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Radar-based pluvial flood forecasting over urban areas: Redbridge case study

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Abstract A nowcasting model coupled with an urban drainage model is used in this study to assess the forecasting of pluvial floods in urban areas. The deterministic nowcasting model used in this paper is part of the UK Met Office STEPS (Short-Term Ensemble Prediction System) system, and the hydraulic model is run following the 1D/1D dual drainage simulation scheme. A highly-urbanised catchment, Cranbrook (located in the London borough of Redbridge), is employed as case study to analyse the associated uncertainties. The main aim of this work is to assess the impact of using rainfall forecasts with different spatial and temporal resolutions to forecast pluvial flooding over urban areas. Preliminary results show that promising performance in hydraulic forecasting is in general observed by using higher spatial and temporal resolution nowcasts as inputs; this implies the necessity of using advanced radar-based nowcasting techniques to improve the state-of-the-art pluvial flood forecasting over urban areas.

Key words Nowcasting; Flood forecasting; Urban drainage

INTRODUCTION

In the last decades, urban pluvial (surface) flooding has caused enormous economic losses all over the world and has affected thousands of people. For this reason, it has been pointed out as an important issue that urgently needs to be appropriately tackled (Pitt, 2008). In order to accurately and timely predict floods over urban areas, high-resolution rainfall measurements and forecasts as well as efficient hydraulic models are required.

With this aim in view, many studies have been conducted on the use of weather radar in urban hydrology (Einfalt *et al.*, 2004), as these devices are able to provide rainfall measurements with high spatial and temporal resolutions. Furthermore, the use of radar to produce rainfall forecast and its subsequent combination with runoff models has been recently studied (Schellart *et al.* 2009, Krämer *et al.* 2007) and constitutes the focus of several current studies, like the one presented herein.

With regard to the runoff models used for urban pluvial flood forecasting, the dual-drainage concept, which entails integrating the overland and sewer networks, has been widely accepted as a feasible physically-based representation of pluvial flooding (Leitão *et al.* 2009, Maksimović *et al.* 2009, Simões *et al.* 2010).

A radar-based nowcasting model coupled with an urban drainage model is therefore employed in this study to simulate urban (pluvial) floods. The main aim of this work is to assess the impact of using rainfall nowcasts with different spatial and temporal resolutions to forecast pluvial flooding over urban areas.

EXPERIMENTAL SITE AND DATA SET

Cranbrook Catchment

The case study used for testing our pluvial flood forecasting methodology is the Cranbrook catchment. This catchment is located within the London Borough of Redbridge (situated on the northeast part of Greater London) and is run through by the River Roding (Figure 1(a)). According to the Environment Agency (2006), the Roding has a rapid response to rainfall, which is typical of densely-urbanised catchments overlying London clay. Flood events have been recorded in the Roding catchment since 1926, with the most recent event being in 2000 and 2009, when several properties were flooded.

The drainage area of the Cranbrook catchment is approximately 910 hectares; the main water course is about 5.75 km long, of which 5.69 km are piped or culverted. This catchment has experienced several pluvial flooding events during the past decade, which are relatively well documented and can be used for development of advanced flood prediction methodologies.

Radar Data

The Cranbrook catchment is in the coverage of two radars, Chenies and Thurnham (Figure 1(c)). The radar data are provided by the UK Met Office through the British Atmospheric Data Centre (BADC) with spatial and temporal resolutions of 1 km and 5 min respectively. This data set has been averaged to obtain a spatial resolution of 2 km. The radar data have been quality-controlled by the UK Met Office following the correction techniques proposed by Harrison *et al.* (2000) to account for all the errors inherent to radar rainfall measurements (see Rico-Ramirez *et al.*, 2007).

Monitoring System

A real time accessible monitoring system is installed in this catchment (Figure 1(d)), including three tipping bucket rain gauges, one pressure sensor for Roding River level monitoring, two sensors for water depth measurement in sewers and one sensor for water depth measurement in open channels. The collected measurements however are not used to verify the forecasting results but for the calibration of the hydraulic model because the focus of this study lies on assessing the forecast errors rather than the forecast plus hydraulic errors.

