A methodology for assessing the operational potential of the urban wastewater system using integrated modelling

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Abstract Application of real-time control (RTC) is one possible measure to increase the performance of the urban wastewater system. However, the potential and the benefits of control depend strongly on the characteristics of the individual site under question. Conventionally, RTC potential is evaluated by performing a detailed feasibility study, which in some cases may conclude that for the given site real-time control does not have any significant potential. This can result in spending considerable precious resources for a detailed feasibility study only to identify the non-feasibility of RTC in the system.

It would therefore be desirable to have a methodology that allows simple, and cost-effective, screening of sites for which the analysis of real-time control may be beneficial. Earlier research has led to the provision of an easy-to-apply scoring system allowing a quick assessment of the RTC potential of controlling flow in sewer systems. However, as this procedure does not take into account water quality aspects, nor the treatment plant or the receiving water body, it cannot be used for assessing the potential of RTC of the complete system.

This paper describes the work of an on-going project aimed at establishing an enhanced procedure for assessing the real-time control potential for the entire urban wastewater system. This entails simulating many (partly hypothetical) case studies (varying several key parameters of the wastewater system) using the simulation tool SYNOPSIS. For each of these sites, several real-time control algorithms are developed and optimised, following a general procedure, which allows for local, global and integrated scenarios to be considered. Analysis of the results reveals those system parameters which are of particular significance to the RTC potential of urban wastewater systems. Furthermore, it is recognised that there is considerable uncertainty associated with modelling of such a large and diverse system and a framework is developed for incorporating this in the RTC potential screening tool. Finally, further work is currently underway in broadening the number of case study simulations and developing more complex approaches to quantifying and propagating uncertainty in the model.

Keywords Integrated modelling; optimisation; real-time control; uncertainty; urban wastewater system

Introduction In many cities of the developed world, wastewater is managed by a sewer system and wastewater treatment plant, discharging to a receiving water body. Often, the performance of these parts can be increased by control. Several studies have been done on the control of sewer systems (Schilling, 1989, 1994), wastewater treatment plants (Olsson and Newell, 1999) and, to a lesser extent, receiving water bodies (Beck and Reda, 1994). Only recently, control considering the urban wastewater system as one entity has been analysed in detail (see, for example, Schütze, 1998). Simulation studies have also demonstrated that integrated control characterised by integration of objectives and information exchange (Schütze et al., 1999), can indeed lead to further increased performance of the wastewater system. Integrated control has also been implemented for real case studies (e.g. Malmö and Bournemouth).

However, before the actual implementation in practice, an extensive analysis including detailed modelling studies is usually required to assess the RTC potential for a given site.
Such studies generally involve major expense, possibly resulting in the outcome that RTC is not feasible for the site under investigation. Thus, it would be desirable to be able to apply a screening procedure, which allows a relatively quick assessment to be made as to whether a system appears to gain in performance by application of RTC. The result of this assessment could then be used to justify the effort and cost of a detailed feasibility study. The research outlined in this paper aims at the development of a pre-screening procedure that allows the potential of real-time control of the entire urban wastewater system to be assessed, considering both water quantity and quality aspects.

The definition of real-time control
The presence of measuring devices (sampling, for example, water level, flows, concentrations) and regulating devices (e.g. pumps, gates, aerators) is common in wastewater systems in which real-time control (RTC) is performed. Information from measurement devices is used for describing the state of the system, which, in turn, determines the control action to be taken, according to an RTC algorithm (cf. Figure 1). The proposed control action is transmitted to the regulating devices, which affect the state of the system. The control algorithm, for example, can be a set of rules or an optimisation procedure called on-line at every time step in conjunction with a simulation model (often called “Model-based control”). This is influenced by the control strategy, which outlines the fundamental principles of how control is to be performed in the system (e.g. “utilisation of in-sewer storage volume”). The control strategy, in turn, results from the control objectives which are often imposed by regulations and guidelines.

