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A real-time control strategy for the separation of highly polluted storm water based on UV-Vis online measurements – from theory to operation

Une stratégie de gestion en temps réel pour la séparation des eaux pluviales très polluées d’après des mesures à distance par ultra-violets : de la théorie à la pratique

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RÉSUMÉ

Les stratégies "classiques" de gestion en temps réel (CTR) mises en œuvre dans les systèmes d'assainissement sont basées sur les mesures de niveaux et de débit avec comme but l'activation d'un volume de rétention normalement inutilisé. La règle du système de contrôle reposant sur "les ruissellements propres (d'eau pluviale) dans les eaux réceptrices et les ruissellements pollués dans les stations de traitement" n'a pas été respectée, notamment par des conditions d'exploitation approximatives et l'absence de mesures. Compte tenu des conditions limites spécifiques du système d'assainissement séparatif municipal de Wuppertal, il était nécessaire d'envisager une approche plus élaborée, basée sur la pollution. Au cours des dernières décennies, des cours d’eau canalisés ont été intégrés au système d’assainissement des eaux pluviales, entrainant le mélange des écoulements d’eau de pluie pollués avec les cours d’eau propres. Ces dernières années, les exigences en matière de traitement de l'écoulement des eaux pluviales ont donc été renforcées. Un système de gestion en temps réel axé sur la pollution (P-RTC) a été développé et installé afin de séparer les écoulements fortement pollués lors d'événements pluvieux et les cours d’eau propres. Les mesures UV-Vis en ligne constituent les paramètres d’entrée. Cet article décrit les équipements de mesure et de P-RTC, définit l'analyse des matières solides en suspension comme paramètre indicateur de pollution, présente les fonctionnalités du système, et donne une évaluation des coûts. Une analyse de sensibilité et des calculs des charges polluantes ont été effectués pour améliorer l’algorithme P-RTC. Un examen des mesures réelles montre clairement les avantages écologiques et économiques de la stratégie P-RTC.

ABSTRACT

“Classical” real-time control (RTC) strategies in sewer systems are based on water level and flow measurements with the goal of activation of retention volume that is normally unused. The control system rule of “clean (storm water) runoff into the receiving water – polluted runoff into the treatment plant” has been thwarted, above all, by the rough operating conditions and lack of measurements. Due to the specific boundary conditions in the city of Wuppertal’s separate sewer system a more sophisticated – pollution-based – approach was needed. Here canalised streams have become part of the storm water sewer system in the recent decades, with the result that clean stream water is mixed with polluted storm water runoff. In addition the requirements to be met by the treatment of storm water runoff have become more stringent in recent years. To separate the highly-polluted storm water runoff during rain events from the cleaner stream flow a pollution-based real-time control (P-RTC) system was developed and installed. Online UV-Vis measurements form the input parameters. The paper describes the measurement and P-RTC equipment, the definition of total suspended solids as the pollution-indicating parameter, and the serviceability of the system, and also gives a cost assessment. A sensitivity analysis and pollution load calculations have been carried out in order to improve the P-RTC algorithm. An examination of actual measurements clearly shows the ecological and economical advantages of the P-RTC strategy.

KEYWORDS

Online measurement, real-time control, spectrometric probe (UV-Vis), storm water
1 INTRODUCTION

1.1 Development of a pollution based real-time control system (P-RTC)

As in most urbanised areas, in the city of Wuppertal too the dynamics of urban development have eclipsed the preservation of natural watercourse patterns. The main body of receiving water, the river Wupper, flows along the length of the valley right through the area of the city. Numerous discharging streams have become part of the drainage system in the course of industrialisation. Apart from a few exceptions, a separate sewage system is used for domestic drainage in Wuppertal. The sewer system is operated by WSW Energie und Wasser AG. As people’s environmental awareness has increased, the requirements to be met by the treatment of storm water runoff have become more stringent in recent years. At the moment, runoff from certain areas has to be treated depending on the way the surface is utilised. This necessitates efficient treatment measures either within the storm sewage system or upstream of discharge points (Gruening and Hoppe, 2006 and 2007). Direct discharge of treatable runoff and mixing it with the canalised stream water are methods that are no longer consistent with water law standards. However, in Wuppertal it is not possible for all canalised streams to be drained separately in the foreseeable future. Due to the high density of urban development in the inner-city area the realisation of separately-channelled streams that are at least slightly natural in character is only possible over the long term.

