The need for high resolution data to improve urban flood risk assessment

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Abstract

Cities are particularly vulnerable to rainfall-generated floods that are typically characterised by their rapid onset and localised nature. This implies that precipitation and catchment information need to be available at high resolution to reliably predict hydrological response and potential flooding. On the contrary, urban areas constitute a major knowledge gap as most flood risk studies have concentrated on natural basins and records of rain gauges and water level gauges in cities are scarce. While increase in intense precipitation as a result of climate change is expected in many areas around the world, it is at present not possible to assess how this will affect urban pluvial flood risk. Collection of reliable, high resolution data in cities needs to start urgently to build up datasets in support of urban flood risk assessment and to enable detection of changes in flood risk whether these are induced by climate change, urbanisation or other future developments. This study shows how implementation of polarimetric X-band radar can contribute to filling the knowledge gap of flood risk quantification in cities.

1 Introduction

Cities are particularly sensitive to flooding induced by short-duration, high-intensity precipitation, due to their high degree of imperviousness, resulting in fast runoff processes and lack of available water storage. Moreover, the high density of population and economic assets in urban areas results in high vulnerability to flooding. Ongoing urbanisation and urban densification further contribute to exacerbating flood vulnerability, thus increasing urban pluvial flood risk.

Based on climate models, increases in the frequency and intensity of heavy precipitation are projected for the 21st century in several regions of the world. It is "likely that the frequency of heavy precipitation will increase in the 21st century, particularly in the case of high latitudes and tropical regions and in winter in the northern mid-latitudes" (Kundzewicz, 2014). Increase in heavy precipitation could in turn be expected to contribute to increases in precipitation-generated flood risk; however, insufficient evidence is currently available on both flood frequency and magnitudes as well as on flood losses to assess climate-driven changes (Kundzewicz, 2014). Urban areas in particular represent a major knowledge gap, since most flood risk studies refer to "natural" basins and records of rain gauges and water level gauges in cities are scarce and essentially insufficient to represent the fine-scale urban hydro-meteorological variability (Schellart et al., 2012, Jensen and Pedersen, 2005).

The focus of this paper is on risks associated with urban, rainfall-generated flooding. It introduces new approaches and technologies to characterise high resolution temporal and spatial characteristics of rainfall, hydrological response and flood vulnerability in urban catchments. Information on these characteristics is crucial to be able to reliably quantify urban flood risk. This is in turn a first requirement to be able to build up the datasets required to assess potential changes in rainfall-generated flood risk in cities. The final challenge will be to identify drivers from the complex interactions of rainfall, urban development, concentration of asset value and development of man-made drainage infrastructure in cities.

High resolution data at urban scales

The spatial-temporal characteristics of urban catchments and stormwater drainage systems are generally small, often of the order of 1-10 km^2 and a few minutes, respectively (Arnbjerg-Nielsen et al., 2013; Ochoa-Rodriguez et al., submitted). Cities typically display high spatial variability in land-use, small catchment areas and a high degree of imperviousness. Stormwater drainage systems are predominantly man-made and consist of complex networks of channel and pipe networks. For the hazard component of flood risk assessment this implies that precipitation information needs to be available at high resolution to reliably predict hydrological response and potential flooding. With respect to flood vulnerability, cities typically comprise a high concentration of assets (infrastructure, buildings), economic value and, most importantly, people. Unlike river and coastal flooding, potential locations of rainfall-generated flooding are not concentrated along line-elements like coasts of river banks, as localised storms can occur anywhere in a catchment. Moreover, artificial drainage networks can lead to redistribution of flows, away from natural drainage paths. Not only the position and capacity of drainage systems is important, also their condition needs to be known, as man-made drainage systems in cities (especially underground sewer pipes) are sensitive to blockage and flow disruption which can induce localised floods in areas that would not normally be susceptible to flooding (ten Veldhuis et al., 2009).