Control objectives in an integrated system
Real-time control is usually applied to make better use of existing infrastructure. In many cases, expensive construction or expansion of the wastewater system (e.g. by provision of additional storage tanks), can be avoided by prudent utilisation of the existing storage and treatment facilities. In conventional applications of real-time control, the control objectives (for sewer systems) are often described in terms of flow volumes or pollutant loads discharged at combined sewer overflows. In operational practice, usually an additional objective is to maintain cost-efficiency. However, neither of these approaches considers the water quality of the receiving water body directly. For example, owing to different dilution and degradation capacities of different receiving water bodies, the same wastewater discharged into different receiving water bodies can have different effects. Also, the timing of discharges can play an important role. Recent advances in integrated modelling (Schütze et al., 1999; Meirlaen et al., 2000; Tomicic, 2000) enable such effects to be studied in an
appropriate way by using an integrated simulation tool capable of simulating real-time control options. Related objectives can be based, for example, on concentrations of ammonium and dissolved oxygen, as suggested by the criteria defined in the Danish guidelines (Spildevandskomiteen, 1984) and in the British “Urban Pollution Management Manual” (FWR, 1994, 1998). A ranked list of potential RTC objectives is shown below (cost-related aspects are deliberately excluded):

1. Maximise the time period during which standards are adhered to.
2. Mimimise the extent to which the standards are breached.
3. Maximise the recovery potential of the system.
4. Maximise the resistance potential of the system against future perturbations.
5. Improve river water quality above minimum standards.

RTC objectives may also focus, possibly with lower priority, on aiming to bring the system back to “ideal” state or on preventing it from deviating from “ideal” state (cf. objectives 3 and 4; see also Beck (1999)). For simplicity, however, in the present study, the objective used was based on the duration of critically low DO concentrations in the receiving river.

After the specification of control objectives, the control potential of any given system can be described as its ability to achieve the control objectives (Beck, 1999). More specifically, it designates the potential to improve the systems’ performance by real-time control. Improvement of the potential is measured against the performance of the system at a reference scenario (e.g. a base-case of static control). The control potential also depends on the control algorithm applied. The definition of an appropriate control algorithm is, therefore, of crucial importance for any study of RTC potential.

Developing an assessment procedure
The screening procedure for the assessment of the RTC potential of a given urban wastewater system taking into consideration both water quantity and water quality aspects was developed in several stages. Initially, a list of the properties of the urban wastewater system that are believed to have significant influence on the control potential was compiled. Selected system characteristics are then subjected to a detailed simulation study, aiming at determining the relative importance of the various system parameters.

To derive general statements that are valid for a wide range of case studies and topologies of urban wastewater systems, the analysis is done for many case study sites, comprising sewer system, wastewater treatment plant and receiving waters of different layout. For this purpose, many hypothetical case study sites were generated. The findings from the theoretical simulation study will be complemented by an analysis of various

Table 1 Properties of the urban wastewater system relevant to RTC potential

<table>
<thead>
<tr>
<th>Element of system</th>
<th>Property</th>
</tr>
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<tbody>
<tr>
<td>Storage volume</td>
<td>Total amount and distribution of storage</td>
</tr>
<tr>
<td>Sewer network</td>
<td>Sewer flow time within the sewer catchment</td>
</tr>
<tr>
<td></td>
<td>Catchment rainfall-runoff characteristics</td>
</tr>
<tr>
<td></td>
<td>Network topology, degree of “loopedness”, slope, flow velocity</td>
</tr>
<tr>
<td>CSOs</td>
<td>Number and location of discharges of CSOs</td>
</tr>
<tr>
<td>Dry weather flow</td>
<td>Spatial and temporal variation of dry weather flow and quality</td>
</tr>
<tr>
<td>Treatment plant</td>
<td>Treatment schemes and control options</td>
</tr>
<tr>
<td>Receiving water</td>
<td>Amount of baseflow (dilution capacity)</td>
</tr>
<tr>
<td></td>
<td>Seasonal and diurnal variations in flow and quality of baseflow</td>
</tr>
<tr>
<td></td>
<td>River catchment rainfall-runoff characteristics</td>
</tr>
<tr>
<td></td>
<td>Number, location and type of receiving water bodies</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Availability of prediction and spatial distribution</td>
</tr>
</tbody>
</table>
wastewater systems currently under RTC in various countries. To demonstrate here the methodology embarked upon in this project, a subset of six properties has been selected from those in Table 1. Taking all possible combinations of high and low values of these six properties (cf. Table 2), sixty-four ($2^6$) hypothetical instances of urban wastewater systems have been generated.

