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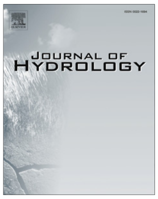

Impact of spatial and temporal resolution of rainfall inputs on urban hydrodynamic modelling outputs: A multi-catchment investigation

Susana Ochoa-Rodriguez [a,*], Li-Pen Wang [b], Auguste Gires [c], Rui Daniel Pina [a], Ricardo Reinoso-Rondinel [d], Guendalina Bruni [e], Abdellah Ichiba [c,f], Santiago Gaitan [e], Elena Cristiano [e], Johan van Assel [g], Stefan Kroll [g], Damian Murlà-Tuyls [b], Bruno Tisserand [h], Daniel Schertzer [c], Ioulia Tchiguirinskaia [c], Christian Onof [a], Patrick Willems [b], Marie-Claire ten Veldhuis [e]

[a] *Urban Water Research Group, Department of Civil and Environmental Engineering, Imperial College London, Skempton Building, London SW7 2AZ, UK*
[b] *Hydraulics Laboratory, KU Leuven, 3001 Heverlee (Leuven), Belgium*
[c] *Université Paris-Est, École des Ponts ParisTech, LEESU, 6-8 Av Blaise Pascal Cité Descartes, Marne-la-Vallée, 77455 Cx2, France*
[d] *Department of Geoscience and Remote Sensing, Faculty of Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands*
[e] *Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands*
[f] *Conseil Général du Val-de-Marne, Direction des Services de l'Environnement et de l'Assainissement (DSEA), Bonneuil-sur-Marne, 94381, France*
[g] *Aquafin NV, Dijkstraat 8, 2630 Aartselaar, Belgium*
[h] *Veolia Environment Research and Innovation, Chemin de la Digue, BP 76, 78603 Maisons Laffitte Cedex, France*

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SUMMARY

Urban catchments are typically characterised by high spatial variability and fast runoff processes resulting in short response times. Hydrological analysis of such catchments requires high resolution precipitation and catchment information to properly represent catchment response. This study investigated the impact of rainfall input resolution on the outputs of detailed hydrodynamic models of seven urban catchments in North-West Europe. The aim was to identify critical rainfall resolutions for urban catchments to properly characterise catchment response. Nine storm events measured by a dual-polarimetric X-band weather radar, located in the Cabauw Experimental Site for Atmospheric Research (CESAR) of the Netherlands, were selected for analysis. Based on the original radar estimates, at 100 m and 1 min resolutions, 15 different combinations of coarser spatial and temporal resolutions, up to 3000 m and 10 min, were generated. These estimates were then applied to the operational semi-distributed hydrodynamic models of the urban catchments, all of which have similar size (between 3 and 8 km^2), but different morphological, hydrological and hydraulic characteristics. When doing so, methodologies for standardising model outputs and making results comparable were implemented. Results were analysed in the light of storm and catchment characteristics. Three main features were observed in the results: (1) the impact of rainfall input resolution decreases rapidly as catchment drainage area increases; (2) in general, variations in temporal resolution of rainfall inputs affect hydrodynamic modelling results more strongly than variations in spatial resolution; (3) there is a strong interaction between the spatial and temporal resolution of rainfall input estimates. Based upon these results, methods to quantify the impact of rainfall input resolution as a function of catchment size and spatial–temporal characteristics of storms are proposed and discussed.

1. Introduction

The impact of spatial–temporal variability of rainfall on catchment response and the sensitivity of hydrological models to the spatial–temporal resolution of rainfall inputs have been active topics of research over the last few decades (e.g. Singh, 1997; Berndtsson and Niemczynowicz, 1988; Lobligeois et al., 2014). Several studies have shown that the spatial–temporal variability of rainfall fields can translate into large variations in flows; as a result, it is necessary to account for this variability in order to