For the damage component of flood risk assessment, collection of damage data associated with urban pluvial flooding is complicated by the fact that in cities damage is borne by a wide range of individual property owners, industries as well as governmental authorities. Insurance databases constitute a valuable source of damage information, albeit difficult to access due to privacy issues and data quality (Spekkers et al., 2014). Kundzewicz at al. (2014) show that globally about 9% of flood damage in the period 2001-2011 was insured, which implies that dedicated methods for damage data collection need to be found to obtain comprehensive insight into urban pluvial flood damage. Reports of localised flooding and damage reports need to be collected in a structured way over long periods of time before changes in urban flood risk can be assessed and drivers of changes can be identified.

In summary, analysis of rainfall-generated flooding in cities requires high resolution data in space and time of precipitation intensities, catchment characteristics, hydrological response, vulnerability and historical flood damage. This will support quantification of current urban pluvial flood risk and will constitute a starting point for building up time series of high resolution rainfall intensities, occurrence of flood events and flood damage which will enable detection of changes to date and forecasting of future changes in urban pluvial flood risk.

The EU-funded RainGain project set out to collect reliable, high resolution precipitation data in four cities in North-West-Europe, based on innovative technology: state-of-the-art dual-polarimetric weather radars for retrieval or rainfall information. Ten pilot sites were selected in the four cities based on availability of recent topographic datasets and detailed hydrodynamic models representing the drainage networks and drainage area characteristics. Through collaboration with local authorities holding operational knowledge of the urban drainage networks and historical flood events, valuable information for flood risk assessment was generated. In this paper, we will present findings of a recent study in which high resolution precipitation datasets derived from a dual-polarimetric X-band radar were used to examine hydrological response patterns in seven of the 10 pilot catchments. We will build upon these findings and ongoing work of the RainGain project to identify some critical requirements for data collection in support of urban flood risk analysis and detection of changes in flood risk characteristics. We will also outline some approaches and methodologies to meet such requirements.

2 Methods and dataset

2.1 Urban catchment characteristics

Seven urban catchments, located at each of the four RainGain partner 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 catchments can be found in Figure 1. More detailed information on each of these catchments is available on the RainGain project website: http://www.raingain.eu/en/actualite/learn-more-about-ten-locations-where-raingain-solutions-will-be-implemented. As can be seen, the selected pilot catchments cover a wide range of morphological, topographic and land use conditions.

2.2 Precipitation dataset: dual-polarimetric X-band radar

One of the aims of the RainGain project is to obtain high resolution precipitation estimates in cities. To this end, four different radar-rain gauges configurations are set up for precipitation estimation in Leuven, London, Paris and Rotterdam (figure 2). Configurations vary from a single polarisation radar and a network of rain gauges for ground truthing in Leuven, providing rainfall estimates at 125x125m^2 and 1 minute resolution. In London, pilot sites are within coverage of 2 radars of the national C-band radar network, equipped and being upgraded to dual-polarisation, where super-resolution protocols are applied, i.e. by adjusting signal pulse length, to obtain high resolution precipitation estimates. In Paris and in Rotterdam, new dual polarisation X-band radars were installed, a pulse radar and a Frequency-Modulated Continuous Wave (FMCW) radar, respectively. All sites are equipped with a network of rain gauges; additionally, disdrometers are installed in Paris and Rotterdam.

While radar rainfall products are under development in the four pilot cities, high resolution data were obtained for this study from a polarimetric radar located in Cabauw, the Netherlands (Leijnse et al., 2010). Data were derived for nine storms in the period 2011-2014 and were used to conduct analyses of the space-time scales of storm cells and study hydrological modelling response at a range of space-time resolutions.

The estimated spatial and temporal characteristics of the nine storm events are summarised in table 2. For information on the method applied for estimating space-time scales of the storms we refer to Ochoa-Rodrigues et al. (submitted). Mean velocity of the nine storms varies from 6.4 m/s to 19.3 m/s (34 to 69 km/h) and storm ranges vary from 1700 to 4660 m. The combination of storm velocity and storm range, together with catchment dimensions, determines the time during which the storm core passes through a given catchment. For the storms and catchments considered in this study, this time varied between ~2-12 min. Moreover, based upon the estimated spatial and temporal characteristics of the storms, and making use of communication theory concepts (Shannon, 1948), the minimum required space-time resolutions for precipitation sampling were computed for the nine storms under consideration. This resulted in required precipitation sampling resolution varying between ~1 minute and ~6 minutes and spatial resolution varying from ~700m to ~2000m. This implies that the typical resolutions of rainfall estimates provided by national radar networks (i.e. 5 min, 1000 m) matches required space-time resolution for only four out of the nine storms under consideration. It should be noted that within the spatial scale of the storm core, high intensity storm cells can still be detected (see for instance figure 3). Given the small size of drainage areas in the urban catchments, down to below the 100 m scale, such cells can still be potential triggers for localised flooding, in cases where local drainage capacity is limited.