In total ten canalised streams are part of Wuppertal’s storm sewage system. The current solution provides for continuous online detection of pollutants in the runoff as the basis for a real-time control (RTC) system. Accordingly, in phases in which there is little pollution of the runoff or during dry weather periods characterised solely by stream water flows, discharges are made directly into the Wupper without further treatment. During a defined period of runoff pollution, the streams are diverted into the main intercepting sewer (MIS) and finally to the waste water treatment plant (WWTP).

1.2 P-RTC systems based on UV-Vis measurements

The “classical” discharge RTC strategies are based on the activation of retention basins that are normally unused (e.g. de Korte et al., 2009). In many cases the pollution-specific retention of discharges is based at best on empirical approaches (e.g. retention of flushing surges).

So far, the control system rule of

“clean (storm water) runoff into the receiving water – polluted runoff into the treatment plant”

has been thwarted, above all, by the rough operating conditions in the sewer and the mechanical requirements the latter impose on the measuring equipment. On the other hand, research projects (Lacour et al., 2009) show there is a great potential for pollution-based real-time control (P-RTC).

The solutions to be designed for discharge control purposes have to be capable of being officially approved. Besides, the operating staff have to be included in the arrangements so as to ensure the permanent acceptability of the control system. Finally, the cost efficiency of the solution provides a major incentive. Experience shows that sewage system operators (and not only the latter) are interested first and foremost in an economical solution, with ecological efficiency only coming in second place. Even if the advantages of a totally effective sewage control system are obvious, RTC systems in drainage systems have so far only been implemented and operated at a rather measured pace (Fuchs and Beeneken, 2005; Maeda et al., 2005; Schroeder and Pawlowsky-Reusing, 2005). The P-RTC system in a separated sewer system based on UV-Vis measurements as described in this paper was implemented in 2008-2009 and has been operated continuously since May 2009.

2 METHODS

2.1 Implementing a P-RTC system to control storm-water runoff

Online measurements of a wide range of parameters are a routine matter in wastewater treatment plants (e.g. Matsché and Sturmwoehrer, 1996; Geenens and Thoeye, 1998). In the sewage system, however, considerably more stringent requirements have to be met by measuring equipment and real-time data evaluation, especially if the results form the basis for a P-RTC system (Langeveld et al., 2005; Gruber et al., 2006, Joannis, et al. 2008; Lacour et al., 2009).
2.2 Determination of pollution-indicating parameters and threshold values

Before implementing a UV-Vis based P-RTC system it is necessary to determine the "pollution-indicating parameter" and the threshold value of the latter. In this application the purpose of these is to record the degree of storm-water runoff pollution and to control the system. There are three main requirements linked to this "indicating parameter":

- Stable and continuous availability of online readings output by online-measurement systems in the sewer (in situ)
- Representation of the main pollutants in the wastewater (here: storm water) stream by the measured parameter
- Acceptance of the measurements and the measured value (indicating parameter) by the authorities supervising and approving the P-RTC system.

A parameter that is representative of the degree of storm water pollution is wastewater turbidity, which can be recorded exactly enough by photometric means and which, by means of calibration and correlation, enables the total suspended solids (TSS) to be determined (Hoppe et al., 2009; Lacour et al., 2009). As regards storm water pollution, heavy metals and petroleum hydrocarbons, a substantial portion of which are adsorbed onto solids, constitute a major problem. That means that TSS actually represent the degree of runoff pollution to a great extent.

