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Influence of rainfall estimation error and spatial variability on sewer flow prediction at a small urban scale

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ABSTRACT

Legislative drivers for water quality and urban flood risk are driving a growing need to accurately determine the performance of urban drainage systems in near real time. Rainfall data are clearly a key input to urban drainage system models. Historically rain gauge data have been used, however radar rainfall data are now widely available and benefits from significantly higher spatial coverage than rain gauges in most UK urban catchments. This paper describes a detailed study based on a small (11 km^2) urban catchment in West Yorkshire, England. Radar and rain gauge data have been compared and used as the input to hydrodynamic sewer flow simulations, and the results of these simulations have been compared with measured flows in the sewer system. The results showed that for this size of catchment, there can be significant differences in simulated peak flows and combined sewer overflow spill volumes due to inherent uncertainties between the two rainfall estimates.

1. Introduction

There is a growing need to accurately determine the performance of urban drainage systems both in terms of water quality and urban flood risk. Within the EU this is largely driven by the Water Framework Directive [1] and the Floods Directive [2], whilst in the UK specific consideration has to be given to the Flood and Water Management Act [3]. To better understand the response of drainage systems to rainfall there is considerable interest in the use of rainfall data recorded by radar. This is especially so when attempts are made to predict the future performance of systems [4–7]. As described by Einfalt et al. [4], urban catchments are usually relatively small when compared to upland and river basin catchments. Thus, in response to rainfall, the reaction speed of urban catchments is faster and the reaction threshold is lower when compared to a rural catchment. This is primarily due to significantly lower natural retention (e.g. interception by vegetation) and much larger areas of impervious surfaces within the urban area. Hence the application of weather radar to the urban area requires that the rainfall data are of high frequency and high spatial resolution [4,8–10]. The use of weather radar systems may be considered advantageous over the use of traditional rain gauges, as they provide spatial rainfall data over an entire region compared to the sparse multiple single point measurements that are usually available from rain gauges.

Radar and rain gauges are fundamentally different types of measurement system and thus have different error characteristics. Potential problems and error sources in tipping bucket rain gauge data, including blockages, wetting and evaporation, high rain rates, wind effects, position and shelter, are described in [11]. The estimation of random errors in tipping bucket rain gauge measurements are described in [12], where errors in the region of 16% were found at rain rates around 10 mm/h at the 5 min time scale. Relative standard errors of 6.4% for rainfall intensities of 10 mm/h at the 5 min time scale were reported by Habib et al. [13].

There are also numerous sources of potential error in radar data, although as described by Krajewski et al. [14], over the past 30 years gradual improvements have been made in the estimation of rainfall from radar data. An extensive overview of error sources in single polarization radar-based estimates of rainfall was reported by Villarini and Krajewski [15] with shorter summaries provided by Einfalt et al. [4] and Harrison et al. [16] and an illustrated summary in [17]. The rainfall estimation and error removal techniques used by the UK Met Office prior to the provision of operational weather radar rainfall data are described in [16,18,19]. A full discussion of error sources is outside the scope of this paper, although a brief discussion of the most common error sources in radar rainfall data follows. Spurious echoes can occur in the radar reflections, for example clutter from buildings, trees or hills blocking the signal. Refraction of the radar beam occurs as the beam passes through layers of air with varying density; when a low level temperature inversion exists the radar beam can be bent towards the ground resulting in strong echoes being returned, described as anomalous

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propagation. The radar reflectivity (Z) has to be translated to a rainfall rate (R), the 'Z-R' relationship, which is an empirical relationship dependent on the drop size distribution (DSD) of the rainfall. A large number of references on this topic are included in [15]. The radar beam sweeps at a number of elevation angles, resulting in measurements at different heights, depending on the distance from the radar. This height dependency can result in features such as bright band (high reflectivity caused by melting snowflakes), orographic enhancement (growth of precipitation at low levels over hills), or beam overshooting (whereby the radar beam overshoots the rainfall at distances further away from the radar). Attenuation of the radar signal occurs when the radar signal gets absorbed by high intensity rainfall, which leads to underestimation of any radar echoes from beyond the heavy rainfall event. Attenuation mainly affects radars with shorter wavelengths, such as C-band and X-band radars. Furthermore, systematic errors can occur as a result of hardware calibration, as well as almost random spatial and temporal uncertainties linked to rainfall drift.

Finally there can be sampling uncertainties in both radar and rain gauge measurements, depending on the space and time scales considered, due to spatial and temporal representativeness errors as described in [20,21].

Some radar rainfall estimation errors can be more pronounced when using high spatial and temporal frequency data that is necessary for urban applications. It was shown in [22] that, for a given time resolution, there is an optimum spatial resolution which minimizes errors. The effects of the drift of rainfall between the height of the radar beam and ground level are described in [23]. It was concluded that the use of resolutions higher than 1 km demanded that wind drift should be taken into account. Radar data are generally calibrated by reference to rain gauge data. However, as described by Tilford et al. [24] and Jessen et al. [25], rain gauge adjustment does not always improve the radar data and, in instances where rainfall is highly spatially varied, the use of a limited number of rain gauge measurements may be unrepresentative of a wider area. A number of studies have compared radar data with a dense network of rain gauge data [26] found that a rain gauge was only better at estimating the 2 km grid square rainfall if the gauge was located within 3–4 km of the grid square centre. Localised spatial variability of rainfall within a single 500 m rainfall radar grid square from X-band local area weather radar was studied by Jensen and Pedersen [27], by installing 9 rain gauges within the pixel. It was shown that the total rainfall depth could vary by a factor of two. Temporal and spatial scales of rainfall over urban catchments have been studied by Berne et al. [10], in order to better understand the rainfall resolutions required for urban hydrological applications. A number of studies have investigated the effects of errors and uncertainties from rainfall measurement methods on flow simulations. Much of this work has studied flows from relatively large urban river catchments [18,28–30].

