High Resolution Radar Rainfall for Urban Pluvial Flood Control

Lessons Learnt From Ten Pilots in North-West Europe Within the RainGain Project

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ABSTRACT

Precipitation and catchment information need to be available at high resolution to reliably predict hydrological response and potential flooding in urban catchments. Due to recent advances in weather radar technology and DTM availability for urban flood modelling, the question arises whether these are sufficient to provide reliable predictions for urban pluvial flood control. The RainGain project (EU-Interreg IVB NWE) brings together radar technologists and hydrologists to explore a variety of rainfall sensors, rainfall data processing techniques and hydrodynamic models for the purpose of fine-scale prediction of urban hydrodynamic response. High resolution rainfall and hydrodynamic modelling techniques were implemented at ten different pilot locations under real-life conditions. In this article, the pilot locations, configurations of rainfall sensors (including X-Band and C-Band radars, rain gauges and disdrometers) and modelling approaches used in the RainGain project were introduced. Initial results presented the hydrodynamic modelling using high resolution precipitation inputs from dual-polarisation X-band radar, followed by a discussion of differences in hydrodynamic response behaviour between the pilots.

KEYWORDS

Radar rainfall, urban hydrology, urban flood modelling

INTRODUCTION

Urban catchments are characterised by high spatial variability, fast runoff processes and short response times. This implies that precipitation and catchment information needs to be available at high resolution to reliably predict urban hydrological processes (Aronica & Cannarozzo, 2000; Einfalt, 2005; Segond et al., 2007). Several studies have shown that despite recent advances in the use of weather radar, the resolution of the currently available rainfall estimates (typically 1 x 1 km^2 in space and 5 min in time) may still be too coarse to match the spatial-temporal scales of urban catchments (Fabry et al., 1994; Gires et al., 2012a). In this regard and in the light of recent developments, new questions arise, such as: what rainfall resolution is needed for different urban applications? How do rainfall data resolution and data reliability interrelate? What reliability can be delivered by different configurations of radar and rain gauges in cities? What modelling approaches are best suited to obtain reliable results in terms of water level and flood predictions? How sensitive are hydrodynamic models to rainfall spatial variability? What is the influence of catchment variability? With the aim of answering some of these questions, the RainGain project (EU-Interreg IVB NWE) has set to explore the use of a variety of rainfall sensors (including X-Band and C-Band radars, rain gauges and disdrometers), to develop and test a number of rainfall data processing techniques and to test the response of hydrodynamic models with different characteristics to varying rainfall inputs. In addition, the needs of the stakeholders involved in flood risk management are assessed and ways of using high resolution rainfall and hydrodynamic model outputs for improving flood risk management are explored.

In this paper, the main characteristics of the 10 pilot locations adopted within the RainGain project are presented. Initial experiences and results are presented with respect to implementation of high resolution radars in urban settings and to application of resolution precipitation estimation in hydrodynamic modelling at different catchments.

EXPERIMENTAL SITES – 10 PILOT LOCATIONS

Ten experimental sites have been implemented within the RainGain project; pilot sites have been selected so as to represent a range of varying urban catchment characteristics and different types of pluvial flooding problems. Characteristics of the pilot sites are summarised in table 1. Most of the sites are highly urbanised and vary in size from about 1.4 to 34 km^2. Half of the sites are fairly flat, the other half are characterised by a combination of plateaus and steep slopes along river banks. Some of the sites are located in urban polders, without natural drainage outlets; in these areas stormwater needs to be locally stored and evacuated through pumps. Applied model software includes semi-distributed and fully distributed modelling approaches, one-dimensional and two-dimensional overland flow modules.