UV-Vis readings taken so far in canalised streams in Wuppertal confirm the value of TSS measurements as a suitable indicator of storm water pollution (Gruening and Hoppe, 2007). In the discussion with the supervisory authorities, a matter to be agreed in addition to the general recognition of the process was the threshold value to be set for the control system. For storm water treatment, however, so far no indicating parameter has been officially defined (as is the case for COD in the treatment of combined sewage). Accordingly, there are no generally binding limit values either. Some initial information regarding a duration- and frequency-dependent peak concentration for solids is yielded e.g. by worksheet BWK M7 relating to salmon spawning waters in Germany (BWK, 2008; see also FWR, 1998).

One advantage of parameters measured by UV-Vis probes (equivalences for TSS, COD, NO₃-N) and a control system dependent on them lies in their flexibility. Currently, the limit value for this catchment area in Wuppertal is geared to the TSS concentration of 100 mg/l. This value can be varied individually depending on the degree of runoff pollution in the catchment area or immission criteria exhibiting seasonal fluctuations. The direct management of pollutant loads is not possible even with this innovative solution. The P-RTC system currently implemented attaches priority to the treatment of discharges with a high degree of pollution. In the framework of the sensitivity analysis described in Section 2.4 the pollutant load retention ensuing from different (P-)RTC strategies has been examined.

2.3 Measurement devices and P-RTC equipment

The first of twelve P-RTC equipment set-ups is currently being implemented in Wuppertal in a storm water bifurcation structure. Following test measurements in various canalised streams (2005-2008), an P-RTC system that depends on the pollution of runoff in the “Briller Creek” canalised stream has been operating since May 2009. The structure is located roughly 50 m upstream of the stream’s discharge outlet into the main body of receiving water, the river Wupper. Figure 1 illustrates the principle of controlled flow bifurcation. The basic runoff fraction of the stream and the flow constituents that do not have to be treated flow directly into the receiving water. A valve in a branching-off line controls the inflow of the fraction of runoff that has to be treated into the main intercepting sewer (MIS), which accommodates the treatable runoff in the Wuppertal urban area. The current regulations stipulate that a runoff fraction of 15 l/(s·ha) from areas with runoff requiring purification has to be treated. Besides this, 5 l/(s·ha) of the runoff from areas with a land use that does not require purification have to be channelled via the MIS to the WWTP. In the “Briller Creek” catchment area that is roughly 1 m³/s.

The photometric probe is attached to the bottom of the canalised stream. If the limit value (TSS > 100 mg/l) is exceeded, a hydraulic valve opens the outlet duct leading to the MIS, and the fraction of the discharge requiring treatment is diverted. A magnetic-inductive flowmeter with a control valve installed downstream allows the discharge to the MIS to be controlled – for example to a level of 15 l/(s·ha). In addition, an ultrasonic water level probe is installed about two metres before the photometric probe in the soffit of the main channel. This allows the total discharge to be estimated before application of a theoretical water level/discharge ratio. Another flowmeter will be installed in the autumn of 2009 to verify the calculations. Furthermore several rain gauges are installed all over the
city area to provide rainfall data.

At various locations in Wuppertal, in particular the probe systems of the s::can company (Vienna) have been used for several years now. These probes are of the hazardous-duty type and have a compressed air cleaning system for the measuring window, thus permitting their use in the sewer without any sensitive precision mechanisms (e.g. wipers).

![Figure 1: Storm water bifurcation structure in a P-RTC system installed in a canalised creek in Wuppertal](image)

2.4 Sensitivity analysis of different control strategies

As part of an overall control concept a sensitivity analysis was carried out to describe the impact and possible ways of varying the fractions of flow depending on the pollutants present. For this analysis spectrometer data (only TSS) and water level data for August 2009 (1-minute records) were used. The total flow in the main channel was calculated on the basis of the water level. The TSS pollution load was calculated on the basis of the flow and the TSS concentration.

Two control concepts (RTC and P-RTC) were compared:

RTC-Concept 1 (C1) – water quantity-based: operating the hydraulic valve on the basis of water level data. A simple control strategy that opens the valve during a rainfall event when a predefined water level threshold is exceeded and keeps the valve closed during dry weather periods when the discharge falls below the threshold. This is based on the assumptions that water level only rises due to rainfall events and that an increase in storm water pollution is generally determined on the basis of surface runoff and re-sedimentation in the channels.

