Towards fault-tolerant strategies for water quality-based control of the integrated urban wastewater system

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Highlights

- An integrated sewer-WRRF model simulating particulate water quality has been developed.
- Water quality-based control shows potential to reduce particulate pollutant discharge.
- Fault detection and fall-back control mode are essential to maintain control performance.

Introduction

Automatic control of integrated urban wastewater systems (IUWS) is generally accepted as an efficient way to deal with highly variable flow and pollution load caused by wet weather. While within water resource recovery facilities (WRRF), use of online water quality sensors for automatic control strategies is state-of-the-art (Harremoës et al., 1993), their use in sewer networks is more recent. Online monitoring and control in sewers are often limited to water quantity information for operational implementation (Pleau et al., 2001). With the development of advanced sensors, water quality-based control has also been investigated (Alferes et al., 2013). While interesting results have been generated, their application is still at the research level (Seggelke et al., 2013). The main constraint to operational implementation comes from the reliability of the water quality sensors under the harsh conditions encountered in sewer networks, leading to the operators' concern that control systems using a faulty signal may result in worse performance than a situation without control.

In the context of IUWS, the different local controllers are spatially distributed over a wide territory, making routine maintenance laborious. Hence, one may avoid the burden of regular manual data quality evaluation – resource and time-consuming – by using automatic fault detection systems (Alferes et al., 2013). Since operator interventions are required for many types of sensor faults, the sensors may stay un-operational for an extended period of time, rising the necessity to equip control systems with fault detection methods combined with downgraded of fall-back strategies not relying on the faulty sensor signal. Such control system is considered fault-tolerant and often works with a supervisory control that enables re-configuration of the controller to accommodate the new state of the system (Blanke, 1997).

In this paper, faults on water quality sensor signals are addressed by a reconfiguration of the proposed controller. Using a realistic model, different scenarios representing typical faults observed with turbidity sensors have been evaluated.

Material and methods

Case study

An integrated sewer-WRRF model was built for the IUWS of Québec City (QC, Canada). The model including catchment areas, the main sewer network, pumped retention tanks (RT), and chemically enhanced primary treatment (CEPT), gives realistic results of flow and total suspended solids (TSS) with rain intensity series as only input (Tik, 2020). Several local controllers based on turbidity data have been implemented: in the sewer network, to manage the filling and emptying of RT in order to balance the particle pollutant load sent to the WRRF; and inside the WRRF, to optimize the CEPT in order to maintain a sufficient treatment capacity at minimal cost in term of chemical addition. Those water quality-based control strategies have led to a better overall performance of the system by minimizing both chemical consumption in the WRRF and the overall particulate pollutant emissions to the receiving water.

Scenarios simulation

In this study, the strategies to control the filling of the RT are re-considered. The objectives for wet weather management are, in order of priority: (1) to avoid combined sewer overflows (CSO); and (2) to minimize the overall discharge of pollutants to the receiving water.
When a major rain event – for which all storage volume is required – is forecast, the control system is set to comply with objective (1), this is the *reference scenario*. For a smaller rain event, objective (2) is also envisioned, defining the *optimal scenario*.

The *reference scenario* uses a constant flow threshold above which the RT starts to be filled. When the downstream sewer system recovers its hydraulic capacity, emptying of the RT is managed in a way that balances the WRRF inflow from the different RTs in the sewer system and makes their storage volume available again. The chemical addition by CEPT is such that a constant alum concentration is maintained.

The *optimal scenario* is designed to capture highly polluted sewage at the beginning of a rain event, often called “first flush”. To this end, when in-sewer turbidity increases above a defined threshold during wet weather, an indication of a first flush, the flowrate threshold for RT filling (e.g. a weir) is lowered. The objective of this configuration is to protect the WRRF from overloading by limiting the incoming TSS load. When the TSS concentration drops again below the TSS-threshold, the flow threshold is brought back to the normal value, and it is accepted that more (diluted) water is sent directly to treatment. CEPT is controlled by the primary clarifier’s effluent turbidity to avoid biofiltration capacity loss by clogging.

On top of the optimal scenario, typical faults on turbidity signals with different magnitude have been modelled and their impacts evaluated. Ultimately, to evaluate the performance recovery that can be obtained by a fault-tolerant control system, it is considered that a fault detection method (as in Alferes et al., 2013) rises a flag when the sensor signal becomes unreliable. The supervisory controller then switches the controller to a downgraded mode (here the reference scenario), until the reliability of the sensor has been recovered. Different recovery times have been evaluated.

Faults description

A fault is defined as an event that changes some properties of the system (Blanke, 1997). Any event affecting the sensor or its environment making the sensor signal no longer representative of the system is considered a fault. While some of these faults, mostly the ones inherent to the sensor, are easily filtered out (e.g. noise, outliers), faults that originate from external conditions (e.g. sensor fouling) may need a manual intervention to recover. Two types of faults (bias and calibration error) often observed on a turbidity sensor and simulated in this study.

Results and Discussion

Table 1: Compilation of the volume of water and TSS load capture by the RT and sent to the WRRF.