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* Corresponding author. Tel.: +44 (0)20 7594 6018.
E-mail addresses: s.ochoa-rodriguez@imperial.ac.uk (S. Ochoa-Rodriguez), Lipen.Wang@bwk.kuleuven.be (L.-P. Wang), auguste.gires@leesu.enpc.fr (A. Gires), r.pina13@imperial.ac.uk (R.D. Pina), r.r.reinosorondinel@tudelft.nl (R. Reinoso-Rondinel), G.Bruni@tudelft.nl (G. Bruni), abdellah.ichiba@leesu.enpc.fr (A. Ichiba), S.Gaitan@tudelft.nl (S. Gaitan), E.Cristiano@tudelft.nl (E. Cristiano), johan.vanassel@aquafin.be (J. van Assel), stefan.kroll@aquafin.be (S. Kroll), Damian.MurlaTuyls@bwk.kuleuven.be (D. Murlà-Tuyls), bruno.tisserand@veoliaeau.fr (B. Tisserand), Daniel.Schertzer@enpc.fr (D. Schertzer), ioulia.tchiguirinskaia@enpc.fr (I. Tchiguirinskaia), c.onof@imperial.ac.uk (C. Onof), Patrick.Willems@bwk.kuleuven.be (P. Willems), j.a.e.tenveldhuis@tudelft.nl (M.-C. ten Veldhuis).

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properly characterise hydrological response (Tabios and Salas, 1985; Berndtsson and Niemczynowicz, 1988; Krajewski et al., 1991; Obled et al., 1994; Singh, 1997; Chaubey et al., 1999; Arnaud et al., 2002; Syed et al., 2003; Smith et al., 2004; Kavetski et al., 2006). This is particularly the case in small urban catchments, which are characterised by fast runoff processes and short response times, and are therefore very sensitive to the spatial and temporal variability of precipitation (this variability was found to be significant even at the small scales of urban catchments (Emmanuel et al., 2012; Gires et al., 2014b)). In order to well represent urban runoff processes, high resolution precipitation information is therefore needed (Schilling, 1991; Faurès et al., 1995; Shah et al., 1996; Aronica and Cannarozzo, 2000; Einfalt, 2005; Tetzlaff and Uhlenbrook, 2005; Segond et al., 2007; Vieux and Imgarten, 2012; Schellart et al., 2012). This need has been further fuelled by recent developments in, and increasing use of, higher-resolution urban hydrological models (e.g. Fewtrell et al., 2011; Giangola-Murzyn et al., 2012; Pina et al., 2014), which allow incorporation of detailed rainfall, surface and runoff information. With regards to rainfall monitoring, significant progress has been made over the last few decades, including widespread increase in the use of weather radar rainfall estimates, generally provided by national meteorological services at 1 km/5–10 min resolutions. Multiple studies have been conducted in recent years aimed at analysing urban hydrological/hydraulic model sensitivity to the spatial–temporal resolution of rainfall inputs and at establishing required rainfall input resolutions for urban hydrological applications. However, there is not as yet a consensus on these topics.

A theoretical study undertaken by Schilling (1991) suggested that, for urban drainage modelling, rainfall data of at least 1–5 min and 1 km resolutions should be used. Another study undertaken by Fabry et al. (1994) suggested that finer resolution data (i.e. 1–5 min in time and 100–500 m in space) are required for urban hydrological applications. This however may vary according to the application (Einfalt et al., 2004; Einfalt, 2005); for detailed sewer system simulation, for example, it is believed that the spatial–temporal resolutions suggested in Fabry et al. (1994) are essential.

Berne et al. (2004) analysed the relation between catchment size and minimum required spatial and temporal resolutions or rainfall measurements in a study involving very high resolution precipitation data ($\sim$7.5 m/4 s) and runoff records from six urban catchments on the French Mediterranean coast (but not models were used). Their study suggests that for small urban catchments, of the order of 3 ha, $\sim$1.5 km/1 min resolution, rainfall estimates are recommended, whereas for larger catchments, of the order of 500 ha, $\sim$3 km/5 min estimates may suffice. Slightly more stringent resolution requirements were identified by Notaro et al. (2013): using high spatial–temporal resolution rain gauge records as input to the semi-distributed urban drainage model of a 700 ha urban catchment in Italy, the authors investigated the uncertainty in runoff estimates resulting from coarser resolution rainfall inputs and concluded that temporal resolutions below 5 min and spatial resolutions of $\sim$1.7 km are generally required for urban hydrological applications.