NOWCASTING MODEL

The deterministic nowcasting system employed in this study is the Short-Term Ensemble Prediction System (STEPS) developed by the UK Met Office and the Australian Bureau of Meteorology. The deterministic nowcasting system in STEPS is based on the spectral decomposition proposed by Seed (2003) with the incorporation of the optical flow equation proposed by Bowler et al. (2004). The deterministic nowcasts produced in this study are purely based on radar.

The nowcasting model has been setup to run at 1 km and 2 km spatial resolutions and 5 min, 10 min and 15 min temporal resolutions. At both spatial resolutions, the domain size was fixed to 500 km x 500 km covering the window with lower left coordinates of 200 km (easting), -100 km (northing) and top right coordinates of 700 km (easting), 400 km (northing). The radar data have been pre-processed to cover this domain size and also to remove any spurious echoes. The nowcasting model has been setup to produce 3 h forecasts initialised every 10 min for all the events.

HYDRAULIC MODEL

Based upon the dual-drainage concept, the hydraulic model of the Cranbrook catchment was implemented in InfoWorks CS by coupling the overland network generated by the AOFD (Automatic Overland Flow Delineation) (Maksimovic *et al.* 2009) and the sewer system. The overland network model is implemented using a LiDAR (Light Detection And Ranging) DEM with 1 m resolution and vertical accuracy of approximately 0.15 m. The sewer network model was obtained from the water utility of the study area. . The simulation parameters were maintained unchanged for all simulations

The AOFD, an in-house tool developed by the Urban Water Research Group (UWRG) from Imperial College London, is employed in this study to generate the overland network. This tool automatically creates the overland flow network to enable its interaction with the sewer drainage system. The AOFD analyses several GIS layers such as Digital Elevation Model (DEM), buildings, manhole location, etc. to generate a 1 dimensional (1D) overland flow network model (consisting of ponds and flow pathways). The resulting model can be further coupled with the sewer network model in order to simulate and forecast pluvial flooding (Maksimovic *et al.*, 2009, Leitão 2009). The advantage of having a 1D model of the overland network (instead of a 2D model) is its short computational time, which makes it suitable for real time forecasting of pluvial urban flooding. Analyses conducted by Leitão *et al*. (2010) justify the fact that a 1D model produces reasonable results when compared to 2D models, while requiring significantly less computational time.

CASE STUDY

Three events occurring since August 2010 (20100822-23, 20101001 and 20110117-18) are selected in this analysis. The event 20100822-23 was associated with a warm front and the rainfall falling within the Redbridge catchment was approximately 30 mm in around 18 h, with more than 20 mm falling in a period of 5 h. The event 20101001 produced around 35 mm of rain in approximately 72 h. The event 20110117-18 was associated with an occluded front passing over Southeast England, producing heavy rain in the Redbridge catchment with total accumulations of around 30 mm in 24 h.