Table 1. General characteristics of pilot urban catchments

Pilot site	Catchment size [km^2]	General catchment characteristics	General characteristics of drainage system	Modelling approach and software
Cranbrook catchment (London Borough of Redbridge)	8.65	Highly urbanised, mildly sloping, coincidental fluvial and pluvial flooding	Mostly separate, main brook has been culverted	Semi distributed, dual drainage (both 1D-1D and 1D-2D models; rainfall applied through subcatchments), InfoWorks CS-2D
Purley Area (London Borough of Croydon)	6.5	Highly urbanised, great density of receptors, slopes drain to natural depression	Mostly separate, combination of natural drainage channels, culverted river and sewers	Semi distributed, sewer system only, simplified modelling of exceedance flow .InfoWorks CS-2D
Torquay Town Centre (Devon Borough of Torbay)	14.5	Coastal city, steep slopes drain to natural depression, flooding worsened by high tides.	Combined sewer system; two CSO’s, discharging into Torquay Harbour under storm conditions.	Semi distributed, 1D 2D dual drainage (with rainfall applied through subcatchments). InfoWorks CS-2D
Morée Sausset, incl. Kodak subcatchment (Seine-Saint-Denis, Paris region)	34 Kodak: 1.44	Highly urbanised, rather flat. Several retention basins for flood control.	Mostly separate, main brook has been culverted, several storm water retention basins	Semi-distributed, sewer system only, simplified exceedance flow (Canoe) Kodak: Fully distributed, 1D 2D dual drainage

				(rainfall applied directly on 2D model of surface) Multi-Hydro
Jouy en Josas (Seine-Saint-Denis, Paris region)	2.5	Combination of residential and green areas. River bank, steep slopes (100m elevation difference) and plateau.	Mostly separate, several storm water retention basins	Fully distributed, 1D-2D dual drainage: Multi-Hydro
Sucy en Brie (Val de Marne, Paris region)	2.69	Residential and industrial use. River bank, steep slopes (32 m elevation difference) and plateau.	Mostly separate, new retention basin (interest on RT control of it)	Current semi-distributed (Canoe). New: fully distributed, 1D 2D dual drainage: Multi-Hydro
Herent (Leuven, northern part)	4.75	Densely built village centres and rural areas; fairly flat.	Mostly combined sewer system, CSOs discharging to two local rivers running through the city	Current semi- distributed. New: semi distributed, 1D 2D dual-drainage (rainfall applied through subcatchments). InfoWorks ICM
Kralingen-(Rotterdam)	6.70	Residential and industrial use, flat polder area	Combined, looped system; CSOs discharging to local channels, sewer pumps evacuate water from urban polder	Semi-distributed, simplified modelling of exceedance flow (Sobek Urban)
Spaanse Polder (Rotterdam)	1.9	Industrial area, densely urbanised, flat polder area	Combined, looped; CSOs discharging to local channels, sewer pumps evacuate water from urban polder	Semi-distributed, simplified modelling of exceedance flow (Sobek Urban)
Centrum district (Rotterdam)	3.7	Residential and commercial area, 2 urban parks, flat polder area	Combined, looped; CSOs discharging to local channels, sewer pumps evacuate water from urban polder	Semi-distributed, simplified modelling of exceedance flow (Sobek Urban)

HIGH RESOLUTION PRECIPITATION DATASETS

Four different radar-rain gauges configurations are used for precipitation estimation in Leuven, London, Paris and Rotterdam (figure 1). In Leuven, a single polarisation radar has been operational since 2008 providing rainfall estimates at $125x125m^2$ and 1 minute resolution. Original data processing algorithms are adjusted under the project, in order to improve the quality of radar rainfall estimates. Pilot sites in London are within coverage of 2 radars of the national C-band radar network, equipped and being upgraded to dual-polarisation. Experiments are being conducted for improving resolution of the radar rainfall estimates by adjusting signal pulse length and shortening the repetition cycle. In addition, a short testing of a single polarisation X-band radar was carried out in London between May and October 2014. In Paris and in Rotterdam, new, dual polarisation X-band radars are 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.