2.3 Hydrological response: sensitivity to space-time resolution

In order to investigate the sensitivity of urban drainage models to the spatial-temporal resolution of rainfall inputs, the high-resolution precipitation data for the nine (9) storm events, initially at 100 m and 1 min, were aggregated to a number of coarser temporal and spatial resolutions (up to 3000 m and 10 min) and were applied as input to the urban drainage models of the seven (7) pilot catchments. Results were analysed at different drainage areas of varying sizes (~ 1 ha to ~ 800 ha) within each pilot catchment. Some of the main findings of the hydrological response analysis are summarised in this paper; for an in-depth analysis please refer to Ochoa-Rodriquez et al. (submitted).

The results showed that hydrodynamic response behaviour in urban catchments is highly sensitive to combinations of temporal and spatial resolutions of rainfall input: resolution combinations that do not properly reflect storm dynamics lead to large deviations in hydrodynamic model outcomes. For the storms investigated in this study, hydrodynamic response behaviour was more sensitive to temporal than to spatial resolution. Temporal resolution coarsening beyond the estimated required resolution (between 2 and 6 min) led to under- and overestimations of flow peaks by up to 100% with respect to the original 100 m, 1 minute rainfall input. Similarly, it resulted in low explained variance (down to 20% explained variance, median value, at the level of the entire hydrograph) and flow underestimation at the level of the entire hydrograph (figure 4, illustration of results for 1 catchment, 1 storm). Spatial resolution coarsening led to underestimation of hydrographs for spatial scales between 500 m and 1 km for drainage areas of 1 to 100 ha. A special feature observed in the analysis is the strong interaction between the spatial and temporal resolution of rainfall estimates: the two resolutions must be consistent with each other to prevent loss of information from the higher resolution (more detail in Ochoa-Rodriguez et al., submitted).

3 Implications for urban pluvial flood risk analysis

Analysis of critical space-time scales based on high resolution (100 m in space, 1 minute in time) rainfall data obtained from dual-polarimetric X-band radar suggested that, for the nine investigated storms, sampling frequency for rainfall measurement should be at least of the order of ~700m to ~2000m in space and ~1 minute to ~6 minutes in time to capture most of the space-time variability. Still higher space-time resolutions are needed to fully reproduce rainfall variability. Urban hydrological response proved to be highly sensitive to space-time resolution of rainfall input: large deviations in flow peak and hydrograph volumes were found for coarser rainfall input resolutions, especially for small drainage basins of 1 to 100 ha, typical of urban neighbourhoods.

For flood risk analysis, this implies that rainfall as well as catchment data need to be available at the same high resolutions to be able to explain damage-generating processes, to predict and prevent flood risk. If flood risk analysis is conducted based on lower resolution data, large uncertainties occur in hydrological response prediction and in the assessment of expected flood frequencies and magnitude. Moreover, damage-generating mechanisms cannot be well understood at the coarser level of data resolution (see for instance Spekkers et al, 2014), resulting in highly unreliable flood risk predictions.

Detecting changes in urban flood risk will not be possible at the current state of knowledge and data availability. Flood risk generating mechanisms, frequency, vulnerability and damage are too poorly understood to conduct reliable flood risk assessment even in the current situation. First, high resolution, reliable datasets need to be set up to properly understand damage generating mechanisms for urban rainfall-generated floods and to obtain time series of hazard (rainfall), vulnerability (catchment) and damage. Once such datasets have been built up, time series analyses can be conducted, aiming at detecting changes and their underlying mechanisms, whether climate change, urbanisation, ageing infrastructures or other.

