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Author(s):
Mejía-Estrada, P.I.; Bates, P.; Freer, J.; Coxon, G.

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Application of a meteorological-hydrological modelling cascade at high spatial and temporal resolution for flash floods simulation in urban areas

P.I. Mejía-Estrada*[1], P. Bates[1], J. Freer[1], G. Coxon[1]

1 Hydrology Research Group, School of Geographical Sciences, University of Bristol

*Corresponding author: pm15021@bristol.ac.uk

Abstract

Identification and characterisation of extreme flooding have become increasingly crucial given the effects of climate change in the water cycle. When intense, localised rainfall occurs over a small, impervious area where hydraulic structures are unable to cope with water volumes greater than design values, urban flash flooding is likely to occur. The present study outlines a framework to produce robust estimates of urban inundation behavior as studied by Pappenberger, Beven et al. (2005) and Rodríguez-Rincón, Pedrozo-Acuña et al. (2015), with the novelty that the model set-up, sources of uncertainty, physical assumptions, stochasticity of processes and parameterisations are assessed in a high spatial and temporal resolution framework at local scale. The proposed off-line cascade modelling simulates precipitation patterns, rainfall-runoff components and inundation depths and extents in an urban environment in a probabilistic scheme that allows uncertainty propagation. The methodology is currently being tested in the port city of Newcastle, a prominent north-east urban area of the United Kingdom which at the end of June in 2012 was severely flooded after a prolonged dry spell followed 100-year return period storm, resulting also in the loss of power supplies and significant damage and disruption to the road network.

The cascade chain starts with a numerical weather prediction (NWP) tool that includes cumulus and particle size distribution parameterisations as well as urban canopy models with multiple degrees of freedom. The Weather Research and Forecasting (WRF) model (Skamarock, 2008), a non-hydrostatic, meso-scale NWP tool for weather and climate simulation able to reproduce complex rainfall patters associated with flash flood events in places with topography similar to the study case. It is initialised using atmospheric forcing in a convection-permitting scheme. A three-category urban canopy model that considers roofs, walls and streets is coupled with a land surface model within the WRF. These parameterisations were applied to four telescopic, nested domains (54 km, 18 km, 6 km and 2 km) and the hourly-scale simulation ran from 27th June 12:00 to 29th June 00:00. A probabilistic approach is implemented to obtain an ensemble of five equally rainfall likely scenarios.

Results for simulations #2 and #3 are presented in Figure 1, where the accumulated rainfall values during a two-hour period (where values equaled those expected for the whole month of June) for the complete domain are followed by a zoom-in to the innermost domain; interpolated values from gauges are also shown for reference.

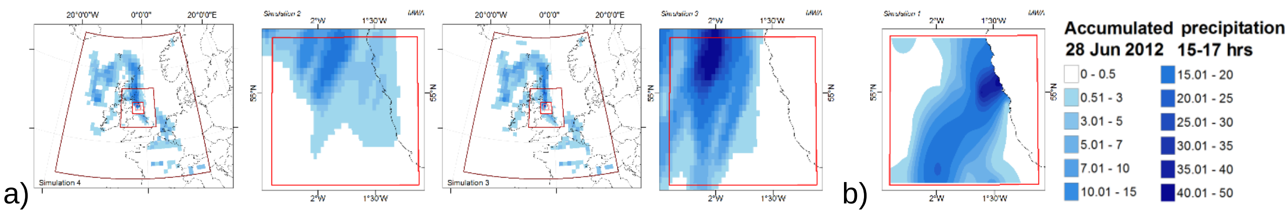

Fig 1: Accumulated precipitation values for 15:00-17:00 hrs on the 28th June 2012 of a) the worst (simulation #2) and best (simulation #3) performing simulations, and b) rain gauges

The second stage involves rainfall-runoff modelling using a semi-distributed hydrological tool (Beven and Freer, 2001) that relies on the well-known topographic index: a ratio between the upslope contributing area that changes over time depending on the wet/dry periods, and the terrain slope that can be easily obtained from high-resolution elevation maps. This computationally efficient model is run at hourly scale for the calibration period 28th February 2008 to 31st May 2012, and the validation period matches the 36-hour meteorological time frame. It is important to note the significant difference in the length of the calibration and the validation period where good model performance is expected nonetheless. The study catchment is a 55 km^2 heavily urbanized area upstream of Newcastle city centre on the River Tyne. The ensemble of rainfall scenarios was used to drive the Dynamic TOPMODEL and evaluated using the Nash-Sutcliffe Efficiency (NSE) score. 10-km gridded rainfall was also used to drive the hydrological model so that the impact of both sources of rainfall (simulated and observed) on the performance of the hydrological model at high spatial and temporal resolutions could be compared. Preliminary results show the importance of developing a function that reproduces the fast response mechanism and the limited infiltration capabilities of an urban environment. Research on this is currently being carried out, considering the popular method of land use categorization depending on urban cover and pervious areas and routing of the flows from impervious surfaces to theoretical detention storage. Figure 2 shows the study catchment highlighted in orange (top left); simulated runoff using gridded rainfall from observations (top right), and simulation #2 (bottom left) and #3 (bottom right).

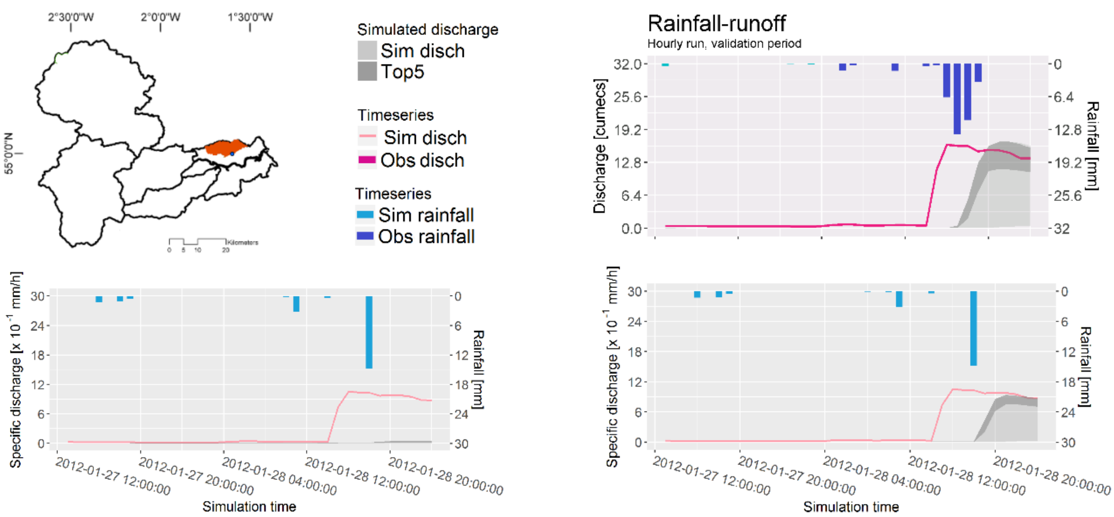

Fig 2: Urban catchment location and rainfall-runoff results using observed and simulated input.

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