P-RTC-Concept 2 (C2) – water quality-oriented: operating the hydraulic valve on the basis of TSS measurements. A more sophisticated control strategy that opens the valve on the basis of emerging pollution of dry weather and storm water flows. During "clean water" periods the valve is closed until the upper TSS threshold is exceeded (pollution event). This happens independently of the water level. When the water gets cleaner again and readings fall below the lower TSS threshold the valve closes again. Upper and lower thresholds (constant Δ of 25 mg/l) are used, because the pollution level measured may change quickly and may cause a permanent movement of the valve for measurements close to the upper threshold.

In the case of both strategies the throttle settings for the discharge to the MIS while the hydraulic valve was opened were varied. During the sensitivity analysis the actual discharge to the MIS (1 m³/s) was varied over a range of +/- 25 %, from 750 l/s to 1,250 l/s.

There are various aims to be achieved by implementing the P-RTC strategy. Besides draining off the
runoff requiring purification to the MIS/WWTP, the aim is to minimise the volume sent via the MIS to the WWTP (cost reduction at the WWTP and limited hydraulic capacity of the MIS). On the other hand, highly-polluted storm water (maximum TSS load) should be sent via the MIS to the WWTP and not be discharged to the receiving water (in order to minimise pollution). To optimise the P-RTC strategy concerning these aims and to underline the advantages and the flexibility of pollution control based on the spectrometric probe (Concept 2), the water level threshold (minimum level of about 11 cm due to a ground sill) was varied for Concept 1 (12, 13, 14, 15, 20, 25 cm) in a fashion similar to the upper TSS threshold in the case of Concept 2 (75, 100, 125, 150, 175, 200 mg/l). Thresholds lower than 75 mg/l have not been taken into account. On this basis the total discharges to the MIS/WWTP and the receiving water and the total TSS pollution loads entering the MIS/WWTP and the receiving water were calculated.

3 MEASUREMENT RESULTS AND SERVICEABILITY OF THE SYSTEM

3.1 Measurement results and sensitivity analysis with regard to pollution load and discharge volume

The results of the sensitivity analysis show that the control strategy parameters (threshold values and throttled discharges to the MIS/WWTP) have to be chosen carefully, because they explicitly affect the quantities of water and the pollution loads that are channelled either to the receiving water or to the MIS/WWTP.

The discharge fractions and the TSS pollution load fraction of the total amount sent to the MIS/WWTP resulting from the implementation of RTC (Concept 1) or P-RTC (Concept 2) are shown in Figure 2. The overall aim is to treat the highly-polluted storm water, discharging less water and the highest possible pollution load to the MIS/WWTP.

As regards C1, the discharge fraction amounts to between 16.2 % (66,966 m³) and 3.6 % (15,045 m³), the figure for C2 ranging from 3.4 % (13,893 m³) to 0.2 % (809 m³). This means that in the case of C1 much more water is channelled to the MIS/WWTP than in that of C2, provided the TSS concentration threshold value in C2 is not set very low. To achieve lower values with C1 quite a high minimum water level threshold value has to be chosen, but then the pollution load of many small rainfall events will not be captured.

With higher TSS concentration threshold values the discharge fraction can be reduced significantly using a P-RTC strategy (C2); a major decrease occurred in the case of an increase in the TSS concentration threshold value from 75 to 100 mg/l.

In the case of C1, the TSS pollution load fraction ranges from 40.3 % (2,862 kg) to 12.0 % (854 kg), the range being from 18.9 % (1,344 kg) to 3.4 % (241 kg) in the case of C2. If the C1 and C2 results are compared on the basis of almost equal discharge fractions (C1: 25 cm, C2: 75 mg/l) it is clear that a greater pollution load can be output to the MIS/WWTP by implementing a P-RTC strategy.

Similarly to the discharge fraction, the pollution load fraction decreases considerably in the case of an increase in the TSS concentration threshold value from 75 to 100 mg/l for C2. This underlines the importance of the threshold value of 100 mg/l TSS. While the discharge fraction can be reduced advantageously by about 60%, the pollution load fraction decreases disadvantageously only by 42%. For this reason and in line with the existing guidelines (BWK M7), the upper TSS concentration threshold value has been set to 100 mg/l in the P-RTC strategy implemented.

