency of inflow control on emission load varies significantly with rain intensity.

KEYWORDS

integrated control, stormwater, treatment capacity, urban drainage systems , waste water treatment plant.

1 BACKGROUND AND OBJECTIVE

The potential to reduce total emission to the receiving water by an integrated operation of sewer network and wastewater treatment plant (WWTP) has been proclaimed from the early 90's (e.g. Lijklema et al., 1993). Approaches have been developed to optimise integrated systems operation systematically by several authors (Schütze et al., 1999, Rauch et al., 2002, Seggelke and Rosenwinkel, 2002, Erbe et al., 2002, Meirlaen et al., 2002). Decisive interface for an integrated control of sewer and WWTP is a flexible maximum inflow to the WWTP depending on its actual treatment capacity and the concentrations in the incoming wastewater. Especially sedimentation in the secondary clarifier, nitrification and enhanced biological phosphorous removal (EBPR) have been identified as limiting processes for an increase of load to the WWTP (Harremoës et al., 1993; Krebs et al., 1999, Niemann & Orth, 2001, Rutsch et al., 2005). Since P-removal can be insured easily by chemical precipitation, potential overloading of EBPR can be handled in most cases.

Almost all control strategies proposed so so far are based on modelling exercises (e.g. Meirlaen et al., 2002) supported in some cases by pilot scale experiments (Seggelke and Rosenwinkel, 2002). First results of an integrated real time control strategy including a full scale SBR are presented in a case study including the operation of an SBR-WWTP (Wiese et al., 2005).

The rare full-scale application of integrated real time control (RTC) is in contradiction to the numerous papers showing its theoretic potential and to the good instrumentation of modern WWTP with various online probes necessary for RTC purposes. The reason for this is presumably the complexity of the proposed strategies. Therefore, while e.g. the integrative concept of Seggelke et al. (2005) was based on sophisticated predictive modelling, the objective of the investigation presented here was to develop a methodology based on simple-to-collect on-line measurements for implementation of inflow control in real world WWTPs. Based on available data records the project includes the following steps:

- identification of appropriate and reliable parameters as a basis for the adaptation of the strongly variable combined water flow to the actual treatment capacity
- development of a control strategy for the tolerable WWTP influent aiming at a reduction of the total emission based on these identified parameters
- model-based test of the concept
- implementation in full scale.

Three catchments in Germany (Bamberg, Bottrop, Chemnitz) including WWTP (size between 240,000 – 1.34 mio p.e.) were selected for the investigation. All catchments are mainly drained by combined sewer systems. Selection criteria were the potential and feasibility of integrated RTC (catchment's characteristics, available control structures), the instrumentation and the data availability of the WWTP.

Chemnitz was selected for full-scale application. For this case study the paper describes the identification of control parameters and the development of control strategies. Further, the strategy has been tested using an integrated model for one of the investigated catchments including WWTP. Full scale application is in preparation.

2 SYSTEMS DESCRIPTION

About 240.000 p.e. are connected to the sewer system of Chemnitz. Nearly 2000 ha of impervious surface are drained by the combined system with a length of 950 km. Some smaller creeks are still discharging into the system. Another 650 km are separate sewers, mainly in the outer suburbs. Currently 104 CSO structures and 18 combined water storage tanks are installed, discharging in different receiving waters. In the coming years, specific storage volume of 6.6 m³/ha shall be increased by nearly 15 m³/ha to reduce the annual COD discharge load to 250 kg/(ha•a), as requested by authority. The last storage basin with a volume of 5.800 m³ is situated directly in front of the WWTP (Figure 1). Presently, maximum inflow is limited to 9,450 m³/h and controlled by two throttle sluices. The WWTP consist of primary clarifier, activated sludge system and secondary clarifier, carrying out carbon removal, nitrification, denitrification and biological phosphorous removal. Chemical precipitation aids are dosed on demand in front of the secondary clarifiers.