Polarimetric X-band radar has proved to provide valuable, high resolution information in support of hydrological response analysis in urban areas, a first crucial step in urban flood risk assessment.

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Table 1. Summary characteristics of pilot urban catchments

	Cran-brook	**Torquay**	**Morée-Sausset**	**Sucy-en-Brie**	**Herent**	**Ghent**	**Kralin-gen**
Area [ha]	865.2	570.03	560.4	269	511.5	649.33	670
Catchment length and width [km]*	6.1/1.4	5.4/1.1	5.3/1.1	4.0/0.7	8.2/0.6	4.7/1.4	2.1/3.2
Catchment shape factor [-]	0.23	0.2	0.2	0.17	0.08	0.29	1.49
Slope [m/m]***	0.0093	0.0262	0.0029	0.0062	0.0083	0.0001	0.0003
Main flow direction [deg]	239	270	198	138	40	235	152
Type of drainage system	Mostly separate, branched	Mostly combined, branched	Mostly separate, branched	Separate, branched	Mostly combined, branched	Mostly combined, branched	Mostly combined, looped
Is flow mainly driven by gravity?	Yes	Yes	Yes	Yes	Yes	Yes	No
Control elements	3 storage lakes	3 storage tanks, 1 pumping station	2 storage tanks	1 storage basin, 1 pumping station	5 main CSO's with control	15 pumping stations	20 pumping stations
IMP (%)****	52%	26%	37%	34%	27%	41%	48%
Predominant land-use	R&C	R&C	R&C	R&C	R	R	R&C
Population density [pp/ha]	47	60	70	95	20	24	154

*Length = Length of longest flow path (through sewers) to catchment outfall; Width = Catchment Area / Catchment Length;

**Shape factor = Width / Length (this parameter is lower for elongated catchments)

***Catchment slope = Difference in ground elevation between upstream most point and outlet / catchment length

****IMP: total proportion of impervious areas in relation to total catchment area

Table 2: Estimated spatial and temporal characteristics and required resolutions of the storm events under consideration

Storm event ID	Spatial Range [m]	Mean Velocity [m/s]	Anisotropic Coefficient	Required Spatial Resolution [m]	Required Temporal Resolution [min]
E1	4056.69	9.76	0.38	1694.77	5.79
E2	3524.76	9.91	0.38	1472.54	4.95
E3	4655.10	14.04	0.55	1944.77	4.62
E4	3218.91	11.71	0.34	1344.77	3.83
E5	2061.98	14.11	0.59	861.43	2.03
E6	3737.52	11.68	0.26	1561.43	4.46
E7	1702.93	13.95	0.24	711.43	1.70
E8	3644.43	18.40	0.36	1522.54	2.76
E9	2354.53	16.97	0.08	983.66	1.93