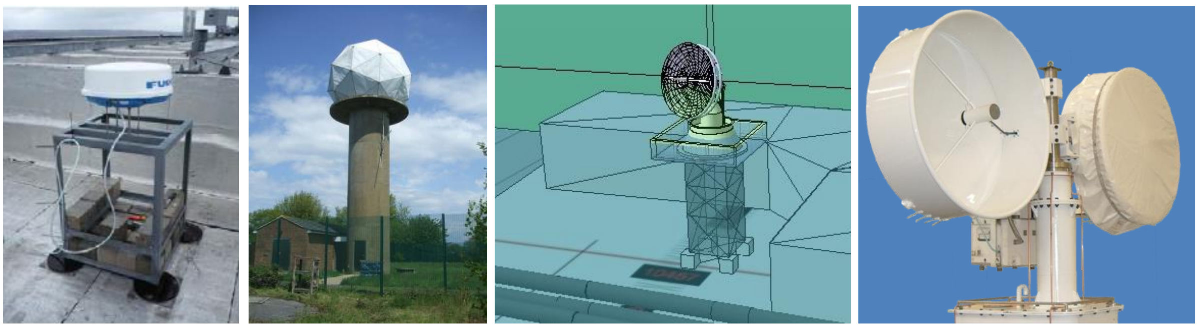


Figure 1. Radar implemented at the pilots sites of RainGain (from left to right): X-band single pol radar implemented in Leuven, Chenies C-band radar of the UK national network, impression of dual-pol X-band radar under construction in Paris, dual-pol X-band radar to be installed in Rotterdam.

Implementation of radar in densely urbanised environments, experiences

Through the installation of X-band radars at heart of the highly urbanised RainGain pilot locations, many lessons have been learned. Weather radars used for high resolution precipitation estimation are preferably installed within a city area, above the urban canopy. This generally means installation on existing high-rise, in agreement with constraints set by building owner, architect, signal emission standards and other radar applications, especially near airports. Clutter correction is especially important in urban areas due to the relatively frequent presence of objects and other signals compared to a rural setting.

Radar signal correction for single polarisation radar to obtain quantitative precipitation estimates has proven complicated and the added value compared to rain gauge networks has found to be small in several cases (e.g. Goormans and Willems, 2013; Shrestha et al., 2013; Ochoa-Rodriguez et al. 2014). Additional Doppler and dual-polarisation measurements provide valuable information to improve reliability of precipitation estimates (Van de Beek et al., 2010; Otto and Russchenberg, 2013). Another important aspect that the project is investigating is the effect of wind drift on rainfall patterns. High resolution precipitation estimates are more sensitive to this effect, which plays an important role in urban areas due to their highly variable microclimate induced by urban structures.

Rainfall data downscaling

The availability of rainfall data at different spatio-temporal resolutions in the RainGain project provide the opportunity to compare characteristics of downscaled rainfall data from C-band weather radar networks to high resolution rainfall data from X-band radar. One of the downscaling processes implemented within the RainGain project relies on Universal Multifractals which have been extensively used to characterize and simulate geophysical fields extremely variable over wide range of scales such as rainfall (see Schertzer and Lovejoy 2011 for a recent review). In this framework rainfall is expected to be generated through a scale invariant cascade process. This framework is very convenient for downscaling (Biaou et al., 2003), which can be done by first assessing the relevant features of the underlying cascade process on the available range of scales and second continuing the cascade process beyond the observation scale. See Gires et al. (2014) for a validation with networks if point measurement devices deployed over 1 km^2 areas and Gires et al. (2012) for applications in urban hydrology.

HIGH RESOLUTION MODELLING APPROACHES

Initial results of modelling studies conducted at the pilot sites in the RainGain projects, are summarised in this paper. Modelling results of rainfall input from X-band radar are presented for different pilot sites as well as results of a comparison between fully and semi-distributed approaches. For more details on modelling results, the authors refer to relevant papers.

The modelling approaches adopted at each pilot site are as summarised in table 1. Semi-distributed models have been current practice at most locations. Semi-distributed one-dimensional sewer and two-dimensional overland flow models are tested at 4 pilot sites. Two types of overland flow models are tested; a fast, one-dimensional model for real-time prediction and a detailed, two-dimensional model aiming at accurate water level predictions. A fully distributed model, Multi-Hydro, is being tested at 3, potentially 4 sites. This model is under development at Ecole des Ponts ParisTech, see also Giangola et al., 2012). The model includes a 2-dimensional model representing surface runoff, infiltration and overland flow, as well as a one-dimensional sewer model which interacts with the surface model through connecting elements such as manholes or gullies. Fully distributed hydrologic models are based on a gridded input structure that can be directly adjusted to the spatial resolution of rainfall input. In semi-distributed models, rainfall input values are routed through subcatchments of varying size and shape, with a lumped representation of hydrological run-off processes.

