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Probabilistic runoff volume forecasting in risk-based optimization for RTC of urban drainage systems

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ABSTRACT

This article demonstrates the incorporation of stochastic grey-box models for urban runoff forecasting into a full-scale, system-wide control setup where setpoints are dynamically optimized considering forecast uncertainty and sensitivity of overflow locations in order to reduce combined sewer overflow risk. The stochastic control framework and the performance of the runoff forecasting models are tested in a case study in Copenhagen (76 km^2 with 6 sub-catchments and 7 control points) using 2-h radar rainfall forecasts and inlet flows to control points computed from a variety of noisy/oscillating in-sewer measurements. Radar rainfall forecasts as model inputs yield considerably lower runoff forecast skills than "perfect" gauge-based rainfall observations (ex-post hindcasting). Nevertheless, the stochastic grey-box models clearly outperform benchmark forecast models based on exponential smoothing. Simulations demonstrate notable improvements of the control efficiency when considering forecast information and additionally when considering forecast uncertainty, compared with optimization based on current basin fillings only.

1. Introduction

This article investigates the application of probabilistic multi-step runoff forecasts generated by simple, conceptual stochastic models (in the form of so-called stochastic grey-box models) in system-wide, forecast-based optimization for real-time control (RTC) of urban drainage networks. A drainage network is considered to be controlled in real time if process variables are monitored in the system and used to operate actuators affecting the flow process (Schütze et al., 2004). RTC is an efficient tool for responding to changing demands that are defined for urban drainage systems (Rauch et al., 2005; Vanrolleghem et al., 2005) and is increasingly applied to operate these infrastructures in an efficient manner (for example, Mollerup et al., 2013; Nielsen et al., 2010; Pabst et al., 2011; Pleau et al., 2005; Puig et al., 2009 and Seggelke et al., 2013). In particular, RTC can support the operation of combined sewer systems, which are used in most of the larger European cities and are constantly challenged by increased impervious area and changing rainfall patterns (Arnbjerg-Nielsen et al., 2013; Willems et al., 2012).

Most RTC implementations aim to minimize the volume of combined sewer overflows (CSO). This is achieved by dynamically controlling flows in the system to achieve an optimal exploitation of the available storage volume, especially in cases with an uneven spatial rainfall distribution over the catchment. RTC is classically performed using static if-then-else rules (Seggelke et al., 2013; for example) that are optimized off-line based on heuristics and model simulations, but mathematical optimization routines are also applied (Pleau et al., 2005, Puig et al., 2009).

Clearly, information on the future evolution of the urban drainage system (i.e., the runoff expected in the near future) should contribute to a more efficient optimization of the controlled

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system. Significant developments have been made in the last decade in terms of radar-based rainfall forecasting (Krämer et al., 2005, 2007; Thorndahl et al., 2014; Vieux and Vieux, 2005) and radar-based urban runoff forecasting (Achleitner et al., 2009; Löwe et al., 2014a; Schellart et al., 2014; Thorndahl and Rasmussen, 2013), paving the way for the application of radar-based online runoff forecasts in RTC.

However, multiple sources of uncertainty affect the runoff forecasts generated by models (see the discussions in Deletic et al. (2012), Schilling and Fuchs (1986) and Sun and Bertrand-Krajewski (2013)): input uncertainty, model structure uncertainty, parameter uncertainty and measurement uncertainty (e.g., level and flow). The examples in Schilling and Fuchs (1986), Schilling (1991) and Schellart et al. (2011) demonstrate that uncertainty of the measured and forecasted rainfall input is often the major factor affecting the online performance of runoff forecast models. Previous studies have evaluated the accuracy of online runoff forecasts based on radar rainfall input in an urban setting and found the forecast performance diminished for lead-times greater than 90 min (Achleitner et al., 2009) and between 60 and 120 min (Thorndahl and Rasmussen, 2013).

Considering the large uncertainties of urban runoff forecasts, it has been hypothesized that the uncertainties may adversely impact the efficiency of forecast-based RTC schemes (Breinholt et al., 2008; Schütze et al., 2004). As a result, RTC algorithms that account for these uncertainties in mathematical optimization have recently emerged. Examples include the tree-based control algorithm, which was proposed for control of (non-urban) drainage water systems by Maestre et al. (2013), and the dynamic overflow risk assessment (DORA; Vezzaro and Grum, 2014) for urban drainage systems that performs a system-wide optimization based on the computed risk of overflow.