Only a limited number of studies have quantitatively investigated how the spatial and temporal variability of rainfall and the use of different rainfall measurement techniques can affect the simulation of urban runoff in relatively small scale urban drainage systems. A detailed analysis of the radar rainfall estimation and flood response for a number of flash flooding events in the drainage channels of two urbanised catchments of 9.1 km^2 and 14.3 km^2, respectively, including a sub-catchment of 1.6 km^2 is described by Smith et al. [31,32]. It was concluded that measurement errors in the small scale short duration rainfall estimate are a significant problem for flood peak estimates, and the dominant source of errors in flash flood forecasts. A detailed analysis of flooding events in an urban drainage basin was also carried out by Villarini et al. [33], who described how runoff production was characterised by a striking variability in runoff ratio both between different sub-catchment areas as well as between consecutive rainfall peaks during the same event. This was attributed to the large spatial heterogeneities typically found in densely urbanised areas and the poorly understood storage processes. They concluded that more accurate rainfall and discharge observations for extreme events in small urban watersheds were needed to advance understanding of these processes.

A comparison between radar and rain gauge data used to simulate rainfall runoff in an urban catchment of 3.6 km^2 drained solely to a sewer network is described in [34]. Three rain gauges were used within the catchment, and a further two rain gauges were located 3.5 and 6 km from the catchment, and the radar data had a 1 km spatial and 5 min temporal resolution. They concluded that radar should be used if the distance between rain gauge and catchment was larger than 4 km and where the density of rain gauges in the catchment was less than 1 per 16 km^2.

The aim of this paper is to examine the effects of the inherent uncertainty in rainfall estimates from rain gauges and radar rainfall at relatively small spatial and temporal scales on the simulation of sewer flows in an urban case study catchment located in West Yorkshire, England. It is hypothesised that, at the scale of the case study catchment, the differences between radar and rain gauge measurements can have a considerable impact on the simulation of flow peaks occurring within the sewer system. Eight recorded rainfall events have been selected for the study. Following this introduction the paper has been divided into four further sections: Section 2 describes the case study catchment and data collected, Section 3 describes the hydraulic model, Section 4 presents the results, analysis and discussion and Section 5 describes the conclusions.

2. Study area and available data

The case study area is a town in the north of England with a population of approximately 13,000 and a catchment area of approximately 11 km^2. The catchment contains a main town and several villages that drain to the sewer system. The main town lies on the side of a hill and the catchment is steep, while the villages lie in the valley bottom. The sewer network is predominantly combined; flows from the surrounding villages are pumped to the treatment works. Fig. 1 shows the sewer network, the main town lies in the centre, the largest village to the west and smaller villages to the east.

The study area has been the subject of a flow survey, which included 16 flow monitors (combining depth and velocity measurements) and 7 depth monitors within the sewer system. The monitors were clustered around key features such as combined sewer overflows and pump stations; data were recorded at a 2 min resolution. Four tipping bucket rain gauges have been installed and are sited to maximise spatial coverage over the catchment; the rain gauges log the time of each tip of the bucket,

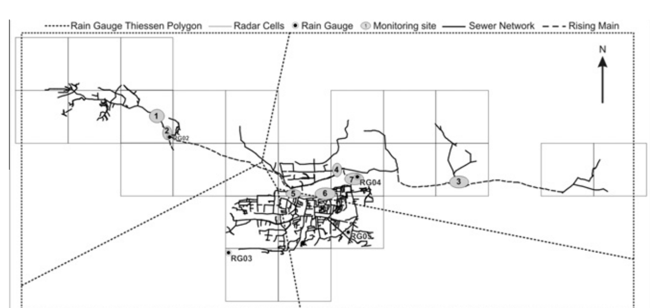

Fig. 1. Layout of sewerage network showing monitoring sites, radar cells and Thiessen polygons for rain gauges.

which represents a rainfall depth of 0.2 mm. The tip data were processed by the flow survey contractor using a standard algorithm to convert the number and time of bucket tips into rainfall intensity at a time resolution of 2 min. All of the monitors were visited by the flow survey contractor on a monthly basis when the data were downloaded and, when necessary, the monitors were cleaned and batteries and faulty components replaced. The data were then checked by the contractor, data errors (for example debris clogging a tipping bucket rain gauge) were flagged in the report and values zeroed. The authors carried out additional checks on the consistency of the data between monitors. The data were generally found to be good and data that were found to be of poor quality have not been used further.

Fig. 1 shows the radar rainfall coverage used in the study, which consists of 25 radar pixels each of 1 km^2, located above the sewered area. The Nimrod rainfall product, purchased from the UK Met Office, is a composite of data from the network of C-band radars at 5 min time resolution; the nearest radar in the network is located 30 km from the catchment. The data have been pre-processed by the 'Nimrod' system [16,18,19].