High resolution rainfall from X-band radar: hydrodynamic modelling results at four pilot catchments

Two storm events, one convective and one stratiform, measured by a polarimetric X-band radar located in Cabauw (The Netherlands) were used as input into semi-distributed models at four pilot locations of similar size (between 5 and 8 km2; more catchments characteristics in table 2), the Cranbrook catchment (UK), the Herent catchment (Belgium), the Morée Sausset catchment (France) and the Kralingen District (The Netherlands). Storm events were applied in such a way that: (1) the centroid of the selected rainfall area coincides with the centroid of each catchment, and (2) storm direction is approximately perpendicular to the main flow direction at each catchment (in order to avoid variations in response due to differences in relative storm/flow direction (Singh, 1997)). For each of the model runs the simulated flow and water depth time series at the downstream end of three pipes located in the upstream, mid-stream and downstream sections of the catchments were selected for analysis (see table 3). The looped nature of the Dutch catchment and the fact that flows may change direction throughout a storm event make it difficult to determine an exact area drained by a given pipe.

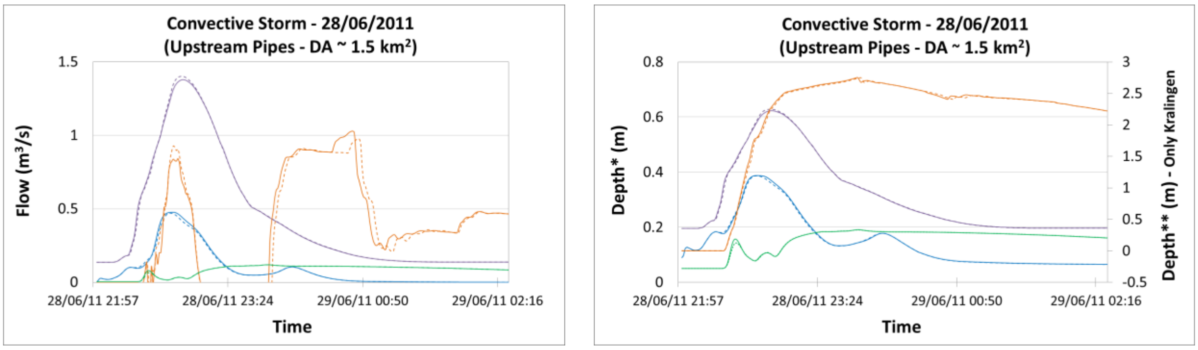
Table 2. Summary catchment characteristics of 4 pilot catchments used for high resolution hydrodynamic modelling

Pilot site	Catchment size [km^2]	Catchment length* and width** [km]	Catchment shape factor*** [-]	Catchment slope**** [m/m]	Imperviousness (%)
Cranbrook, UK	8.65	6.10/1.42	0.23	0.0093	66
Morée-Sausset, FR	5.60	5.28/1.06	0.20	0.0029	37
Herent, BE	4.75	8.16/0.58	0.07	0.0220	18
Kralingen, NL	6.70	2.12/3.16	1.49	0.0003	48

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

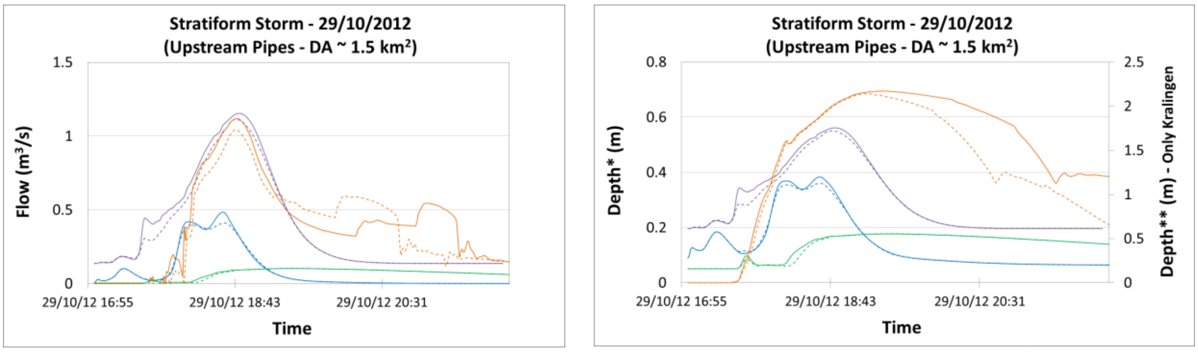
****Shape factor = Width / Length (this parameter is lower for elongated catchments)
****Catchment slope=Difference in ground elevation between upstream most point and outlet / catchment length