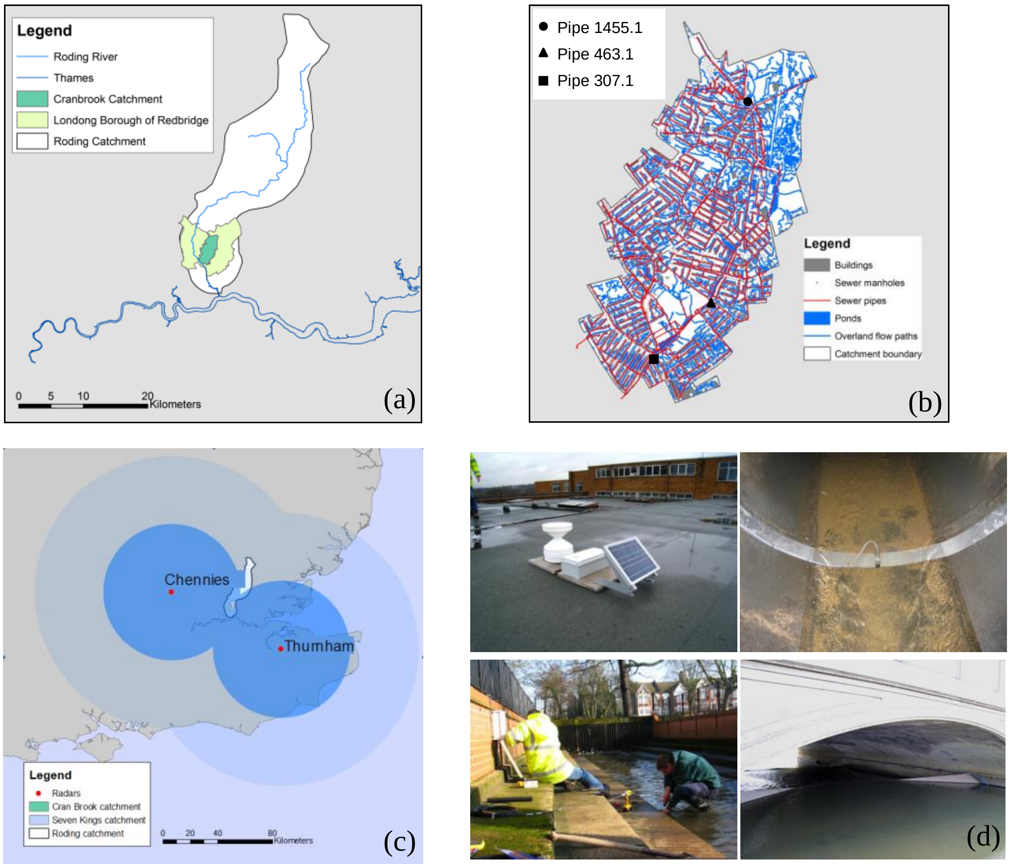

Fig. 1. Cranbrook catchment. (a) location of Cranbrook catchment in relation to the Roding River catchment; (b) dual drainage networks of the Cranbrook catchment; (c) radars which coverage over the study area; (d) monitoring system installed in the study area.

RESULTS

Precipitation Forecasting

Figure 2 shows the skill of all rainfall forecasts for the event 20100822-23 against lead time at several spatial and temporal scales. The top figures 2a-2c show the results of the simulations performed at 1 km spatial resolution and 5 min, 10 min and 15 min temporal resolutions. In the same figures, the performances of the forecasts are also shown when averaging the rainfall forecasts at 1 km to produce larger spatial scales (e.g. 2 km, 5 km and 10 km). As shown in these figures (2a to 2c), the performance of the rainfall forecasts is very similar for the different temporal resolutions (i.e. 5 min, 10 min and 15 min). On the other hand, figures 2d-2e show the results of the simulations performed at 2 km spatial resolution and different temporal resolutions. These results indicate that the performance of the forecasts shown in figures 2d-2e is slightly higher than the performance of the forecasts shown in figures 2a-2c for the same spatial scale of 2 km. Similar results are obtained for the other two events (not shown in this paper). These results have important implications for urban flood forecasting, where forecasts with small spatial scales are required. The results shown in Figure 2 also indicate that the skill or performance of the precipitation forecast depends on the spatial scale, with lower skill obtained at small scales but higher skill at larger scales, which is consistent with the results shown by Schellart *et al*. (2010).

