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Probabilistic online runoff forecasting for urban catchments using inputs from rain gauges as well as statically and dynamically adjusted weather radar

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SUMMARY

We investigate the application of rainfall observations and forecasts from rain gauges and weather radar as input to operational urban runoff forecasting models. We apply lumped rainfall runoff models implemented in a stochastic grey-box modelling framework. Different model structures are considered that account for the spatial distribution of rainfall in different degrees of detail.

Considering two urban example catchments, we show that statically adjusted radar rainfall input improves the quality of probabilistic runoff forecasts as compared to input based on rain gauge observations, although the characteristics of these radar measurements are rather different from those on the ground. Data driven runoff forecasting models can to some extent adapt to bias of the rainfall input by model parameter calibration and state-updating. More detailed structures in these models provide improved runoff forecasts compared to the structures considering mean areal rainfall only.

A time-dynamic adjustment of the radar data to rain gauge data provides improved rainfall forecasts when compared with rainfall observations on the ground. However, dynamic adjustment reduces the potential for creating runoff forecasts and in fact also leads to reduced cross correlation between radar rainfall and runoff measurements. We conclude that evaluating the performance of radar rainfall adjustment against rain gauges may not always be adequate and that adjustment procedure and online runoff forecasting should ideally be considered as one unit.

1. Introduction

Urban catchments are typically of a spatial extent where a homogeneous distribution of rainfall over the catchment cannot be assumed. This is one of the main drivers for developing real time control (RTC) setups for urban drainage systems. The load on the sewer network is higher in some places than in others, which results in an uneven use of the available storage capacities. This suboptimal load distribution can be improved by a dynamic operation of the network. As a result, combined sewer overflows can be reduced, for example.

Real time control systems are in operation in a multitude of urban catchments (Fuchs and Beeneken, 2005; Pleau et al., 2005; Sharma et al., 2013; Seggelke et al., 2013). Classically, decision making is done on the basis of offline knowledge about the system, for example in a framework of decision rules. More recent developments incorporate an online optimization of the system that accounts for runoff forecasts (Puig et al., 2009; Vezzaro and Grum, 2012). The control setup suggested in Vezzaro and Grum (2012) makes it possible to account for forecast uncertainties in the optimization and decision making process.

In a dynamic optimization based real time control setup, simplified rainfall runoff models that lump a bigger part of the catchment are typically applied for forecasting over short horizons of a few hours as they are fast enough to generate forecasts within seconds to minutes (for example Pleau et al., 2001; Puig et al., 2009; Vezzaro and Grum, 2012). Using highly simplified models for forecasting is also common in other fields like district heating (Nielsen and Madsen, 2006) or wind power forecasting (Giebel et al., 2011). Apart from being computationally efficient, lumped models make the application of statistical techniques such as state-updating and automated parameter calibration easier. Generating runoff forecasts in such an on-line setup is the case we consider here.

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Generating runoff forecasts on-line requires rainfall inputs. For forecast horizons up to 2 h, rainfall radars are currently the only means that provide the possibility to generate rainfall forecasts with a spatial and temporal resolution suitable for urban catchments. Examples of radar rainfall forecasting systems applied for quantitative online predictions in urban drainage systems are rare (Einfalt et al., 2004), but can for example be found in Einfalt et al. (1990), Kraemer et al. (2005) and Thorndahl and Rasmussen (2013).

Emmanuel et al. (2012a) discourage the direct application of the French operational weather radar product for quantitative purposes in urban hydrology. Similarly, other authors propose an adjustment of radar data to rain gauge measurements (Thorndahl et al., 2009; Villarini et al., 2010). Whereas the results of Villarini et al. (2010) suggest a constant bias between radar and rain gauge measurements during an event, other authors propose adjustment of radar measurements to gauge data also in the course of an event (Borup et al., 2009; Brown et al., 2001; Chumchean et al., 2006; Thorndahl et al., 2009; Wang et al., 2013; Wood et al., 2000). Gjertsen et al. (2003) and Goudenhoofdt and Delobbe (2009) give overviews of different methods applied in Europe.

Radar adjustment is quite usually demonstrated to be beneficial by validating adjusted radar observations against rain gauge observations (Goudenhoofdt and Delobbe, 2009, Thorndahl et al., 2014; Wang et al., 2013) or by generating runoff forecasts from models that were statically calibrated using rain gauge input (Borup et al., 2009; Cole and Moore, 2008; Vieux and Bedient, 2004; Wang et al., 2013). The improvement in runoff forecasting performance may however be less clear for auto-calibrated online models that can dynamically adapt to observations as well as different rainfall inputs. In such cases the skill of different quantitative precipitation estimates to describe runoff should be assessed instead. Gourley and Vieux (2005) follow this thought on a 1200 km^2 catchment to compare results of spatially variable radar adjustments against mean field bias adjustment by evaluating hydrologic simulation results with different rainfall inputs and ensembles of different model parameters. They argue that rain gauge data may not be sufficient for the validation of quantitative precipitation estimates (QPE) as they are often used in the QPE algorithm itself, because rain gauge point measurements are often inaccurate and because there are issues of different scales between rain gauges and remotely sensed rainfall. The value of time varying radar adjustments for urban online runoff forecasting is in our view unclear.