3. Data analysis and modelling methodology

3.1. Urban rainfall runoff and sewer flow model description

A commercial hydrodynamic sewer network modelling package (InfoWorks CS v8.0) was used to model the rainfall runoff from the urban area as well as the flow through the sewer system. The modelled network includes the main pipes within the system, modelled as 'links'. Flows are generated within sub-catchments in terms of domestic and industrial wastewater flows as well as rainfall runoff from pervious and impervious areas and input to the links at 'nodes' (which represent gullies and manholes). The InfoWorks CS software incorporates a mixture of runoff volume and runoff routing models, the New UK Percentage Runoff model [35] was used for calculating the runoff volume from large pervious areas and the Wallingford model [36] or a fixed percentage runoff model was adopted for impervious and small pervious areas. The Double Linear Reservoir (Wallingford) model [37] was used for runoff routing. The St Venant equations are used to calculate the flows through the sewer system. The case study catchment and sewer system have been modelled using 432 nodes, 444 links, 13 pumps and 134 sub-catchments. The total length of the sewers modelled is 60 km and the sub-catchment areas range between 0.1 and 300 hectares. The sewer system is relatively steep: 15% of the modelled pipes have a gradient between 0.1 and 0.25 m/m, 57% have a gradient between 0.01 and 0.1 m/m, and 28% have a gradient <0.01 m/m. The modelled sub-catchments have similar gradients, 8% being between 0.1 and 0.4 m/m, 61% are between 0.01 and 0.1 m/m, and 31% are <0.01 m/m. The total contributing area of the sub-catchments is 11.06 km^2, of which 0.71 km^2 is impermeable area within the town, 3.15 km^2 is pervious area within the town and 7.2 km^2 is pervious area representing the surrounding moorland which is responsible for delayed runoff response.

3.2. Model verification and simulation set-up

The hydrodynamic sewer flow model was verified in 2003, using guidelines developed by the UK water industry [38]. The guidelines specify that the model should be verified against measurements of depth, velocity and flow in the sewer for one dry weather day and three storm events. Storm events used in the verification should meet criteria for minimum depth, for minimum intensity and have low spatial variability (in terms of total depth, peak intensity and timing of rainfall peaks); the events should also meet criteria for minimum flow depths and velocities in the sewer as well as causing key ancillary structures (e.g. CSOs) to operate. The guidelines for a model to pass verification include matching the measured peak flow rates within +25% and −15%, the volume of flows within +20% and −10% and the timing of the peaks and troughs to be 'similar having regard to the duration of the event'.

The wet weather performance of the model used in this paper was verified using three storm events with mean recorded rainfall depths of 11.6, 35.0 and 9.8 mm and peak intensities of 14.4, 9.6 and 6.0 mm/h respectively based on data from five tipping bucket rain gauges. As radar rainfall has a greater number of measurement points and there are fundamental differences in the measurement technique, the model has been re-verified using both rain gauge and radar rainfall data from three events in 2007 which satisfied the water industry criteria [38] as an input. Both radar rainfall and rain gauge based model results provide similar performance against the verification guidelines.

4. Results and discussion

Eight rainfall events which occurred between June 2007 and July 2008 have been selected to compare rain gauge and radar measurements and the effect of any differences on simulated flows. The event selection criteria were that the main Combined Sewer Overflow (CSO) had spilled and good data were available from most of the flow monitors.

4.1. Comparison of radar and rain gauge measurement

Tables 1 and 2 give an overview of the selected rainfall events, as recorded by the 25 radar pixels overlying the catchment and the 4 rain gauges (see Fig. 1). Table 1 compares the range of cumulative rainfall measured by these rain gauges and radar pixels, as well as the spatial variation of cumulative rainfall. The spatial variation of the rainfall has been expressed as a ratio of maximum/minimum cumulative rainfall recorded amongst the 4 rain gauges and 25 radar pixels respectively. Table 2 shows the range of peak intensi-

Table 1
Cumulative rainfall comparison for selected events.

	Event date and duration	Rain gauges – range of cum. rainfall (mm)	Radar pixels – range of cum. rainfall (mm)	Ratio (max/min) cum. rainfall	
				RG	Radar
A	25/06/07 00:30 – 14:35	41.6–47.0	36–46.7	1.1	1.3
B	3/7/07 01:00 – 04:40	15.0–18.0	17.1–25.1	1.2	1.5
C	5/07/07 – 6/07/07 15:15 – 05:35	19.2–37.6	18.2–24.4	2.0	1.3
D	21/09/07 03:15 – 12:30	22.2–24.4	16.5–18.9	1.1	1.1
E	9/10/07 03:00 – 09:00	15.0–15.0	15.0–18.8	1.0	1.3
F	21/01/08 00:30 – 20:55	42.8–46.4	45.5–54.6	1.1	1.2
G	1/07/08 19:00 – 21:10	4.0–6.0	5.6–41.7	1.5	7.4
H	7/07/08 10:15 – 17:00	8.6–12.2	7.5–16.8	1.5	2.2

Table 2
Peak rainfall intensity comparisons for selected events.