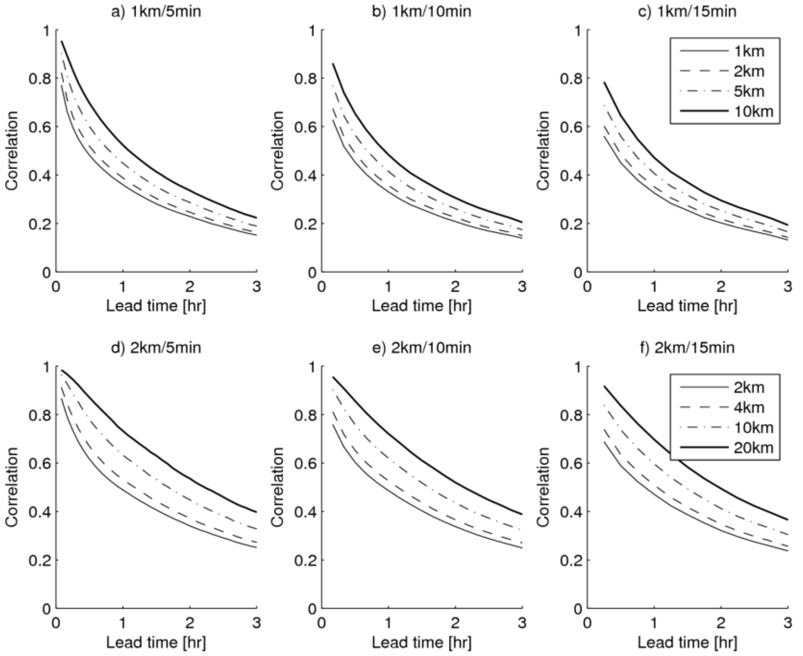

Fig. 2 Performance of the radar-based forecasts versus lead time at different spatial and temporal scales for event 20100822-23.

Hydraulic Modelling

Three pipes with significantly different drainage area (located in the upper, mid and lower part of the Cranbrook catchment) have been selected to demonstrate the impact of the spatial and temporal resolution of rainfall forecasts in the forecast of pluvial flooding over the Cranbrook catchment. The location of these pipes is shown in Figure 1(b).

Figure 3 shows the performance of different flood forecasts for the event 20100822-23 against lead time for each pipe considered in the analysis. The different flood forecasts are obtained by feeding rainfall forecasts with different spatial and temporal resolution into the hydraulic model. The benchmark results are the hydraulic model results obtained using the real Nimrod data with 1 km and 5 min resolution. In the figure '*1-Relative Error*' is used as surrogate measure of performance. The *Relative Error* (*RE*) is termed as

$$RE = \frac{\left|Y_{Nimrod} - Y_{Nowcast}\right|}{Y_{Nimrod}} \ ,$$

where the Y_{Nimrod} and $Y_{Nowcast}$ represent the flow depths in a specific pipe estimated respectively from the Nimrod data and Nowcasting results. When ‘*1-Relative Error*’ equals to unity, it represents a perfect forecast. It is expected that this quantity will decrease with increasing forecasting lead time. Furthermore, Figure 4 shows the rain rate profiles over the Cranbrook catchment on 23 October 2010 (00:00-08:00), as well as the water levels estimated in pipe 1455.1 with Nimrod data and with Nowcasting results at different spatial and temporal resolutions.

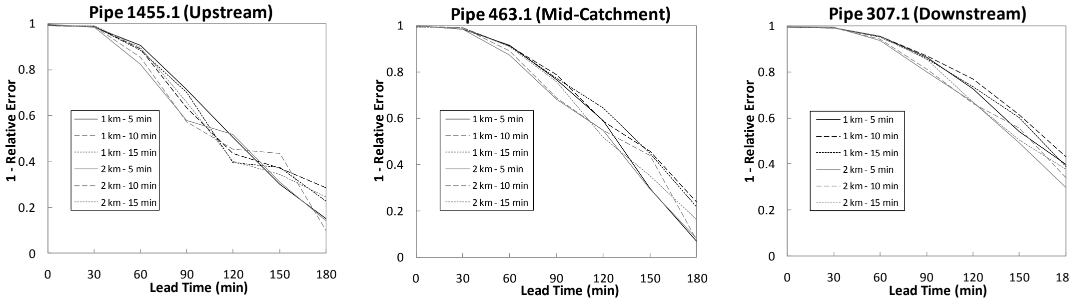

Fig. 3 Three pipes (1455.1, 463.1 and 307.1, respectively located at the upstream, mid-catchment and downstream areas of the Cranbrook catchment) are used herein to show the uncertainties of using rainfall nowcasts over different spatial and temporal scales for event 20100822-23.