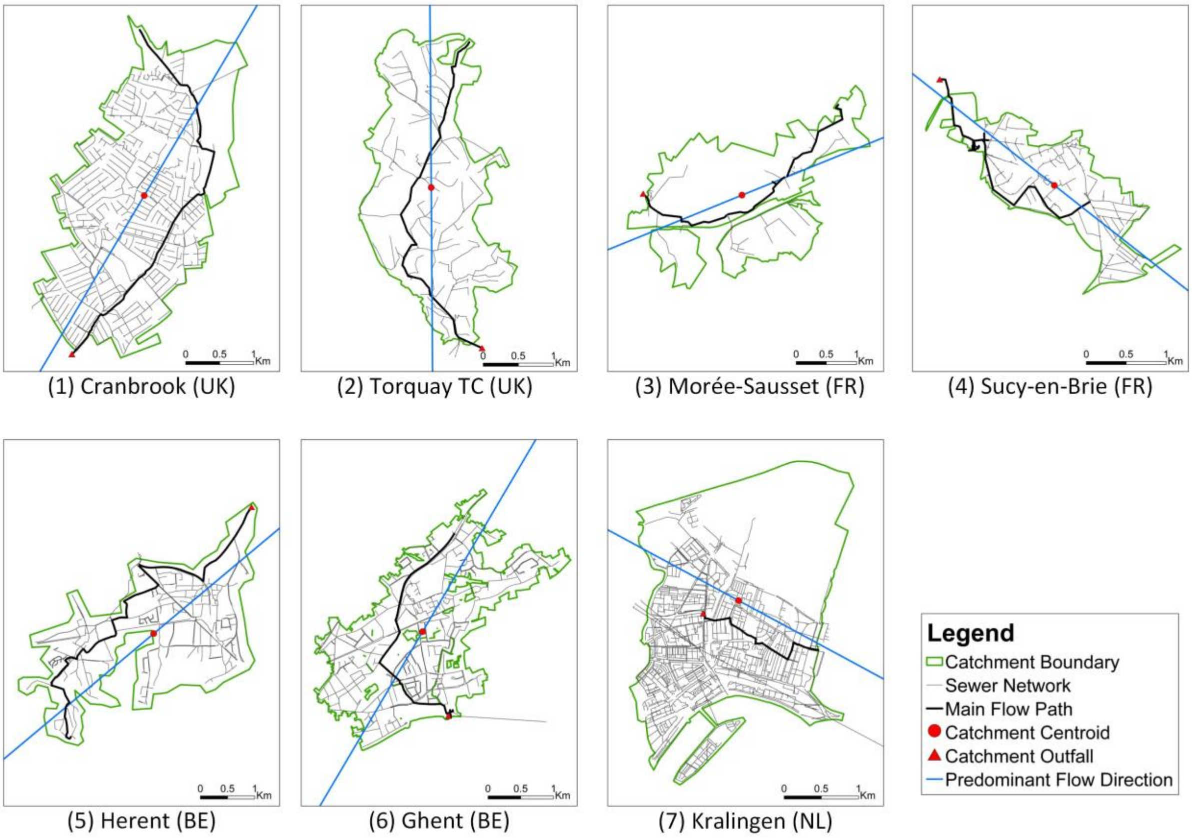

Figure 1. Catchment boundary and sewer layout for the pilot urban catchments

Figure 2. Radars implemented at the pilots sites of RainGain (from left to right): X-band single pol radar implemented in Leuven, Chenies C-band radar of the UK national network, dual-pol X-band radar installed in Paris, dual-pol X-band radar to be installed in Rotterdam.