Further examination has shown that the Briller Creek had a (relatively high) basic TSS concentration of 11.3 mg/l on average and 59.7 mg/l TSS at the maximum during dry weather periods and TSS concentration of 42.6 mg/l on average and 487.4 mg/l TSS at the maximum during wet weather in August 2009 (7 rainfall events with water level > 20 cm).

Comparing the TSS concentrations of the volumes discharged to the MIS/WWTP under the RTC (C1) and P-RTC (C2) strategies makes the advantage of the P-RTC strategy clearly visible. While the average TSS concentration of storm water discharged to the MIS/WWTP under the RTC system (C1) is between 43 mg/l and 57 mg/l, for the P-RTC strategies (C2) investigated the concentration is between 97 mg/l and 307 mg/l. This shows that the target of “clean (storm water) runoff into the receiving water – polluted runoff into the treatment plant” can be achieved by a P-RTC strategy much more efficiently. Very low-pollution storm water runoff is kept away from the WWTP by this strategy.

Optimising the P-RTC strategy so as to include more bifurcation/overflow structures in the near future should reduce the total pollutant emissions from the sewer system and the WWTP into the receiving
Figure 2: Discharge fractions, TSS pollution load fractions and average TSS concentrations in the storm water flow to the MIS/WWTP in the case of Concepts C1 (RTC) and C2 (P-RTC).
3.2 Serviceability of the system

The P-RTC system now works soundly. Figure 3 shows how the items of system information are recorded. As well as the photometric probe readings (only TSS are presented) the water level and position of the valve are also recorded. The data are transferred online to the main WSW Energie & Wasser AG control system. System behaviour after two rainfall events is presented. Precipitation on 9 June 2009 led to an increase in the water level and the TSS concentration.

Figure 3: Valve setting in response to the result of TSS measurements by means of a photometric probe (records 9 June 2009)
If the threshold value of 100 mg/l that provides the actuating pulse is exceeded, the otherwise-closed hydraulic valve is opened within a matter of seconds and the fraction of runoff requiring treatment flows into the MIS via the opening in the bottom of the canalised stream. If the TSS concentration falls below 75 mg/l, the valve is closed. The storm water runoff is then discharged solely into the receiving water.

To reduce the maintenance effort, a camera system is installed near the bifurcation of the sewer. This permits constant monitoring of the system and, if the stream base flow is low during dry weather, it also enables the measuring probe and rinsing mechanism to be monitored visually. Figure 4 presents the discharge situation during a period of base flow (including stream water) and during a storm runoff period.

Problems that should not be underestimated are the means by which the probe is fixed in the sewage stream and the routing of the cable. On the one hand, the probe has to be fixed in the discharge area in a fashion that affords protection against coarse floating matter, but on the other hand, it is necessary that the runoff should flow immediately past the measuring window (in-situ measurement) and that it should be possible to reach the probe or remove it for maintenance purposes. Due to the steep gradient, very high flow velocities are usually prevalent in the Wuppertal sewage system, in some cases considerably exceeding 5 m/s. Therefore a special attachment system has been developed to deal with this in recent years. To achieve a minimum water level to ensure that sound readings are obtained during dry weather periods, a ground sill has been installed about 2 m downstream of the spectrometric probe. In other applications a pontoon system is used to carry the probe (Gruber et al., 2006).

Maintenance work currently consists of a check and system maintenance, these two operations being carried out in a roughly 3-week cycle. In addition, there is continuous monitoring by means of a camera system, so that any momentary functional impairments (e.g. blocking or failure of the rinsing mechanism) can be registered directly from the control room. The purpose of this combination of monitoring mechanisms is to extend the maintenance intervals to a minimum of once every three months.