For each of these sixty-four sites, two paradigms of RTC are tested: one relates to a scenario of optimised integrated control, while the other reflects an example of optimised local control. Detailed analysis of the control scenarios is presented in Schütze (1998).

SYNOPSIS is used as the simulation engine for the simulation of the RTC options in the integrated system presented in detail in Schütze (1998) and Schütze et al. (1999). As control potential also depends on the particular control algorithm applied, they are evaluated with regard to the performance criterion chosen to ensure that the best one is applied. This way, a fair comparison of the effects of RTC at various sites is feasible.

Shuffled Complex Evolution (Duan et al., 1992) was chosen as the optimisation algorithm. This is an efficient global optimisation procedure, suitable for optimisation of objective functions of complicated nature, which are not tractable by classical, gradient-based methods. In this study, the optimisation aims at minimising the time periods during which the dissolved oxygen concentration in the river falls below a critical threshold value of 4 mg/l at any point in the river. The performance of the systems under the two different RTC scenarios defined above has been compared with their performance under the base case scenario. Comparison of the oxygen balance in the river under the various scenarios with the base case then allows conclusions to be drawn about the RTC potential of the various case studies.

Figure 2 summarises the findings obtained for the integrated control scenario are summarised. Because optimisation runs were carried out for 64 different urban wastewater systems, the figure is organised in an 8-by-8 scheme, with each of the two axes representing

Table 2  Generation of case study sites by variation of system properties

<table>
<thead>
<tr>
<th>System property</th>
<th>Original, “normal” value</th>
<th>Modified value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge location of treatment plant</td>
<td>3 km downstream of CSO</td>
<td>5 km downstream of CSO</td>
</tr>
<tr>
<td>River dilution</td>
<td>1 in 5</td>
<td>1 in 3</td>
</tr>
<tr>
<td>Catchment rainfall-runoff</td>
<td>As original case study</td>
<td>2/3 of original case study</td>
</tr>
<tr>
<td>Flow time in sewer system</td>
<td>As original case study</td>
<td>2/3 original case study</td>
</tr>
<tr>
<td>Total storage volume</td>
<td>19,950 m$^3$ (27.5 m$^3$/ha)</td>
<td>13,300 m$^3$ (18.3 m$^3$/ha)</td>
</tr>
<tr>
<td>Storage distribution</td>
<td>As original case study</td>
<td>1/3 more storage upstream,</td>
</tr>
<tr>
<td>(Total storage kept constant)</td>
<td></td>
<td>1/3 less storage downstream</td>
</tr>
</tbody>
</table>

Table 3  Control scenarios investigated

<table>
<thead>
<tr>
<th>Control scenario</th>
<th>Parameters considered for optimisation</th>
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</table>
| 0. Base case: fixed setpoints | None: local control is carried out with constant set points for:
  – Pumps in the sewer system
  – Maximum inflow to the treatment plant
  – Flow threshold triggering emptying of the storm tank
  – Return and waste sludge rates in the treatment plant |
| 1. Optimised setpoints | As above, but the following setpoints are optimised:
  – One pump in the sewer system
  – Maximum inflow to the treatment plant
  – Flow threshold triggering emptying of the storm tank |
| 2. Integrated control   | Hierarchical control:
  As before, but the setpoints are overridden in extreme situations                                  |
all possible combinations of three system properties. It is revealing to analyse Figure 2 for regions of particular high RTC potential. Ridges with high potential can be found for large amounts of total storage, combined with a relatively short distance between CSO and treatment plant location (cf. the dark region between the lines marked “4” and “5”).

A particularly large RTC potential is indicated for normal river dilution, normal catchment rainfall-runoff and large total storage volume in sewer system and wastewater treatment plant. A detailed statistical evaluation (Analysis of Variance) indicates the following ranking of the influence of the system properties to RTC potential (Table 4).

It is not surprising that the total storage volume available within the system is of significant influence to the RTC potential. This was recognised long ago in design and operation of sewer systems (cf. the German ATV guideline A128 (ATV, 1992, 1995)). However, the fact that river base flow and the location of the discharge points also have large influence stresses the importance of an integrated approach to the analysis of urban wastewater systems.

