Rainfall products from weather radar, rain gauges, and microwave links in the context of city-scale rainfall-runoff modelling

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Highlights

- Rainfall-runoff is simulated at city scale using weather radar, microwave links, and rain gauges
- Runoff simulated from microwave links is highly correlated to observed runoff
- Inflow to WWTP is unlike CSOs almost insensitive to underestimation of observed rainfall

Introduction

Reliable modeling of rainfall-runoff is crucial prerequisite for efficient management of urban drainage systems and waste water treatment plants. Distributed rainfall models capable to represent highly diverse runoff characteristics of urban catchments have been therefore used already since 1970's. During last three decades these models are increasingly used also with distributed rainfall information from weather radars (Thorndahl et al., 2017). Weather radar quantitative precipitation estimates are, however, often affected by significant errors and they are not available at many locations around the World. Commercial microwave links (CMLs), point-to-point radio connections constituting backbone of cellular networks, represent appealing alternative (or complement) to traditional observation systems as they are available worldwide and are especially dense in populated areas. CMLs are attenuated by raindrops and this attenuation is almost linearly related to rainfall intensity (Leijnse et al., 2007). The CML rainfall estimation is, however, not yet mature and practical experience with rainfall estimation at smaller scales required for urban drainage modelling is limited to several case studies, for overview see e.g. Chwala and Kunstmann, (2019).
In this contribution three different rainfall observation systems are compared in terms of their ability to reproduce urban rainfall-runoff at city scale: i) rain gauge network operated by city of Prague, ii) unadjusted weather radar product provided by Czech Meteorological Institute, and iii) rainfall retrieved from a network of commercial microwave links operated within cellular backhaul. The evaluation focuses on the runoff at the outlet of the catchment (WWTP inflow) which is monitored by flow gauges operated by water utility and on the differences in simulated CSOs. Rainfall data are processed using methods suitable for real-time applications.

Methodology

Experimental catchment and rainfall-runoff model

Case study catchment (30 km^2) belongs to two trunk sewers (EF) draining north-eastern part of city of Prague (Czech Republic). The area is mostly drained by combined sewer system. The sewer network has complex topology with 24 CSOs and several bifurcations and the time of concentration reaches up to 9 hours. The catchment is represented by a distributed model implemented within MIKE URBAN+. The model has 19604 nodes, 20114 links, and 5660 subcatchments. Average size of a subcatchment is 0.75 ha. For the calibration and the verification of the model rainfall data from a RG network was used.

Observation period and data

The evaluation is performed for 10 heavy rainfall events which occurred in the years 2014, 2015 and 2017. The maximal 10-min rainfall intensities observed by single rain gauges during these events are between 27 mm h^{-1} and 112 mm h^{-1}.
Rain gauge data. The catchment is covered by six tipping bucket rain gauges (MR3, METEOSERVIS v.o.s., catch area 500 cm^2, resolution 0.1 mm) located from approx. three to six kilometers from each other.

C-band weather radar is operated by Czech Hydro-Meteorological Institute and is located about 50 km southwards from the catchment. Base reflectivity from the lowest scan which was used for rainfall estimation is provided at 5 min temporal and 1 km^2 spatial resolution. Weather radar reflectivity is transformed to rainfall intensity *R* (mm h^{-1}) using Marshall-Palmer power-law relation with fixed parameters.

CML rainfall product is derived from devices available in Prague area, specifically in the domain of 30 x 30 km^2. The number of CMLs available in this domain varies between different events from 159 to 191 radio connections. It is approx. 1/4 of all available CML devices in the region. All the CMLs are operated within cellular backhaul of T-Mobile and use Ericsson MINILINK platform. CMLs are polled for transmitted and received signal powers using SNMP based server-sided software. Data are collected with approx. 10 s time step and aggregated to regular 1 min attenuation time series. CML data are first preprocessed to separate raindrop-path attenuation from other sources of attenuation as described e.g. in (Pastorek, Fencl, et al., 2019). Power-law model with parameters taken from (ITU-R P.838-3, 2005) is used for converting raindrop path attenuation of CMLs to rainfall intensity. The gridded product is reconstructed from path-averaged CML rainfall estimates using Goldshtein algorithm (Goldshtein, et al., 2009).

Gridded rainfall products from weather radar and microwave links are assigned to the subcatchments using module implemented directly in MIKE Urban+. Rainfall from rain gauges is assigned to model's subcatchments using Thiessen polygons.

The reference flow data are obtained from area-velocity flow gauge located at the outlet of the catchment before the trunk sewer reaches Prague waste water treatment plant.

Performance evaluation

Rainfall products: Total rainfall depths are averaged over Thiessen polygons used for assigning rain-gauge observations to subcatchments of the model. The rainfall depths obtained from different observation systems are compared with each other in terms of relative differences.

Simulated runoff at the outlet of the catchment is compared to observed runoff and evaluated for each event in terms of Person Correlation Coefficient and relative error in hydrograph volume.

Combined sewer overflows (CSOs): There are no reference flow data at CSOs. We, therefore, compare CSO hydrographs simulated from different rainfall products with each other. CSOs hydrographs are compared in terms of Person Correlation Coefficient and relative differences in discharged volume.

Results and discussion

Figure 1 show cumulative distributed rainfall for convective storm on 8th July 2014 during which the maximal 10-min rainfall intensity observed by rain gauges reached 112 mm h^{-1}. The spatial structure of rainfall as captured by radar is similarly reproduced by CMLs, nevertheless, CMLs tend to overestimate low rainfall intensities (probably due to errors caused by wet antenna attenuation) and smooth local peaks. When evaluating rainfall products over all 10 events (Figure 2a), the radar estimates are on average by 17 % underestimated compared to rain gauges, whereas CMLs overestimate rainfall on average by 36 %.