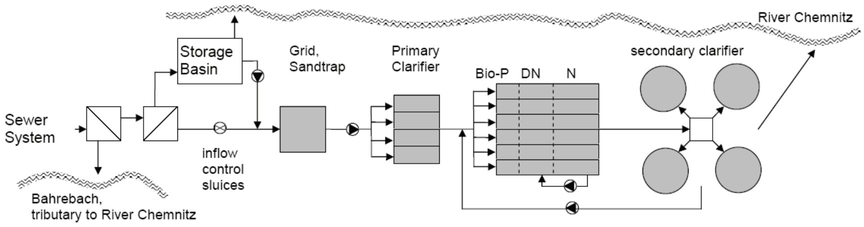

Figure 1 : Scheme of WWTP Chemnitz-Heinersdorf

3 DEVELOPMENT OF CONTROL STRATEGIES

3.1 Reaction of the WWTPs due to storm water events

Online and lab-measured operational data of at least one year have been analysed. In a first fairly simple screening procedure we identified parameters sensitive to increased hydraulic loads.

To study the reaction of the WWTP to increased flow, time series of inflow were filtered automatically for exceeding dry-weather flow (Q_{DWF}). The results were double checked for rain events in that time. Inflow was grouped as x times foul water flow plus extraneous water ($x \cdot Q_f + Q_e$). Extraneous water ratio was determined to 55%.

WWTP Chemnitz was loaded in 2004 more than 40 times with $5 \cdot Q_f + Q_e$ or higher (with respect to current DWF). Parts of the data screening for WWTP Chemnitz with box-whisker-plots, i.e. the classification of effluent concentrations and other parameters in classes $x \cdot Q_f + Q_e$ are shown in Figure 2. Visual interpretations are:

1. The ammonia concentrations in the effluent are very low compared to other WWTPs. However, while up to x = 7 the effluent NH_4 concentrations are stable they strongly increase at very large hydraulic loadings x > 7.
2. Nitrate concentrations do not vary significantly with flow rate and are in a range that the effluent standard of 16.5 mg/L total N is always kept.
3. There is a strong correlation between sludge blanket and flow rate. This parameter is proposed in some papers for influent control (e.g. Meierlaen et al. 2002).
4. The capacity of the secondary clarifier is best expressed with turbidity. There is a significant correlation between turbidity and flow rate with a lower spread between minimum and maximum values compared to other WWTPs. Correlations of COD and P-total effluent values with flow rate were not significant. Single events with increased concentrations could be due to loss of suspended solids.