**Implementing uncertainty**

Uncertainty in the modelling process has three major components: data uncertainty, which arises from errors introduced by measurements, structural uncertainty, relating to the models’ capability to represent the actual processes and parameter uncertainty, which reflects the ability to converge to a single “best” parameter set using the information provided by the available data. Parameter uncertainty is mainly a consequence of data and structural uncertainties as firstly, the calibration procedure propagates data uncertainty into the model parameters and secondly, the characteristics of the model structure result in

<table>
<thead>
<tr>
<th>Most significant</th>
<th>Least significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total storage volume</td>
<td>River catchment rainfall-runoff factor</td>
</tr>
<tr>
<td>River baseflow (dilution capacity)</td>
<td>Flow time within the sewer system</td>
</tr>
<tr>
<td>Location of CSO and treatment plant discharges</td>
<td>Storage distribution</td>
</tr>
</tbody>
</table>

**Figure 2** RTC potential achieved by application of integrated control (N.B. Improvement is expressed as percentage of reduction of periods of critically low DO concentrations in the receiving river)
multiple regions of attraction in the model space and to multiple local optima within those regions which make it difficult to identify the globally optimum model (Duan et al., 1992). Furthermore, uncertainty can also be due to unknown initial and boundary conditions. However, this can often be minimised either by calibrating the initial conditions or by using a warming up period, which allows the internal states to adjust. Finally, it must be kept in mind that there is considerable randomness in the natural processes themselves. This introduces uncertainty that cannot be eliminated but can be treated by associating it with data uncertainty given sufficiently long data records.

Different approaches have been proposed to propagate the uncertainty present in the different components of the modelling process into the predictions. Conventional approaches such as first-order analysis predict the mean and variance of the predicted variable by propagating the mean and variance of input and/or parameters through the model. This approach gives accurate predictions of the first two moments of the output variable in cases where the nonlinearity of the model and/or the uncertainty on the random variables/parameters are considered small. Other methods use Monte Carlo approaches that are mainly based on the Regional Sensitivity Analysis methodology (Spear and Hornberger, 1980). However, these methods provide a methodology only for analysing and propagating parameter uncertainty. Structural uncertainty also presents a very significant issue that becomes visible in the fact that often different parameter sets are required to represent different response modes of the modelled system.

The methodology establishing RTC potential described in the previous section, is not strictly affected by structural uncertainty as the model is not used to model the system explicitly. Rather, by using the same model structure to explore different operational scenarios, all model formulations are equally representative of the system thus uncoupling the results from structural error. That said, the issue of quantifying the models’ capability to represent the actual processes remains very significant. Extensive testing has already been done in establishing the suitability of the individual modules used (sewer system, treatment plant and river) as well as, to a certain extent, the integrated model. An extensive case study must now be performed to complete the task.

On the other hand, data and parameter uncertainties are significant in the functionality of the RTC potential assessment methodology. Most parameters used in the model arise from calibration of the integrated models’ building blocks on actual data and are therefore subject to uncertainty. As the methodology stands at present, these are treated by examining the statistical properties of the optimised objectives. The coefficient of variation is used as a relative measure variability. Using non-descriptive statistics, this can then be used to establish confidence bounds for the result. Thus, the RTC potential indication is presented with an associated confidence limit providing the capability to quantify the effect of uncertainty.

Conclusions
A methodology to establish the RTC potential using integrated modelling of the entire urban wastewater system has been developed. Initial results for six system properties have indicated that the developed methodology is promising. However, the presence of data and parameter uncertainty is recognised and a methodology for treating it is also incorporated. Current work focuses on examining further system properties as well as investigating the effects of additional treatment plant control options. These results will form the basis for compiling a ranked and weighted list of system properties relevant to the RTC potential. This, in turn, can be used to enhance the screening procedure.

The long-term aim is be in a position to verify the results against the RTC potential observed at a number of case studies implemented in several countries. This could lead to a
pre-screening procedure that will assist water companies, consultancies and regulatory agencies in assessing the potential of real-time control measures for sewer system, treatment plant and receiving water bodies. Further development work is also concentrated in extending the methodology for quantifying the effects of uncertainty on RTC potential. This aims at assessing the effects of the length of the input data as well as investigating the significance of the extent differentiation used in the system characteristics analysed.

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References