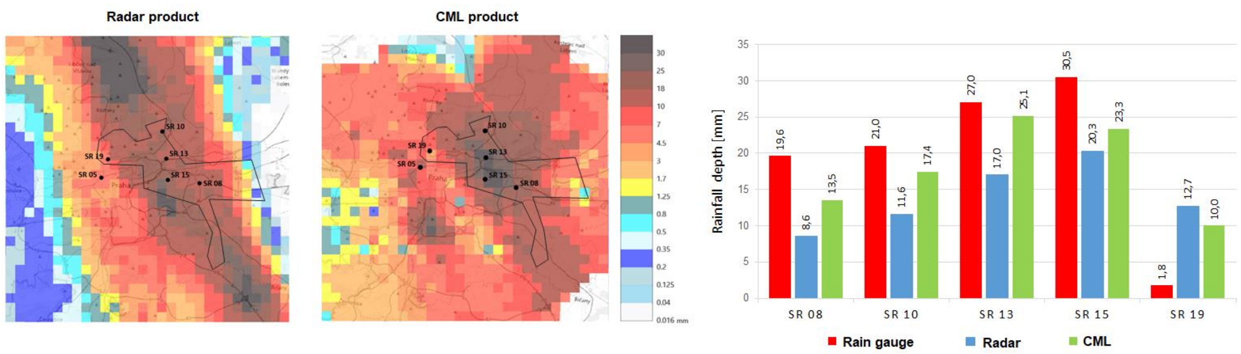

Figure 1. Gridded rainfall map with total rainfall depths of event on 8th July 2014 as captured by radar (left) and CMLs (middle). Barplot (right) shows rainfall depths as observed by rain gauges, radar, and CMLs. Radar and CML rainfall is obtained by averaging pixels corresponding to Thiessen polygons used for assigning rain gauge observations to the subcatchments of the drained area (black polygon).

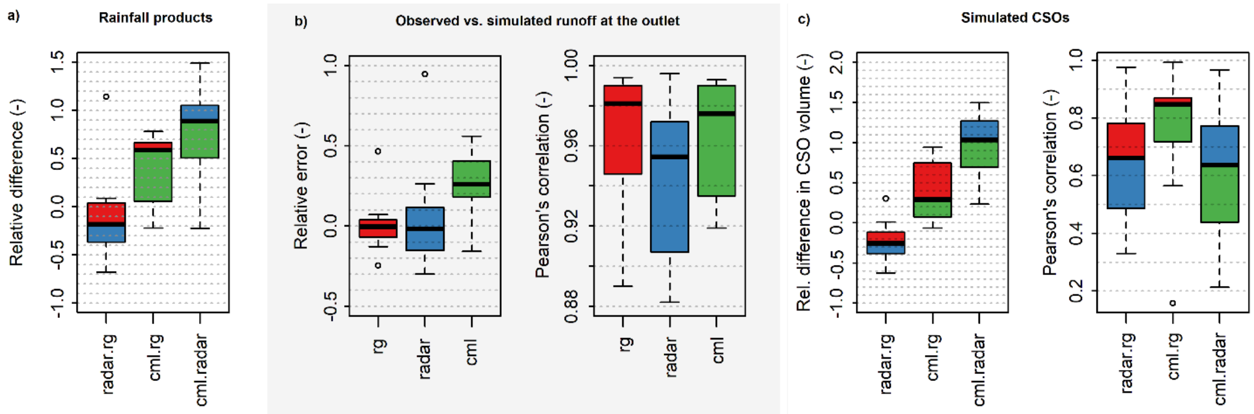

Figure 2. Overall evaluation for all 10 events: a) Relative difference between rainfall depths as captured by different observation systems. b) Comparison of simulated and observed runoff in terms of relative volume error and Pearson's correlation coefficient. c) Relative differences and Pearson's correlation between CSOs when simulated by different observation systems. Each boxplot represents results for 12 CSO structures.

Interestingly, systematic differences between rainfall observation systems are less pronounced when comparing simulated and observed runoff at the outlet of the catchment (Figure 2b): Both the rain-gauge and the radar-based simulations are on average almost unbiased, the CML-based runoff is overestimated on average by 28 %. The simulated runoff is for all three systems highly correlated to the observed runoff, slightly lower Pearson's correlation coefficients are obtained for the radar-based simulations. Relatively small sensitivity of the simulated runoff to the type of input rainfall data is probably caused by upstream CSOs, which were unfortunately not monitored. The CSOs' simulations are, however, much more sensitive to input rainfall data (Figure 2c). The CSO volumes simulated using the radar are systematically underestimated and the CSOs simulated from the CMLs overestimated when compared to the rain-gauge based simulations. The CSO discharges simulated from the rain-gauge data are substantially more correlated to the discharges simulated from the CMLs than to the discharges from the radar.

Conclusions and future work

All three evaluated rainfall product provide relevant information for rainfall-runoff modelling. Runoff at the outlet of the catchment is the best reproduced using the rain-gauge product. Surprisingly good estimates of runoff volumes are obtained also when using the radar product, despite the radar systematically underestimate total rainfall depths. Runoff simulated from the CML product is highly correlated to the observed runoff, nevertheless, systematically overestimated. The differences between the rainfall products are more pronounced when simulating upstream CSOs. The future work will concentrate on the elimination of CML bias through i) introducing quality control routines, ii) improving wet antenna correction, iii) and improving the algorithm for spatial reconstruction.

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