Figure 4: Dry weather flow (left) and discharge after a rainfall event (right) in the canalised Briller Creek

4 CONCLUSIONS AND SUMMARY

4.1 Approval of the P-RTC system by the supervisory authorities

So far, experience regarding the supervisory authorities has been quite positive. Agreement on system design, based on results, has been reached at an early stage and on a regular basis. Temporary approval has been given for the current setup, on the proviso that regular information is supplied and that the competent regional government is involved in the scheme. Total suspended solids concentration is accepted as the indicating parameter. The probe utilised features basic calibration based on extensive readings provided by the manufacturer. Individual calibration is possible, and should be taken into account in every application (Hoppe et al., 2009). The main reason for this is the
wide and dynamic range of concentrations resulting from the different dry weather phases, precipitation intensities, seasonally-induced influences, etc. The TSS values range from low concentration values (< 10 mg/l) in the case of the basic runoff (stream water) to high values (> 1,000 mg/l) in the case of storm water surface runoff, e.g. after long dry periods. So far, comparisons between the measured values and the results of a laboratory analysis (which, incidentally, cannot be 100% representative in the case of TSS) have shown that the readings tally well, so that basic calibration produces values of adequate quality for this measurement site.

4.2 Service challenges and experience

When selecting the measuring point, it has to be ensured that, inter alia, the probe assembly can be reached without any danger, that the inspection entrance is accessible without any major diversion of traffic, and that the medium flows over the probe (in-situ measurement) without the latter being prone to damage from great surges, etc.. Furthermore, the power supply and cable routing often present a challenge. As the probe is cleaned by compressed air, a compressor is required. In residential areas, this may produce a noise nuisance requiring appropriate insulation measures.

4.3 Advantages of P-RTC strategies

The analysis of the UV-Vis measurements and the sensitivity analysis concerning the control strategies has shown the great advantages and flexibility of a P-RTC strategy: water quality-oriented control of the hydraulic valve with a spectrometric probe in this case. It allows the highly polluted storm water runoff to be discharged efficiently via the MIS to the WWTP. On the other hand, the clean stream flow during dry weather and less severely-polluted storm water runoff – e.g. after the first flush during long rainfall events – are discharged directly into the receiving body. Besides cutting costs, this strategy allows the (treatment-)capacity of the sewer system and the WWTP to be optimised. In the near future there are plans to insert more structures into the sewer system (and the WWTP) to form an integrated P-RTC system.

4.4 Comparison on a cost basis: RTC, P-RTC vs. construction of storage volume capacities?

When comparing the costs of the controlled system with those of conventional systems, the basic costs of each of the alternatives have to be set off against one another. For a classical storm water sedimentation tank too, regular maintenance and appropriate instrumentation and control systems are necessary.

The capital cost of the photometric measuring equipment is to be put at roughly €25,000. Currently, about €5,000–€10,000 per yr. is to be earmarked for data evaluation and maintenance – provided the system runs “trouble-free”. At the moment this sum has to be supplemented by development costs, which cannot be quantified as a lump sum. Until the present operationally-reliable status was achievable, numerous hydraulic and engineering problems had to be solved. The P-RTC system design presented above does not (yet) represent a “normal” standard solution. Moreover, every measuring point presents individual requirements (Gruber et al., 2006; Hoppe et al., 2009). Taking all the above-mentioned requirements into account, compared with the alternatives

- Channelling of the stream water through a separate channel
- Construction of a storm water sedimentation tank in the inner-city area

the present solution is clearly the more cost-effective one.

A new, separate sewer right across the Wuppertal urban area, below a road carrying a great deal of traffic, would cost several millions of euros on top of the engineering/logistic effort involved.

Space is simply not available for a storm water sedimentation tank. In this respect, the only design that could be considered would be that of an underground concrete basin requiring elaborate construction work. This too would require construction costs of several millions. Moreover, Wuppertal already has a longitudinally-extended, cascade-type storage sewer (40,000 m³) in the form of the MIS. The installation of major additional storm water sedimentation facilities here would be economically unacceptable. Against this backdrop, the control system design presented above is the more cost-effective and, in all probability, the more ecological variant as well. To demonstrate this, further investigations are planned.
LIST OF REFERENCES