Event and period in which peaks occurred		Rain gauges – range of peak intensities (mm/h)	Radar pixels – range of peak intensities (mm/h)	Spatial variation peak intensities	
				RG	Radar
A	12:00–13:30	6.0–8.4	5.7–9.1	1.4	1.6
B	01:45–04:00	9.6–16.8	13.1–29.8	1.8	2.3
C	15:20–16:00	5.4–8.4	9.3–13.8	1.6	1.5
	18:15–19:00	3.5–8.3	1.3–3.1	2.4	2.5
	00:15–01:20	7.2–13.2	4.3–8.5	1.8	2.0
	03:25–04:10	14.4–26.4	8.8–31.7	1.8	3.6
D	10:00–11:00	9.6–10.8	6.5–19.0	1.1	2.9
E	05:00–05:45	6.6–8.4	7.1–13.3	1.3	1.9
	06:15–07:00	10.8–18.0	7.7–18.9	1.7	2.4
F	09:20–11:00	8.4–10.2	8.8–13.2	1.2	1.5
	11:45–12:15	10.8–18.0	7.1–20.7	1.7	2.9
	15:50–16:10	2.6–12.0	2.1–8.5	4.5	4.1
	17:45–18:15	6.0–9.6	9.7–40.4	1.6	4.2
G	20:00–20:15	7.2–15.6	7.6–286.8*	2.2	37.8
H	11:40–12:00	1.2–25.8	1.3–15.1	21.5	11.2
	13:30–13:45	1.7–7.9	1.6–15.4	4.6	9.5
	15:15–15:35	10.2–16.8	4.3–20.6	1.6	4.8
	16:40–16:55	0–25.2	0–41.6	n/a	n/a

* Suspected anomalous propagation.

ties measured by the rain gauges and radar pixels, and the spatial variation of the peak rainfall intensity. In order to enable direct comparison with the 5 min frequency radar data, the resolution of the rain gauge data has been decreased from 2 min to 5 min. This was done by calculating the cumulative rainfall depths from the given 2 min intensities, then interpolating the cumulative depths for the 5 min intervals before converting back to an intensity.

Table 1 shows that the spatial differences in cumulative rainfall for both rain gauges and radar pixels is generally between 10% and 30%, but is higher for events C, G and H which all occur during the summer. Table 2 shows considerable differences (up to several hundred percent) between peak intensities measured by individual rain gauges and radar pixels, highlighting the significance of short term spatial variations in rainfall intensity. The radar rainfall measurements generally show greater spatial variability in rainfall intensities than the rain gauge measurements, this can largely be attributed to the greater number of radar measurements and hence better spatial coverage of the radar data (25 'measurement locations' instead of 4).

Figs. 2 and 3 show the differences in rainfall intensity measured by the 4 rain gauges and their corresponding overlying 1 km^2 radar pixels, as well as the differences between areal averaged rain gauge and radar rainfall intensities, based on the 4 rain gauges and 25 radar pixels covering the area, as shown in Fig. 1.

Fig. 2 shows the comparison at 5 min time scale and Fig. 3 shows the comparison at 15 min time-scale (the data were converted from 5 min to 15 min resolution using the methodology described earlier in this sub-section). It is shown that there is a greater spread in the point rainfall intensities than the area averaged intensities, which illustrates the level of smoothing created by spatial averaging. The 15 min time scale comparison (Fig. 3) shows a further reduction in the spread of both point and areal average rainfall intensities. For all comparisons shown in Figs. 2 and 3, the difference between rain gauges and radar is larger for higher rainfall intensities.

To assess whether systematic bias exists between radar and rain gauge, the cumulative areal average radar and rain gauge rainfall have been plotted in Fig. 4, along with error bars showing the maximum and minimum cumulative rainfall. Fig. 4 indicates there is no systematic bias based on the 8 events studied. Furthermore, an analysis of the long term mean bias calculated as described in [26], between individual rain gauges and overlying radar pixels showed neither systematic bias nor clear seasonal variations in bias. Figs. 2 and 3 also indicate that it would be problematic to establish a single bias correction factor, as the differences between rainfall intensities measured by radar and rain gauge can vary considerably between events as well as during events.

4.2. Comparison of simulated and measured sewer flows

The implications of the differences in rainfall measurements on sewer flow simulations have been studied by comparing simulated flows using radar or rain gauge measurements against measured flows. Fig. 5 compares the simulated sewer flows based on radar and rain gauge measurements to the measured flow data from monitors producing good data throughout the event. The flow simulations have been created by inputting either radar or rain gauge data into the sewer network model, the storm flow is generated in the model based on the characteristics of sub-catchments. The radar pixel or rain gauge from which data are used is determined based on the location of the node, into which a sub-catchment drains, with respect to the Thiessen polygons (Fig. 1).

The flow simulations show an under prediction of measured flow rate especially for the largest events, A, B and F, irrespective of whether radar or rain gauge has been used as model input. Event G, the smallest event in terms of total rainfall depth, tends towards over-prediction. The tendency for the model to under-predict high flows is assumed to be due to the rainfall events used in the calibration having a smaller total amount of rainfall than most of the events included in this study.

Despite the simulation results showing a tendency towards under-prediction of flow rates, Fig. 5 indicates how differences between radar and rain gauge measurement translate into flow simulations. Considerable scatter is visible at the higher flow rates, especially for events B, C, D, E, G and H, indicating over – as well as under-prediction of the measured flow by as much as 100%. These observations indicate that for the case study catchment, local variations in radar and rain gauge measurements such as shown in Figs. 2 and 3, do translate into local variations in sewer flow peaks. At higher flow rates events C, D and G show a clear difference between radar and rain gauge input to the simulation. During event C the simulation using radar data under-predicts flows, whereas when rain gauge data are used flows are over-predicted, this can largely be attributed to rain gauge 5 recording more than twice as much rainfall as the radar. During event D the flow simulation using radar under-predicts the flow more than the rain gauge, clearly driven by the rain gauges recording more rainfall than the radar. During event G the simulation using radar data over-predicts flow, but Figs. 2 and 3 indicate variable bias between radar and rain gauges, with RG3 recording more rainfall than the overlying radar pixels and RG2 and RG4 recording less rainfall than their overlying radar pixels. Anomalous propagation [39] was suspected to occur in the most easterly pixel overlying the catchment where 286.8 mm/h rainfall was recorded by the radar at one time step. In this case it did not influence flow simulations as the pixel was located over a remote sub-catchment with a very small contributing area. If anomalous propagation had occurred over the centre of the catchment it would have caused an overestimation of simulated flow.

