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Dynamic gauge adjustment of high-resolution X-band radar data for convective rain storms: Model-based evaluation against measured combined sewer overflow

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SUMMARY

Numerous studies have shown that radar rainfall estimates need to be adjusted against rain gauge measurements in order to be useful for hydrological modelling. In the current study we investigate if adjustment can improve radar rainfall estimates to the point where they can be used for modelling overflows from urban drainage systems, and we furthermore investigate the importance of the aggregation period of the adjustment scheme. This is done by continuously adjusting X-band radar data based on the previous 5–30 min of rain data recorded by multiple rain gauges and propagating the rainfall estimates through a hydraulic urban drainage model. The model is built entirely from physical data, without any calibration, to avoid bias towards any specific type of rainfall estimate. The performance is assessed by comparing measured and modelled water levels at a weir downstream of a highly impermeable, well defined, 64 ha urban catchment, for nine overflow generating rain events. The dynamically adjusted radar data perform best when the aggregation period is as small as 10–20 min, in which case it performs much better than static adjusted radar data and data from rain gauges situated 2–3 km away.

1. Introduction

Accurate rainfall estimates are required in much higher temporal and spatial resolution to perform successful hydrological modelling of urban stormwater runoff than for most other uses, due to the fast hydraulic response of the urban stormwater systems. Today's detailed distributed urban drainage models can operate with thousands of sub catchments – often of sizes less than one hectare (1 ha = 10,000 m^2). Nonetheless the typical rainfall inputs to these models are still produced by just a few rain gauges. There have long been big expectations to the use of weather radar data for urban drainage (Einfalt et al., 2004) and it is apparent that the spatially distributed nature of weather radar data fits well with distributed runoff models, but despite the technological development within the last decade most radar rainfall estimates are still affected by significant errors that are difficult to quantify (Berne and Krajewski, 2013). A recent literature study found that the standard deviation of the error of radar rain estimates as a proportion of the rain rate typically lies in the range 0.3–0.5 for hourly data (McMillan et al., 2012). In a thorough study of the uncertainties of radar rainfall estimates produced using the Hydro-NEXRAD algorithm it was found that "radar-rainfall uncertainty is characterized by an almost three times greater standard error at higher resolutions (15-min and 0.5 km scale) than at lower resolutions (1-h and 8 km)" (Seo and Krajewski, 2010). This means that it can be challenging to use radar data for urban catchments where the spatial and temporal scales are relatively small. Fortunately, the quality of weather radar rainfall estimates is continuously improved (e.g. Krämer and Verworn, 2009; Nielsen et al., 2013) and in the recent years several research projects have shown some success in using radar data for urban runoff models. Estimation of the peak rain intensities however continues to be a problem (Thorndahl and Rasmussen, 2012). A recent Belgian case study using a modern X-band weather radar and testing various calibration methods found that rain gauge data generally outperform radar data as input to the distributed urban runoff model used in the study (Goormans and Willems, 2012), despite the radar's advantage of being able to estimate the spatial distribution of rain. This shows that even the newest weather radars have difficulties in producing rainfall estimates that are suitable for urban runoff modelling. The reason for this lies in the way radars detect the rain. Radars do not measure rainfall directly but sends out a pulse of microwave radiation and measures the fraction of backscattered

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energy from whatever obstacles the radar pulse may hit. By using a relationship between the reflected energy and the rain rate (the Z–R relationship) it is possible to estimate the rain rate, a subject already extensively covered in literature (e.g. Atlas, 1990; Rinehart, 1991; Sauvageot, 1992; van de Beek et al., 2010). The Z–R relationship is not constant, however, and has even been observed to change dramatically several times during a rainfall event (Clemens et al., 2006). Since the Z–R relationship is heavily dependent on the drop size distribution (DSD) of the rain these changes can be explained by changes in the DSD, since this has been shown to vary drastically during events in multiple studies (Chapon et al., 2008; Cifelli et al., 2000; Smith and Krajewski, 1993; Smith et al., 2009). These changes pose a limit to how accurate the quantitative precipitation estimates from radars can be when a constant relationship between radar reflectivity and rainfall intensity is used throughout an entire event (Lee and Zawadzki, 2006). Several studies have shown that quantitative precipitation estimates from weather radars are improved by dynamically adjusting the radar data by rain gauge measurements (Cole and Moore, 2008; Creutin et al., 1997; Goudenhoofdt and Delobbe, 2009; Shrestha et al., 2013; Thorndahl et al., 2014; Wood et al., 2000). None of these, however, have focused on producing rainfall estimates suitable for online modelling of urban runoff for high intensity events.