	Reference scenario	Optimal scenario
Volume to RT(m^3)	3 720	3 916
TSS load sent to WWTP (kg)	7 954	7 804
TSS load sent to the RT (kg)	580	728

The scenarios have been evaluated on rain events for which no CSO was recorded thanks to the presence of the large retention tanks. Table 1 shows that with the optimal scenario, 728 kg of TSS could be captured by the RT during the rain event, which is 26% more than by the reference scenario, hence alleviating the impact of the first flush on the WRRF (Figure 1), while using only 5% more volume in the RT. The use of more storage volume is considered as a potential risk of CSO, and it has therefore to be limited. When a fault on the turbidity sensor leads to a positive bias, the controller will continue to send diluted water to the RT at a higher flow rate (see orange dash-dot line on Figure 1b), thus using more volume in the RT.

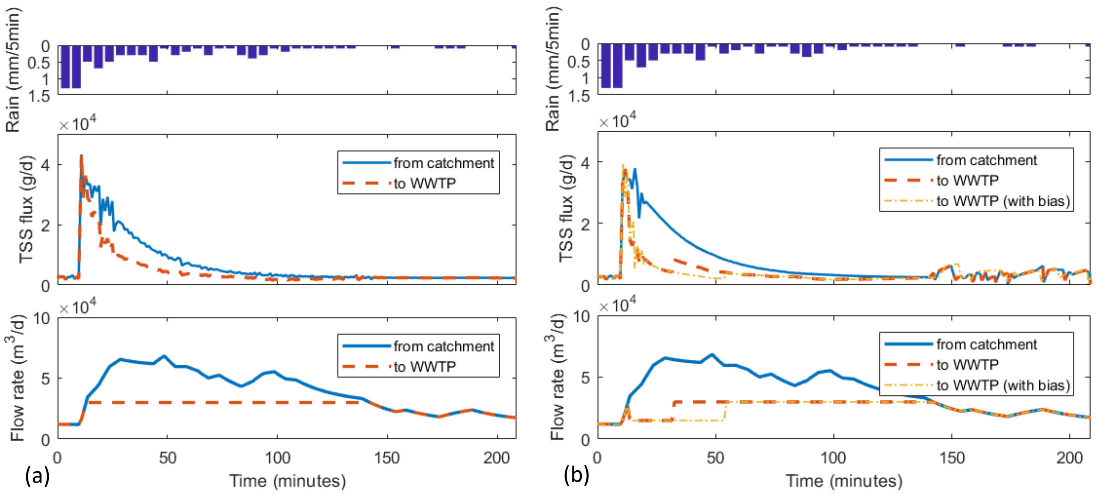

Figure 1: Illustration of the simulation results of (a) the reference scenario and (b) the optimal scenario on a low intensity rain event. On the right figures, results of the scenario with a positive bias are represented by the orange dash-dot line.

Simulations showed that by switching to a downgraded mode – here the reference scenario – within 10 min after the beginning of the rain event allows maintaining the benefits of the water quality-based control (capturing at least 700 kg of TSS, 21% more than the reference) for the worse case while using less than 3960 m³ (7% more than the reference), when the bias is as high as +200 mg/L. At the WRRF, if the downgraded mode is activated within the first 90 min of the rain event, biofilter clogging can be avoided.

Conclusions and future work

Water quality-based control has been proven effective to improve the use of sewer storage capacity to mitigate the impact of highly polluted sewage entering a WRRF. In this study, turbidity sensors have been used to control the filling and emptying of a combined sewer retention tank. The control strategy protects the WRRF by limiting the maximum TSS load and spreading it over a longer period. To ensure reliable functioning of the proposed controller, faults on the turbidity sensor signal have been simulated, showing their negative impact on the control strategy in terms of storage volume used and thus risk of generating combined sewer overflow. However, implementing fault detection to switch the controller to a downgraded mode in case the sensor is no longer reliable, ensures the safe and beneficial use of such controller.

Further experiments will simulate the whole IUWS with random faults distributed among the local controllers. Different detection times, magnitude of errors and detectability will also be experimented.

References

Alferes J., Tik S., Copp J., and Vanrolleghem P.A. (2013). Advanced monitoring of water systems using in situ measurement stations: Data validation and fault detection. *Wat. Sci. Tech.*, 68(5):1022–1030.

Blanke M., Izadi R., Bøgh S., and Lunau C. (1997). Fault-tolerant control systems- a holistic view. *Control Eng. Practice*, 5:693-702.

Harremoës P., Capodaglio A., Hellstrom B., Henze M., Jensen K., Lynggaard-Jensen A., Otterpohl R., and Søeberg H. (1993). Wastewater treatment plants under transient loading: performance, modelling and control. *Wat. Sci. Tech.*, 27(12):71–115.

Pleau M., Pelletier G., Colas H., Lavallée P., and Bonin R. (2001). Global predictive real-time control of Quebec Urban Community's westerly sewer network. *Wat Sci. Tech.*, 43(7):123–130.

Seggelke K., Löwe R., Beeneken T., and Fuchs L. (2013). Implementation of an integrated real-time control system of sewer system and wastewater treatment plant in the city of Wilhelmshaven. *Urban Water J.*, 10(5):330–341.

Tik S. (2020). Contrôle d'un système intégré d'assainissement urbain basé sur la qualité de l'eau : Vers des stratégies tolérantes aux fautes. PhD thesis, Université Laval, Québec, QC, Canada (in French).