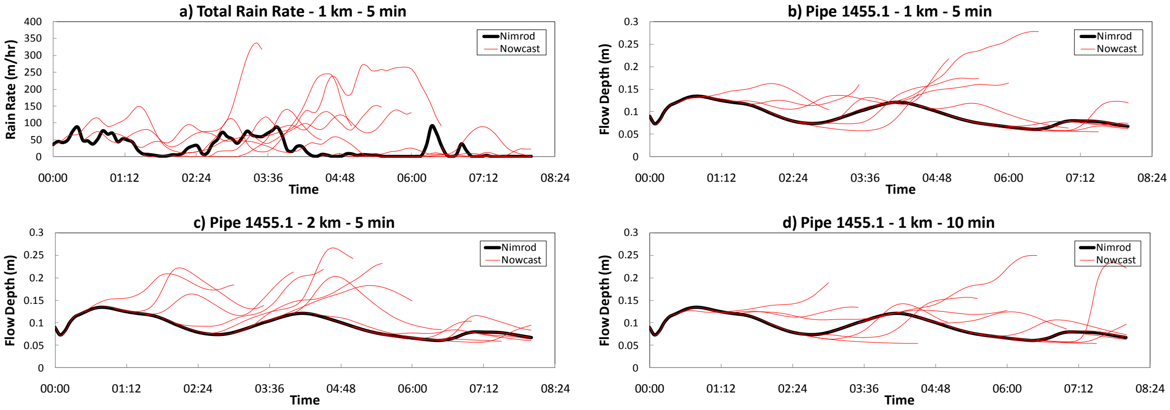

Fig. 4 Profiles of a) the total rain rate over the Cran brook catchment on 23/08/2010 (00:00 – 08:00) and the associated water levels of pipe 1455.1: b) 1 km – 5 min, c) 2 km – 5 min and d) 1km – 10 min scales), respectively generated from Nimrod rainfall (dark lines) data and 3 hr Nowcasting results (red lines).

The results show that both the spatial and temporal resolutions of the rainfall forecast have an impact on the flood forecast. Regarding the spatial resolution, it can be seen that, in general, the flood forecasts obtained with 1 km resolution rainfall forecast are better than those obtained with 2 km resolution rainfall forecast. However, for lead times longer than 120 min the difference in the flood forecast obtained for the two spatial resolutions decreases and in some cases better performance is achieved with 2 km rainfall forecasts as input. This indicates that although 2 km nowcasts have higher correlation with Nimrod data, in this case the 1 km nowcasts, which exhibit higher spatial variability, are better inputs for the hydraulic model with lead times up to 120 min.

In terms of temporal resolution, the results show that for lead times up to 90 minutes the rainfall forecast at 5 min resolution generates the best flood forecast. After 90 minutes lead time the performance of the 5 min resolution rainfall forecast decreases significantly and better flood forecasts are achieved with 10 min and 15 min rainfall forecast.

In addition, it can be noticed that the magnitude of the impact of the spatial and temporal resolution of the rainfall forecast on the flood forecast also depends on the drainage area of the pipe or conduit that is being analysed. As shown in Figure 3, the impact of the temporal and spatial resolution decreases as the area drained by the pipe increases. This can be explained by the fact that in a greater drainage area the differences in the spatial and temporal distribution of the rainfall are smoothed.

CONCLUSIONS

In this study, a radar-based nowcasting model coupled with an advanced 1D/1D hydraulic model is used to simulate flood forecasting over urban areas. The Cranbrook catchment in London is employed as case study to demonstrate the feasibility of using high-resolution radar rainfall data as inputs to forecast floods. Uncertainty study is carried out by applying various spatial (1 and 2 km) and temporal (5, 10 and 15 min) rainfall nowcasts to hydraulic modelling. The results show that better performance in flood simulation is in general obtained using higher spatial resolution rainfall nowcasts as inputs. This implies that the reliability of operational urban flood models may be improved by employing finer resolution rainfall information which has a better ability to reproduce the high spatial and temporal variability of urban rainfall. The perspective research will be focused on generating street-scale rainfall nowcasts using radar-based nowcasting techniques in synergy with statistically-based downscaling methods and studying the associated uncertainties.

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