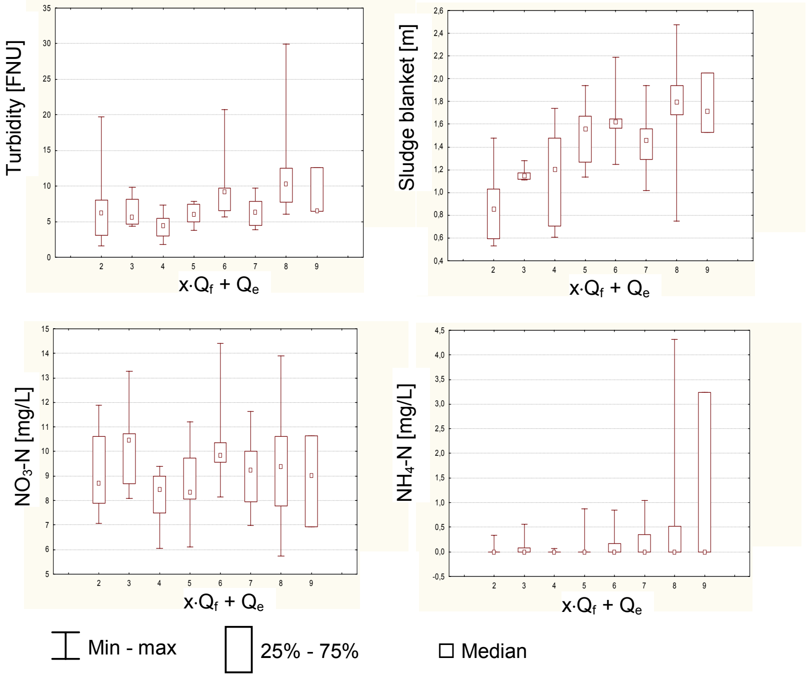

Figure 2 : Screening, maximum values over 15 minutes in the effluent

Further, investigations of single events showed that NH_4 peaks in the effluent are more distinct and higher than NO_3 peaks in both relative and absolute terms. Denitrification rates dropped in some cases drastically but this was compensated by dilution effects. Although nitrate effluent loads increased, this is tolerable from both legal and environmental point of view.

It can be thus concluded, that nitrification and sedimentation are the limiting processes to identify the dynamic WWTP capacity and hence most relevant for RTC purposes as indicated by several authors before.

Based on this analysis we decided to develop a two-step control strategy: (1) predictive control of the most sensitive processes sedimentation in the secondary clarifier and nitrification which is backboned by (2) a reactive control on effluent values of COD, Ammonia, total N (Ammonia and Nitrate) and Phosphorous.

3.2 Control of sedimentation processes

Sedimentation processes are rather difficult to quantify due to numerous process-related and external factors, e.g. sludge and flow characteristics, wind influence and design. For real-time control purposes on-line simulation on the basis of 2D- and 3D-models consume to much simulation time, while simple multilayer models suffer from a lack of accuracy, especially in simulating suspended solids concentration in the supernatant. Instead, we used statistical approaches to identify relationships between independent process parameters and clarifier performance. The statistical models were identified by (1) uni- and bivariate statistics, (2) visual evaluations of hydrographs and scatter plots and (3) multivariate statistics, esp. multiple regression (Fahrmeir et al., 1996). This procedure only serves as a basis for control rather than for simulation as such. Objective was the detection of conditions leading certainly or probably to an overloading of the clarifier. Two basic approaches for building data sets were used: a) values of time series (resolution between 15 min and 2 hours) considered as temporarily independent, single points and b) characteristic values (mean, maximum) of single events.

Due to the multitude of available parameters a factor analysis was applied in order to classify independent parameters into groups (factors) which are a) statistically independent and b) relevant to describe the process. For sedimentation the identified factors were – sorted according to their variance: hydraulic load, sludge properties, change of hydraulic load, and sludge blanket height. To avoid unintentional weighting due to correlation effects, only one parameter per group should be used for further analyses.

In a first step correlations between the independent and dependent parameters were identified by means of time series values. This analysis did not lead to valuable results. Although the correlations are often significant on a 5 % level, they are too weak for deriving appropriate rules.

Scatter plots of independent values vs. turbidity were used to identify limits for critical conditions regarding each independent parameter, separately. Exceeding these limits leads necessarily to effluent deterioration, but even in the non-critical range single events with increased turbidity occur. Thus, the coincidence of several parameters must be taken into account.

Coincidental effects were investigated with regression analysis applied on single event values. The resulting regression functions can not be used directly since not all parameters are *a priori* known (e.g. event duration). Though, it is valuable to identify critical parameter combinations.

Finally, a set of fuzzy rules could be derived limiting the maximum inflow and its change over time, sludge blanket height, sludge volume load and hydraulic load.

3.3 Control of Nitrification

Free nitrification capacity was calculated based on a simplified dynamic model including autotrophic and heterotrophic growth for completely stirred reactors.

$$V\frac{\partial c}{\partial t} = Q \cdot c_{inf} - Q \cdot c + r \cdot V \qquad 1$$