4.3. Implications for combined sewer overflow spill simulations

Although spills from the combined sewer have not been measured, the spill volumes predicted in the simulations are used to estimate impacts on water quality. Table 3 presents an overview

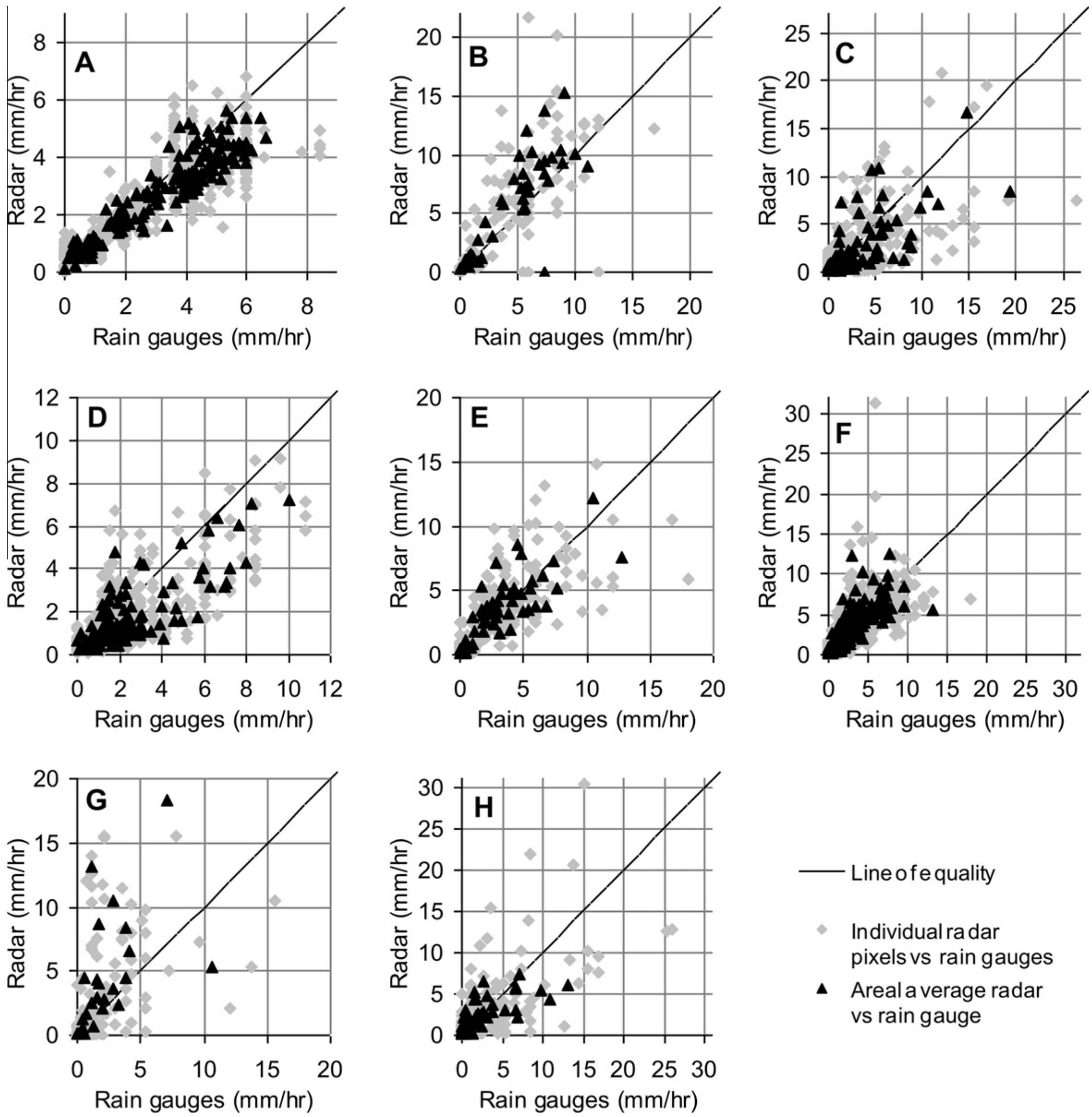

Fig. 2. Comparison of 5 min rainfall intensities from rain gauges and radar.

of the simulated CSO spill volumes from the main CSO in the study area for the three rainfall time scales investigated. The percentage differences between the modelled CSO spill volumes using radar and rain gauge data as input and between the time scales are also shown. The results for the 5 min time scale illustrate that there is a considerable difference in spill volume predicted, the differences between using rain gauge or radar as an input varying between ranging between −65% and +178%. This difference in spill volumes is a direct function of predicted peak flow rates, highlighting the importance of accurate prediction of peak flows. Events C and G show the largest differences, and it is these events where the scatter plots in Fig. 5 show the greatest differences. When the time scale of the input rainfall is changed to 15 min, the effect on spill volumes is relatively small, decreasing by up to 13% compared to the 5 min time scale. However, when the rainfall timescale is increased to 60 min, there is an almost universal decrease in the predicted spill volumes, the maximum being 77%. It can be seen that the differences in spill volume between the two measurement types are considerably larger than the differences caused by using a different time-scale, and stay consistently larger at all time scales.