Figure 2 shows response hydrographs and depth time series for the two storm events, at the upstream pipes selected for analysis at each pilot catchment. The results show that the catchments respond quite differently to the convective storm event precipitation. The Cranbrook and Moree-Sausset catchments' hydrographs have a well-defined single response peak, while the Kralingen hydrograph has multiple peaks and the Herent hydrograph has a quick response peak followed by very slow increase and decrease of the flow. The atypical response behaviour of the Herent and Kralingen catchments can be explained by their specific features: the Herent catchment is equipped with a throttle device in the main sewer transport line to maximise in-sewer storage. This strongly delays the flow upstream and smooths the flow peak. The Kralingen catchment is located in a polder area where in the absence of natural flow directions, sewer networks tend to be strongly looped. As a result, the overall behaviour of the catchments is determined by a filling process of in-sewer storage, as evidenced by a fast rise in water depth leading to surcharged pipes. During the filling process, flow directions can change, as flow first moves towards a pumping station, then, once pumping capacity is exceeded, moves towards combined sewer overflows. Hydrological response of the four catchments shows similar behaviour for the stratiform storm event (not shown here). Response characteristics were also investigated for different rainfall spatial resolutions (100m and 1000m), for a discussion of these results we refer to ten Veldhuis et al. (2014).



(a) Flow hydrographs – Convective storm

(b) Depth time series – Convective storm



(c) Flow hydrographs – Stratiform storm

(d) Depth time series – Stratiform storm

Figure 2: Response hydrographs and water depths at the downstream end of the upstream pipes selected for analysis at each pilot location (with drainage area (DA) ~ 1.5 km^2). The solid lines correspond to the 100 m resolution outputs and the dashed lines to the 1000 m ones. * Water depth scale used for the depths observed in the Cranbrook (UK), Morée-Sausset (FR) and Herent

(BE) pilot locations; **Water depth scale used for the depths observed in the Kralingen (NL) pilot location. In order to avoid distortion, a different y-axis was used for the water depths observed in Kralingen, as these were significantly higher than the ones observed at other locations.

Table 3 provides a summary of the measures which characterise the overall hydrological/hydraulic response of the catchments to rainfall. The results show that characteristic total flow volumes and peak values vary strongly between pilot sites. These variations are mainly explained by different settings in the rainfall-runoff model, especially runoff coefficients applied for impervious areas have an important influence.

Table 3: Response variables of each pilot catchment for each storm event. Characteristic runoff volume (total volume / drainage area) and characteristic peak flow (peak flow / drainage area) values are provided for the three pipe locations selected at each pilot catchment (Upstream/Mid-stream/Downstream)

Pilot site	**Model location***	**Drainage area [km^2]**	**Convective Storm – 28/06/11**			**Stratiform Storm – 29/10/12**		
			Vchar [m3/m2]	**Qchar [m3/m2/s]**	**Tc [min]**	**Vchar [m3/m2]**	**Qchar [m3/m2/s]**	**Tc [min]**
Cranbrook, UK	US	1.65	0.86	0.29	45	0.017	0.29	49
	MS	3.24	0.89	0.27	45	0.015	0.21	49
	DS	5.67	0.91	0.25	45	0.013	0.17	49
Morée-Sausset, FR	US	1.99	3.55	1.4	48	3.5	0.6	52
	MS	3.83	3.88	3.0	48	3.5	0.6	52
	DS	5.60	3.59	3.7	48	2.8	0.5	52
Herent, BE	US	1.51	1.19	0.08	307	1.0	0.07	292
	MS	3.80	1.36	0.04	307	1.4	0.04	292
	DS	4.75	1.31	0.1	307	1.1	0.06	292
Kralingen, NL	US	1.30	7.05	0.79	213	0.11	0.86	169
	MD	3.10	6.71	0.76	213	0.08	0.52	169