Assuming that the influent (c_{inf}) and effluent concentration (c) can be measured the only unknown variable is the reaction rate r. Ammonia removal rate r is composed of nitrogen incorporation by herotrophic growth (r_{NXH}) and nitrification (r_{NXA}). Nitrogen incorporation by heterotrophic growth is calculated based on measured COD removal. Potential nitrification rate of the autotrophic nitrifiers ($r_{N,pot}$) was estimated using a temperature dependent Monod kinetic limited by tolerable ammonia concentration at the effluent. Active autotrophic biomass was stepwise calculated including growth (via measured ammonia removal), decay and removal via the surplus sludge flow. To a certain extent the plant can be overloaded using the storage capacity of the basin in the left term of equation 1. This can be defined by a tolerable ammonia effluent concentration $NH_4\text{-}N_{eff,\,tol}$) and a time interval ($\Delta t$) in which this free "storage capacity" shall be filled. For discrete time steps (i) this yields in equation 2.

$$Q_{inf} = \frac{r^{i}_{N,pot} + \left(COD^{i}_{inf} - COD^{i}_{eff}\right) \cdot i_N \cdot y_H + \dfrac{V_N \cdot \left(NH_4 - N_{eff,\,tol} - NH_4 - N^{i-1}_{eff}\right)}{\Delta t}}{\left(TKN^{i}_{inf} - NH_4 - N^{i-1}_{eff}\right)} \qquad 2$$

The model and control strategy has been tested using long-term data series. The model is fairly stable since it is fed exclusively by measured data.

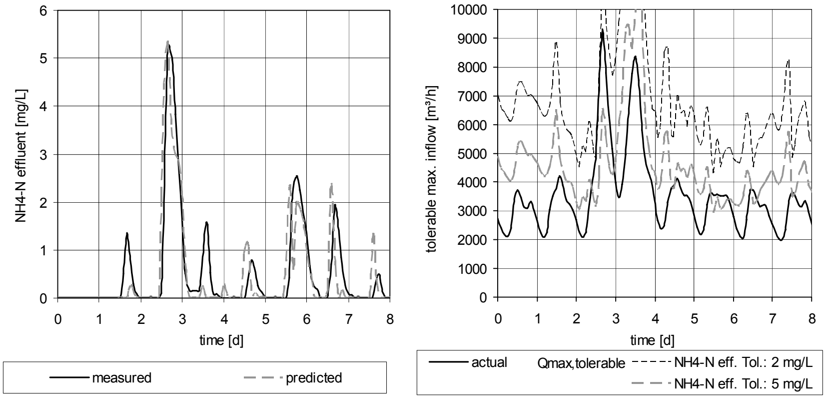

Figure 3: Control strategy for nitrification tested for measured data of WWTP CHEMNITZ
left: accuracy test, prediction of NH_4-N effluent concentration
right: application for inflow control with tolerable effluent concentration of 2 mg/L and 5 mg/L

Figure 3 shows exemplarily a time period of 8 days. The right picture shows the important impact of the chosen tolerable effluent concentration. Here, 2mg/l and 5 mg/L were allowed with a “filling” time Δt of 2 hours. This choice has to be done with prudence to avoid exceedance of effluent standards. Additional information on expected ammonia loads in the next hours (e.g. from sewer models) is useful to further refine the approach.

3.4 Effluent based control

Additionally, a set of fuzzy rules was developed controlling inflow based on COD, Ammonia, total N in the effluent and activated sludge concentration at the biological stage and in the return sludge flow. These rules shall only be active if the predictive strategies fail to control the limiting processes properly. For that reason, the rules were iteratively designed and tested.

Maximum inflow was for technical reasons limited to 10,800 m³/h, which is an increase of about 15% compared to the current value.

4 MODEL BASED TEST OF THE CONCEPT

The developed strategy was tested using an integrated model of sewer and WWTP. Sewer system was modelled with the hydrodynamic pollutant transport model “Hystem-Extran Güte” (Fuchs et al., 1999). Characteristic loads for the modelled pollutants COD, TKN and total Phosphorous were derived reversely from available influent data. Additional rain gauges were installed to enhance calibration accuracy. Processes in the WWTP were modelled in SIMBA (Alex, 2004) using a simple sedimentation model for the primary clarifier (Otterpohl, 1995) and ASM1 for the activated sludge tank, supplemented by chemical Phosphorous removal. The secondary clarifier was modelled using a multi-layer model (Takács et al., 1987), mainly to calculate sludge blanket height and thickening process. The models of sewer and WWTP were first calibrated separately and then validated as integrated model. Data exchange between both models and fuzzy based flow control was established using “itwh-control”(Fuchs et al., 1997). Rain events with different characteristics were used to identify potential and limitations of an integrated RTC in that concrete case.