4.4. Detailed radar image, rain gauge data and flow simulation comparisons and discussion

This section studies events G and H in further detail, which were selected because they show some of the largest differences in predicted flow between the use of rain gauge and radar rainfall data as input to the model. For a single monitoring location, the temporal differences between modelled and simulated flows are investigated; both the measurement technique and the time scale of the input rainfall data are compared.

4.4.1. Event G – 1st July 2008

The event on the 1st of July 2008 was a convective storm event, causing a relatively short combined sewer overflow spill. Fig. 6a shows the measured rainfall and both measured and modelled flow just upstream of the main CSO (FM015). A key notable feature of the spatially averaged rainfall data is that the radar has registered two peaks above 10 mm/h, whereas the rain gauges measured only one. The rainfall peak measured by the radar at 19:30, but not by the rain gauges, results in a corresponding extra peak in the flow prediction. However, the measured flow data do not

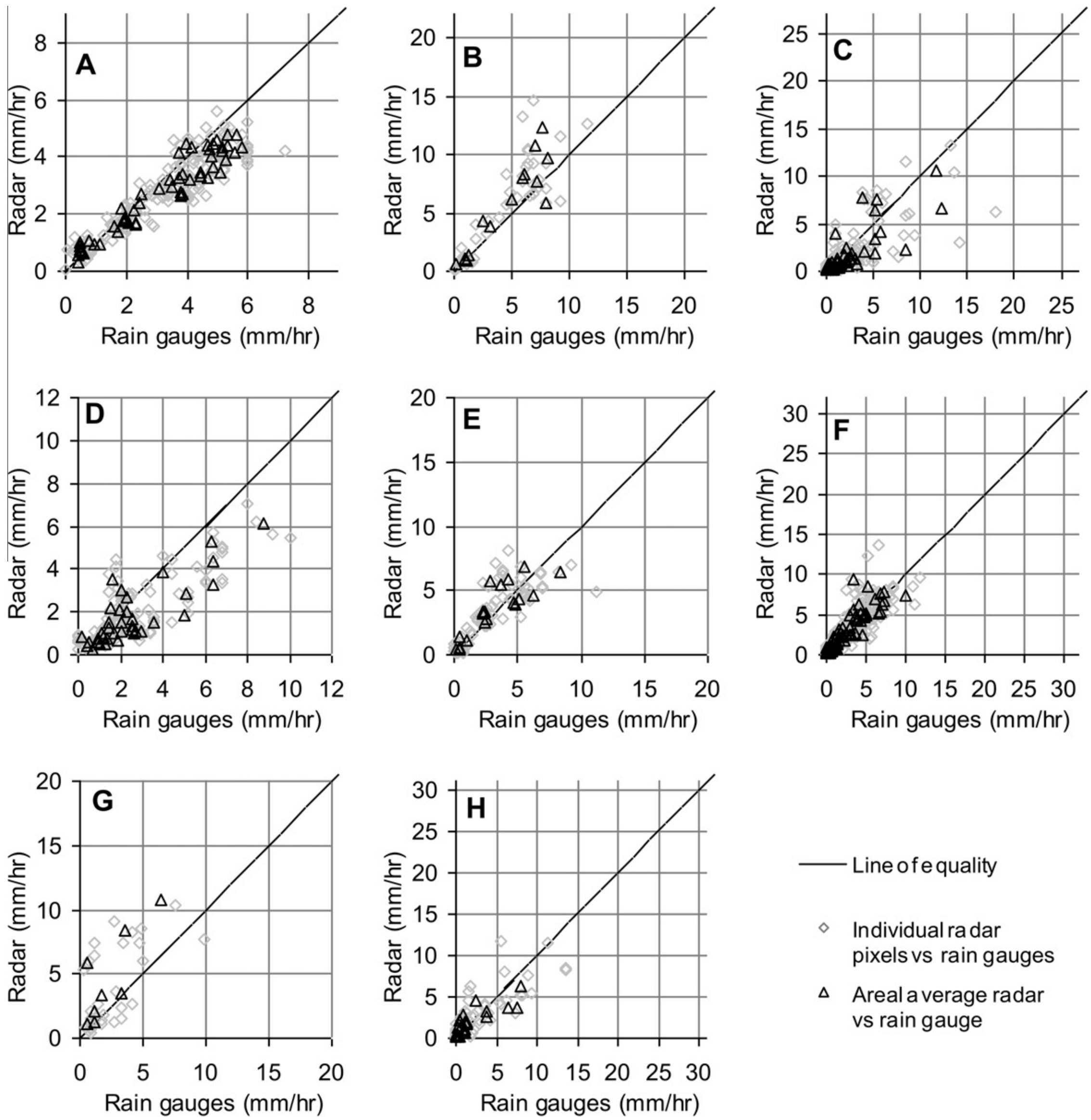

Fig. 3. Comparison of 15 min rainfall intensities from rain gauges and radar.

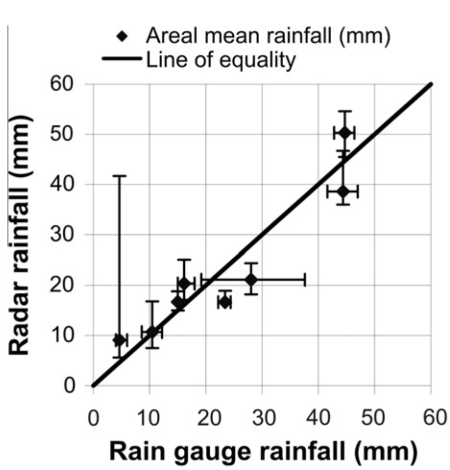

Fig. 4. Comparison of areal average event cumulative rainfall as recorded by rain gauges and radar pixels.

show a peak at this flow monitor. It was hypothesised that the cause of the extra rainfall peak registered by the radar was a combination of wind displacement of the rainfall between measurement and ground level and the high spatial variation of the rainfall, as described by Collier [23]. Due to the difficulty in estimating rain drop fall velocity [40] and a lack of high resolution wind data at different heights, the exact wind displacement could not be calculated to further investigate this hypothesis.