A second issue in the generation of online runoff forecasts is the required spatial resolution of the rainfall input. A multitude of studies have been performed in hydrology as to what degree of spatial model resolution is appropriate. The results from the Distributed Model Intercomparison Project (Reed et al., 2004) show in a non-urban context that conceptual models outperformed distributed models in the majority of cases. Das et al. (2008) give an overview of studies and find that generally, a higher spatial resolution does not necessarily lead to improved model performance. The authors conclude that a multitude of factors like scale of the catchment, physiographic characteristics or data availability influence model performance and that a lower, optimal limit of spatial resolution is to be expected because the model "represents spatial average behaviour". This is underlined by results obtained by the authors in predicting river discharge from a 4000 km^2 catchment using different degrees of spatial resolution of model input data.

In urban hydrology, where catchment response is generally much faster than in natural catchments and data typically available in higher resolutions, Schilling (1984) and Schilling and Fuchs (1986) find that spatial rainfall variability is the key factor for the accuracy of simulations of urban runoff and that rainfall estimation errors are amplified by the rainfall runoff models. The authors suggest the use of high resolution rainfall data and simplified models for on-line operations. Using a hydrodynamic modelling setup for an 1100 ha catchment, Schellart et al. (2011) conclude that spatial resolution of inputs should be high (in their case 1 km^2) in order to obtain a good representation of the observed flows in the sewer network. Finally, Berne et al. (2004) suggest a spatial rainfall resolution of 3 km for a 1000 ha catchment, while Emmanuel et al. (2012b) suggest 2.5 km resolution for a 600 ha catchment and Schilling (1991) suggests 1 km for on-line purposes. Studies in urban hydrology generally point in a direction where improved spatial resolution of rainfall inputs leads to improved model performance, a result which is less clear in modelling of river flows as the spatial scales considered are much larger and data more scarce. We note that previous studies in urban hydrology focused on simulation, not on the case of on-line runoff forecasting with models that adapt to observations, although similar results may be expected.

Despite the above discussed results on model performance considering different spatial resolutions of rainfall inputs, a practitioners approach to building an on-line forecast model for real time control would often be to lump the catchment upstream from a control point. Practical experience suggests that the effect of this lumping on runoff simulation quality is limited (Achleitner et al., 2007; Grum et al., 2011; Wolfs et al., 2013). Similar to previous studies in natural catchments (Das et al., 2008), we therefore consider lumped models of different spatial resolutions for runoff forecasting in urban catchments over short horizons.

Finally, runoff forecasts generated by any model are uncertain due to uncertain measurements and forecasts of the rainfall input as well as an incomplete description of the reality by the model. Achleitner et al. (2009) and Thorndahl and Rasmussen (2013) evaluate the quality of urban runoff forecasts using radar rainfall input. Acceptable forecast errors could be obtained for forecast horizons of 90 and 60 min, respectively. In an online setting, however, predicting also the uncertainty of runoff forecasts is of strong interest. The performance of lumped rainfall–runoff models in a stochastic grey-box layout was evaluated by Breinholt et al. (2011) and Thordarson et al. (2012) but rainfall input was assumed known. We here present an evaluation of probabilistic runoff forecast quality that can be obtained in a realistic on-line setting.

Other approaches for modelling uncertainty in conceptual models exist and these apply Bayesian frameworks (Del Giudice et al., 2013; Kuczera et al., 2006; Renard et al., 2010), for example, GLUE (Breinholt et al., 2013; Dotto et al., 2012; Thorndahl et al., 2008) or simple output error methods (Breinholt et al., 2012). The approach presented here distinguishes itself in the explicit focus on forecasting over a multitude of horizons on a short time scale instead of describing simulation uncertainty and thus improving the capability of the model to describe reality. In addition, high computational efficiency is a focus of the presented approach.

In the following, the article first gives an introduction to the rainfall data considered as input for runoff forecasting in this study. Rainfall observations and forecasts from rain gauges and two types of C-band radar data are evaluated and compared. The types of weather radar data considered are

- temporally and spatially constant adjustment over the whole period (static adjustment),
- time-dynamic mean-field bias adjusted to rain gauge measurements in the course of an event, in addition to the static adjustment (dynamic adjustment).

The purpose of this evaluation is to demonstrate how the different rainfall measurements relate to each other and that the dynamic adjustment indeed makes the radar observations resemble the ground measurements more closely.