In Figure 4 the results of two distinctly different events are illustrated for emission of ammonia from the whole catchment.

	Event 1	**Event 2**
characteristics	Short, intense, rare	Long, smooth, frequent
duration	9h 35 min	1d 1h
rain height	36 mm	13.7 mm
frequency	0.7 a^{-1}	32.7 a^{-1}

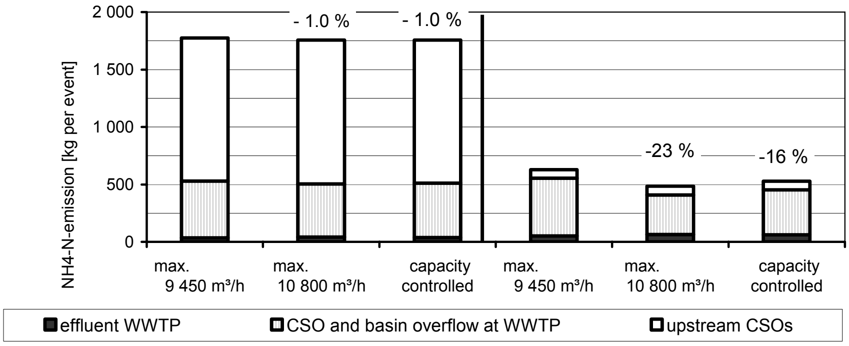

Figure 4: Effect of increased WWTP inflow on Ammonia emission of catchment CHEMNITZ

The intense rain event 1 leads to a sudden flow increase and a rather high spill by the CSOs in the upper part of the catchment. Consequently the effect of increased inflow to the WWTP is weak. In contrast, at weak and long rain events a high portion of ammonia load is transported to the WWTP. In those cases a significant reduction of ammonia emission can be achieved by increasing the inflow. Capacity-control inflow increase is on first sight less efficient than uncontrolled increase of flow. This picture may change quickly when uncontrolled inflow leads to overloading of e.g. the sedimentation process.

The effect of integrated control is slightly less efficient regarding total COD. On the other hand, integrated emission of total COD is not reflecting the real situation appropriately, since COD leaving the WWTP is more or less inert whereas COD in the spilled combined water is to 80-90% degradable, leading to acute oxygen depletion in the receiving water.

The improvement does not seem overwhelming. However, this is the case for the case study conditions where only a moderate increase of WWTP inflow is possible. For a treatment plant with more flexibility, the results may improve more pronounced.

5 CONCLUSIONS

An integrated RTC of sewer and WWTP requires a proper control of the WWTP inflow. A promising approach for the development of control rules is the data analysis of online measurements in order to dynamically identify the WWTP capacity. These data are in many cases available even over long time periods. A resolution of 2 hours is already beneficial, shorter time steps are recommended. In all investigated plants secondary sedimentation and nitrification were the most sensitive processes with regard to overloading during wet-weather events. Hence, these should be the basis of predictive control. The capacity of the sedimentation process was evaluated with some uncertainty by empiric rules derived from statistic data analysis. Nitrification was described by means of deterministic models yielding good results. For this, influent and effluent information of Ammonia and COD was used. Additionally, a second (backup) control loop based on effluent concentrations was implemented in order to omit violation of threshold values. An integrated modelling study showed that a significant reduction of emission can be expected for weak or medium rain events whereas intense stormwater events lead to much more diffused spills at all CSO structures within the catchment and thus WWTP inflow control is of minor relevance. However, medium-type events typically produce critical concentrations in receiving waters as they emit high loads with relatively high compounds concentrations whereas intense events cause a stronger dilution both in the sewer and in the river.

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