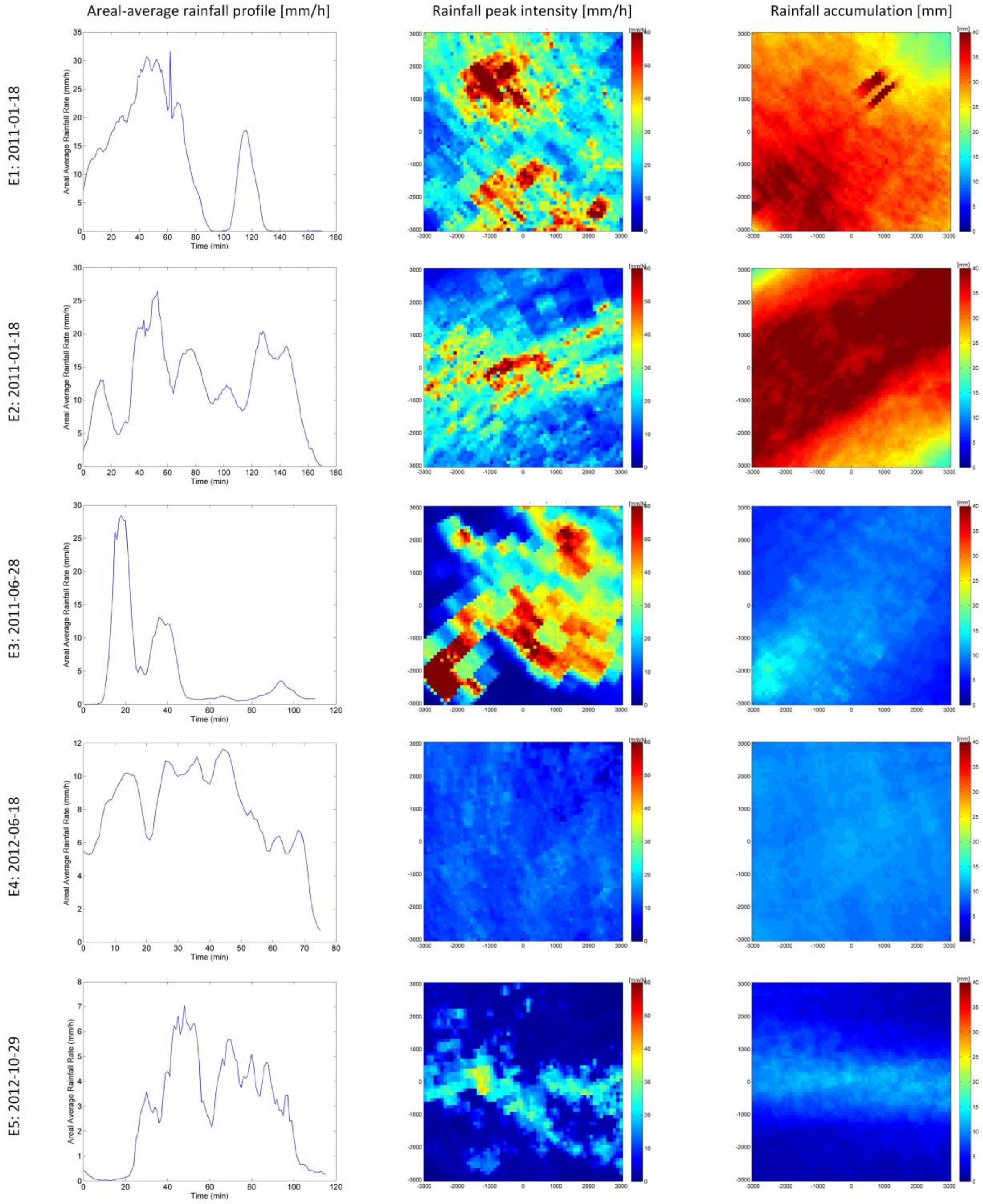

Figure 3. Areal average storm profile (left column), snapshot image during the peak intensity period of the storm (middle column) and total event accumulations for the storm events under consideration.

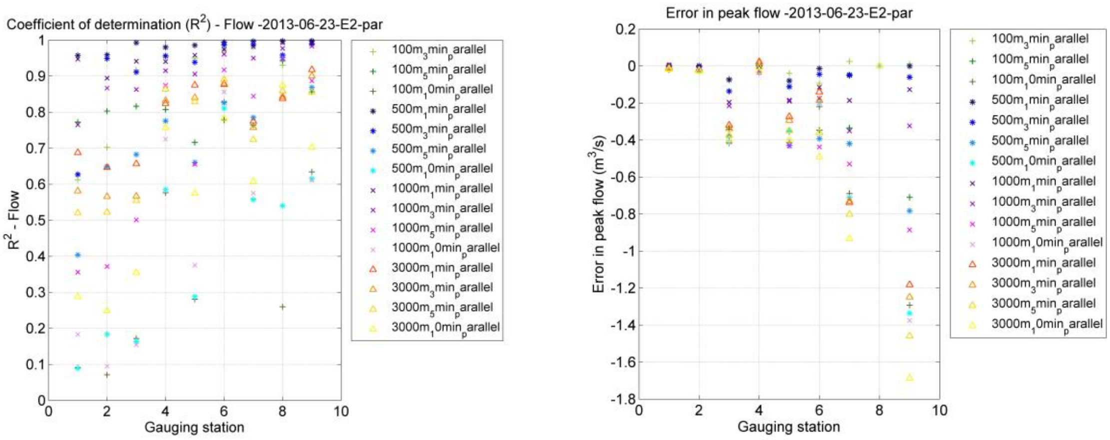

Figure 4. Example of hydrological response characteristics for 1 storm event, 1 catchment, 16 resolution combinations. Coefficient of determination and absolute error in peak flow are plotted for nine gauging stations corresponding with drainage area size increasing from ~1 ha to ~ 800 ha. The original input resolution of 100 m, 1 minute resolution is taken as a reference.