Using a semi-distributed urban drainage model of a small urban catchment in London, and stochastically-downscaled rainfall estimates, Gires et al. (2012) and Wang et al. (2012) showed that the unmeasured small-scale rainfall variability, i.e. occurring below the typically available resolutions of 1 km in space and 5 min in time, may have a significant impact on simulated flows, with the impact decreasing as the drainage area of interest increases. A similar study was undertaken by Gires et al. (2014a), but this time using a fully-distributed model of a small catchment in Paris; similar results were obtained, but the fully-distributed model displayed higher sensitivity to the resolution of rainfall inputs.

More recently, Bruni et al. (2015) analysed the relationship between spatial and temporal resolution of rainfall input, storm and catchment scales, urban hydrodynamic model properties and modelling outputs. This was done using high resolution (100 m/1 min) rainfall data provided by polarimetric weather radar and a semi-distributed urban drainage model of a subcatchment in Rotterdam, the Netherlands. They showed that for a densely built, highly impervious urban catchment, modelling outputs are sensitive to high resolution rainfall variability and that deviations in model outputs significantly increase as rainfall inputs are aggregated to coarser scales, particularly at very small drainage areas (<1 ha).

As can be seen, few studies have analysed measured spatial–temporal variability of rainfall at the 1 min and 100 m scales and those which have not always involved hydrological/hydraulic models and/or are limited to single catchment studies. Hence, evidence to prove the added value of higher resolution rainfall estimates and to provide an answer about actual resolution requirements for urban hydrological applications is still insufficient. With the purpose of providing additional evidence in this direction, the present study investigates the impact of rainfall input variability for a range of spatial and temporal resolutions on the hydrodynamic modelling outputs of seven urban catchments located in each of the partner countries of the European Interreg RainGain project (http://www.raingain.eu/) (i.e. UK, France, Netherlands and Belgium). Rainfall estimates of nine storm events were derived from a polarimetric X-band radar located in Cabauw (The Netherlands). The original radar estimates, at 100 m and 1 min resolutions, were aggregated to spatial resolutions of 500, 1000 and 3000 m, and were sampled at temporal resolutions of 1, 3, 5 and 10 min. These estimates were then applied to high-resolution semi-distributed hydrodynamic models of the seven urban catchments, all of which have similar size (between 3 and 8 km^2), but different morphological, land use and model structure characteristics. Within the catchments, outputs were analysed at different nodes along the main flow path to investigate the effect of drainage areas of different sizes. Methodologies for standardising rainfall inputs and hydrological outputs were implemented to make results comparable. The impact of varying spatial–temporal resolutions of rainfall input on hydrodynamic model outputs was analysed in the light of storm and catchment characteristics. Based upon these results, current research needs and future work are discussed.

The paper is organised as follows. In Section 2, the pilot catchments, hydrodynamic models and radar-rainfall datasets are introduced. Methodologies for selecting relevant spatial–temporal resolution combinations and characterising spatial–temporal characteristics of the nine storms events are explained in Section 3, as well as methodologies used for feeding the rainfall inputs into the hydrodynamic models of the pilot catchments and for extracting and analysing the hydrodynamic modelling results. Results are presented and discussed in Section 4, followed by conclusions and recommendations in Section 5.

2. Pilot catchments and datasets

2.1. Pilot urban catchments

Seven urban catchments, located in four North-West European countries, were adopted as pilot locations in this study. With the aim of facilitating inter-comparison of results, catchment areas of similar size (3–8 km^2) were selected for testing. The main characteristics of the selected pilot catchments are summarised in Table 1. Moreover, images of the boundaries and sewer layouts of all pilot catchment can be found in Fig. 1. More detailed