Accounting for the uncertainty of runoff forecasts in RTC requires that an estimate of this uncertainty is provided as an input to the control algorithm. The literature on uncertainty quantification in rainfall runoff modelling is abundant. Informal approaches (GLUE) are popular in urban hydrology (e.g., Dotto et al., 2012; Freni et al., 2009; Vezzaro and Mikkelsen, 2012), while more formal Bayesian approaches without (Del Giudice et al., 2015a; Kavetski et al., 2006) and with data assimilation routines (Moradkhani et al., 2012; Vrugt et al., 2013) were developed mostly for natural catchment hydrology. Model estimation and updating in these approaches are commonly based on Monte Carlo simulations, and they can therefore be difficult to apply in an online context (Del Giudice et al., 2015b).

Recent research in the Storm- and Wastewater Informatics Project (SWI, 2015) has therefore focused on the application of so-called stochastic grey-box models for probabilistic online runoff forecasting over multiple prediction horizons. This type of model combines a simple and fast stochastic model structure with a data assimilation routine in the form of an extended Kalman filter, allowing the user to generate probabilistic forecasts with time-dynamic uncertainty quantification. The application of such models in urban hydrology was first tested by Carstensen et al. (1998) and Bechmann et al. (1999). Breinholt et al. (2011, 2012) developed rainfall-runoff model structures, and the performance of these for probabilistic flow predictions was assessed by Thordarson et al. (2012). Finally, Löwe et al. (2014a) analysed the influence of different rainfall inputs on runoff forecast performance, while different options for parameter estimation were compared in Löwe et al. (2014b).

The work presented here combines these recent developments: probabilistic, radar-rainfall based runoff forecasts from stochastic grey-box models have been combined with a risk-based optimization algorithm that accounts for time-dynamic forecast uncertainty (DORA, Vezzaro and Grum, 2014) and integrated into a full-scale, system-wide RTC setup, providing a proof of concept for the case of applying stochastic forecasts in RTC. The setup is tested in a case study with noisy real-world measurements and six sub-catchments with distinctly different characteristics. The purpose of this article is to.

- demonstrate this new, stochastic, system-wide real-time control setup for urban drainage systems,
- evaluate how the consideration of runoff forecast uncertainty influences the efficiency of the RTC scheme, and
- evaluate what runoff forecast performance and what control efficiency can be obtained with stochastic grey-box models and radar rainfall input under realistic conditions in a variety of catchments.

The new control setup applies stochastic grey-box models for runoff forecasting. However, other probabilistic forecasting methods (such as the ones presented by Todini (2008), Van Steenbergen et al. (2012), Vrugt et al. (2005) or Weerts et al. (2011)) could easily be implemented. Thus, the proposed framework is generic in this respect.

2. Methods

2.1. Stochastic real-time control setup

2.1.1. General setup

A system-wide control setup was applied. Control points need to be defined by the users and are typically located at major actuators, such as the outlet of storage basins or pumping stations. Runoff forecasts were generated by a separate stochastic model (Section 2.1.2) for the inflow to each control point. Based on the inflow forecasts and online observations of the current basin fillings, the DORA algorithm was then used to optimize the outflow from all of the control points, aiming to minimize the overall overflow risk in the catchment (Section 2.1.3). A control time step of 2 min was applied and a maximum forecast horizon of 2 h was considered. Correspondingly, new runoff forecasts were generated every 2 min for 2 h into the future with a resolution of 60 time steps (intervals of 2 min).

The online operation of the framework is illustrated in Fig. 1. It can be split into 5 steps that are executed every 2 min:

1. Data collection – the runoff forecast models apply rainfall forecasts as an input and flow observations for updating the model states. In addition, the current basin filling is required as an input to the control algorithm. Depending on the source, these data are either downloaded as text files through FTP connections or directly imported from the SCADA system through the standard OPC UA (Unified Architecture) protocol (Mahnke et al., 2009).
2. Pre-processing – flow observations are required to update the states of the runoff forecast models (Section 2.1.2). However, for many control points, no direct inflow measurements are available. Instead, these need to be constructed by "software sensors" from a combination of indirect measurements (such as level in and outflow from a storage basin). Catchment specific pre-processing routines (see Appendix A) are therefore implemented in this module. The software WaterAspects (Grum et al., 2004) was applied for this step in our work, while future implementations will apply JEP and R scripts.
3. Runoff forecasting – a separate stochastic grey-box model (Section 2.1.2) is applied for forecasting the inflow volume to each control point. The model output is a distribution of