Semi-distributed versus fully distributed modelling: sensitivity to small-scale rainfall variability

The uncertainty associated with small scale rainfall variability on urban catchments was assessed through the analysis of the sensitivity to rainfall resolution of hydrologic/hydraulic models. Two models were tested on the same 1.44 km2 Kodak catchment (see Table 1); the fully distributed Multi-Hydro model (grid with 10 m pixels) (Giangola et al. 2012) and the semi-distributed Canoe model (sub-catchments with size ranging from 4 to 16 ha) (Allison et al. 2005) . Only a brief summary of this study is reported here, and more details can be found in Gires et al. (2013). The methodology implemented consists in first generating an ensemble of downscaled rainfall fields with the help of discrete Universal. The raw data is the available Météo-France radar mosaic whose resolution is 1 km in space and 5 min in time, and the final resolution is 12.3 m and 18.75 s for the Multi-Hydro model and 111 m and 1.25 min for the Canoe model (given the size of the sub-catchments it was not relevant to further downscale the data). Then each realisation of the downscaled rainfall field is inputted into the models. Finally the variability among the obtained hydrographs is analysed. To achieve this for each time step the 95, 75, 25 and 5% quantile are estimated. This enables to compute the envelop curves (Q0.1, Q0.25 Q0.75 and Q0.9) corresponding to their temporal evolution. Figure 3 displays these curves along with Qradar (flow simulated with raw radar data) at the outlet of the catchment for the February 2009 event (total depth 8.3 mm). The observed uncertainty reflects a significant impact of small scale rainfall variability on simulated discharge. The uncertainty increases with upstream conduits. Furthermore it appears that the uncertainty revealed by the fully distributed model is much greater. It means the semi-distributed model would not be able to fully benefit from improved rainfall data.

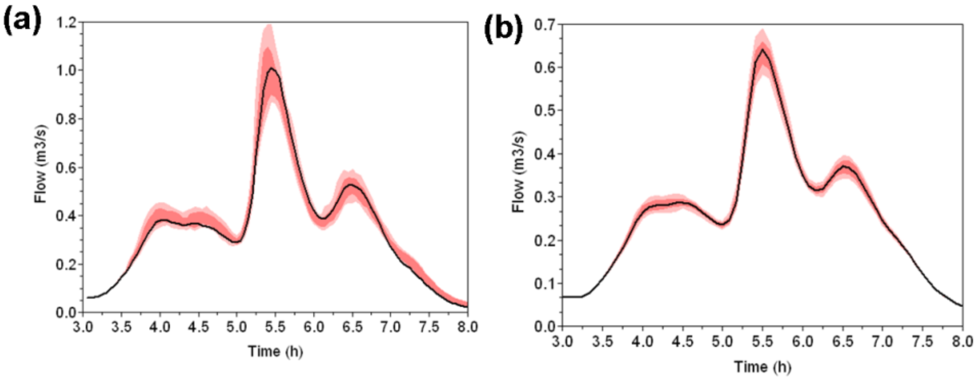


Figure 3. Simulated flow with the raw radar data (black), Q0.25 and Q0.75 (dark colour), Q0.1 and Q0.9 (light colour) for the outlet of the Kodak catchment. (a) Multi-Hydro 10 m, 2009 event; (b) 1D model, 2009 event; (adapted from Gires et al., 2013)

CONCLUSIONS

These first results suggest that model settings, catchment and drainage infrastructure characteristics have a strong influence on hydrological response. Differences in catchment slope and drainage infrastructures have shown to result in entirely different response behaviors. Also, semi-distributed models seem not to be able to fully benefit from high resolution rainfall input data. Further studies into the impact of rainfall input resolution in relation to catchment characteristics, hydrological input data and model features will be conducted to gain more insights into these interactions.

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