The rainfall peak seen in Fig. 6a, shortly after 20:00, was recorded by both radar and rain gauges, but the radar indicated a higher peak intensity, albeit for a shorter period. The radar images at 20:00 and 20:05 (Fig. 7) show rapidly changing spatially varied rainfall. The image at 20:00 shows three 1 km pixels with over 15 mm/h rainfall intensity, located between the rain gauges but not over the rain gauges. Although the exact location of where the rain from these three high intensity rainfall pixels lands is uncertain because of an unknown degree of wind displacement, this image illustrates how 4 rain gauges in a 11 km^2 catchment may not provide sufficient spatial coverage to adequately measure localised intense rainfall cells.

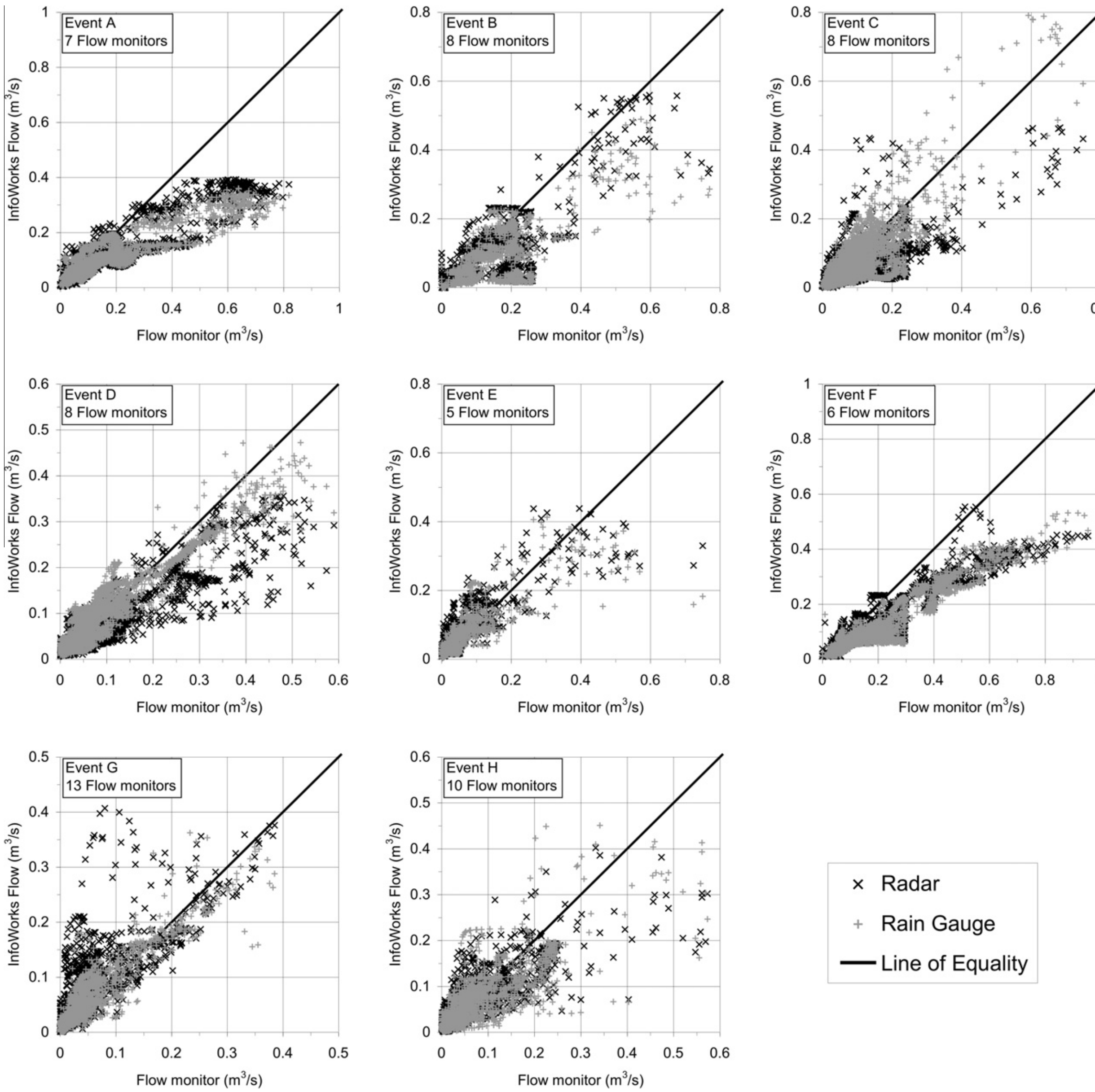

Fig. 5. Comparisons of Infoworks CS modelled flows to measured data, 5 min rainfall from radar and rain gauge.

The flow simulation results in Fig. 6 provide a generally good fit, apart from the early peak in the radar simulation, and a slight lag in the peak flow from the rain gauge prediction. This lag in the rain gauge prediction will provide some of the scatter in Fig. 5, but although the peak is almost the correct value, the time is wrong.