It is rarely the absolute depth of a rain event that induces problems in urban areas such as local flooding, water in the basements and combined sewer overflow (CSO). Problems occur as soon as the mean areal rain intensity exceeds the bottle neck capacity of the sewer system for a period of time that is comparable to the response time of the system. For this reason the highest intensities are of the highest interest for the urban runoff modeller and therefore the dynamic adjustment scheme proposed in this study aims at improving especially the radar's ability to estimate the highest intensities.

In the current study radar data are provided by a DHI LAWR (Local Area Weather Radar) (Jensen, 2000). This is a small X-band weather radar of growing popularity among municipalities due to its low cost and ability to provide rainfall estimates with a pixel size of just 100 m and a 1 min temporal resolution. This means that the resolution of the radar data is more detailed than necessary in order to describe the temporal and spatial variability of the precipitation of importance for urban runoff modelling (Berne et al., 2004; Ochoa-Rodriguez et al., 2015). The most important disadvantages of this radar type, compared with C- and S-band radars, is its limited range (maximum range is 60 km and quantitative estimation is possible up to 20 km) and larger attenuation due to the X-band frequency. Besides that the LAWR has the same problems with quantitative precipitation estimates as other radar types and therefore needs to be adjusted using rain gauge data in order to be useful in urban hydrology (Willems et al., 2012).

The dynamics and depths of the stratiform rain events of the winter season are in general well described by gauges (Shrestha et al., 2013), while these are less good at describing the convective events of the summer season. The latter events happen to be those that most often cause problems in the urban environment due to high local intensities, but to catch the spatial variability of such a convective storm over an entire city an unrealistically high number of gauges would be required. Therefore, these are the kind of events where high resolution radar data could be useful and thus the radar rainfall estimates should be validated against this kind of events. The rain events used in the current study have been selected based on the criterion that they should have resulted in at least 100 m^3 of CSO from a specific structure. This led to nine events which are mainly of a convective nature.

Validation of radar rainfall estimates is not a simple task and using rain gauges as the "ground truth" is problematic. Rain gauges at best represent the rainfall at one specific point covering only a few hundred square centimetres, while the validation ideally should be done on areal rainfall, which is the quantity of interest for runoff modelling. Since runoff is a direct response to the areal rainfall on the catchment, the quality of different rainfall estimates are in this article assessed by comparing modelled and measured runoff from a highly impervious, well defined urban catchment. This validation method is not affected by the various kind of catching errors associated with rain gauge measurements (McMillan et al., 2012), and it focuses on a property of direct interest in urban drainage modelling, here the volume of CSO events. Instead uncertainties regarding the model setup are introduced. These are attempted minimised by building a highly detailed distributed model for an area where the system is very well known and well defined. Furthermore, a very impervious area is chosen as base for the model to minimise the big uncertainties regarding the fast runoff from permeable surfaces. To avoid bias towards any specific type of rainfall estimates, the runoff model is built purely from physical data without any calibration.

The paper has the following main aims:

- Test whether rainfall estimates from an X-band weather radar can be improved by adjusting the rainfall estimates from nearby gauge measurements, to the point where the radar data can be used for modelling urban sewer overflows.
- Explore the impact of the length of the time horizon used for the dynamic adjustment of the radar data.
- Use a well determined runoff model to assess the quality of the rainfall estimates. This is done by using the rainfall estimates as input to a detailed distributed hydrodynamic urban runoff model and comparing the modelled and measured water levels at a downstream overflow structure. In this way the point-area sampling error and other error sources connected with rain gauge observations that often distort studies regarding radar quantitative precipitation estimation (QPE) are minimised.

The paper is structured in the following manner: In Section 2 the data is presented followed by Section 3 in which we present the various ways the final rainfall data products are produced. In Section 4 the model based validation methods are described while the results are presented and discussed in Section 5. Finally the conclusions are presented in Section 6.

2. Data basis

2.1. Instruments

The radar used is a DHI LAWR X-band radar located 7 km from the centre of the Danish city Odense. The processed radar data used as basis for the investigation have a spatial resolution of 100×100 m and a temporal resolution of 1 min. The opening angle of the radar is ±10°, which implies that the radar detects rain up to an elevation of 700 m above the centre of Odense and up to 1200 m in the northern most outskirts of the city. Four RIMCO tipping bucket rain gauges with 0.2 mm resolution are used for the adjustment of the radar data. The raw gauge data are transformed into time series as described in (Jørgensen et al., 1998). The location of the rain gauges and radar can be seen in Fig. 1. Note that gauge A is situated centrally in the small validation catchment and therefore this gauge is expected to represent the rainfall over the catchment much better than the other gauges.

The runoff from the validation catchment is only measured indirectly by a water level gauge situated at the downstream weir. This is used instead of discharge data simply because only water level data are available. A sketch of the overflow structure can be