Fig. 6b shows the effect of using lower temporal resolution rainfall data as input to the model. Clearly when the rainfall resolution is reduced, peak intensities are smoothed, the effect of which is clearly seen in a lower peak when 15 min resolution rainfall data are input. When the resolution is further reduced to 60 min, the peak is almost entirely missing, and the simulated flow mimics few of the features of the measured flow. Scatter plots for all functioning flow monitors against the flow predictions at 15 min and 60 min resolution were studied (not shown), and, as in Fig. 6b, when 15 min resolution rainfall data are used, there is some effect on peak flows, although the highest values are similar to those shown in Fig. 5. For the 60 min resolution rainfall, however it is clear from the scatter plot that simulated peaks are significantly flattened.

4.4.2. Event H – 7th July 2008

Event H contained areas of convective cells embedded in stratiform precipitation. Fig. 8a shows the areal average rainfall intensity, based on the radar and rain gauge data. A number of rainfall peaks can be seen and clearly for some peaks the radar shows higher mean rainfall intensity, whereas for other peaks the mean intensity was greatest when recorded by the rain gauges.

Fig. 8a shows measured and simulated results at the flow monitor located just upstream of the main CSO (FM015). During the flow peaks around 13:30 and 14:00, the flow simulations using radar data as input are closest to the measured sewer flow, whereas for the flow peaks around 16:00 and 17:15, the simulations using rain gauge data as input are closest to the measured sewer flow. As discussed with event G, these differences could be a function of spatial representativeness errors, or other potential error sources such as wind displacement as discussed earlier. It can however be seen that in both cases the highest values are under-predicted, these being either a limitation of the model, or a function of short duration high intensity rainfall peaks not being recorded.

Table 3
Overview of simulated CSO spill volumes using rain gauge or radar data at three rainfall time scales.

Event	Event date	5 min rainfall			15 min rainfall						60 min rainfall			
		Simulated spill volume rain gauge (m^3)	Simulated spill volume radar (m^3)	Difference in radar spill volume compared to rain gauge (%)	Simulated spill volume rain gauge (m^3)	Simulated spill volume radar (m^3)	Difference in radar spill volume compared to rain gauge (%)	Difference in rain gauge spill volume compared to 5 min (%)	Difference in radar spill volume compared to 5 min (%)	Simulated spill volume rain gauge (m^3)	Simulated spill volume radar (m^3)	Difference in radar spill volume compared to rain gauge (%)	Difference in rain gauge spill volume compared to 5 min (%)	Difference in radar spill volume compared to 5 min (%)
A	25th June 2007	8240	5937	−33	8258	5938	−28	0	0	8250	5930	−28	0	0
B	3rd July 2007	2409	4388	82	2395	4341	81	−1	−1	2164	4031	86	−10	−8
C	5th–6th Jul. 2007	4750	1633	−65	4693	1583	−66	−1	−3	4250	1217	−71	−11	−25
D	21st Sept 2007	2387	1115	−53	2364	1103	−53	−1	−1	2246	947	−58	−6	−15
E	9th Oct. 2007	1541	2009	30	1528	1993	30	−1	−1	1492	1977	33	−3	−2
F	21st Jan. 2008	6117	7233	18	6086	7203	18	−1	0	5984	7014	17	−2	−3
G	1st July 2008	268	747	178	238	746	213	−11	0	62	501	708	−77	−33
H	7th July 2008	959	687	−28	912	600	−34	−5	−13	807	499	−38	−16	−27

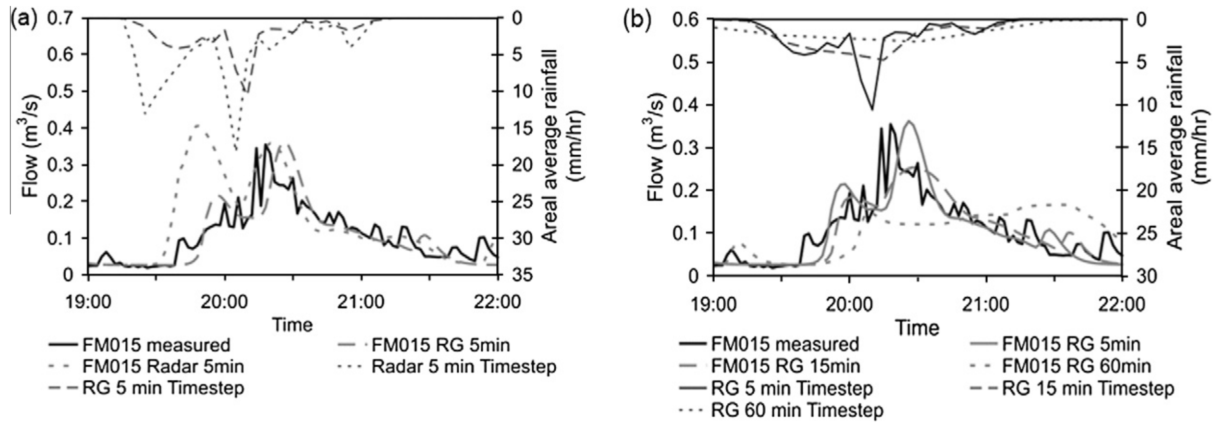

Fig. 6. Comparisons of simulated flows, plotted with measured flows and areal average rainfall for Event G (1st July 2008), (a) 5 min rainfall from radar and rain gauge. (b) 5, 15 and 60 min rainfall from rain gauge.

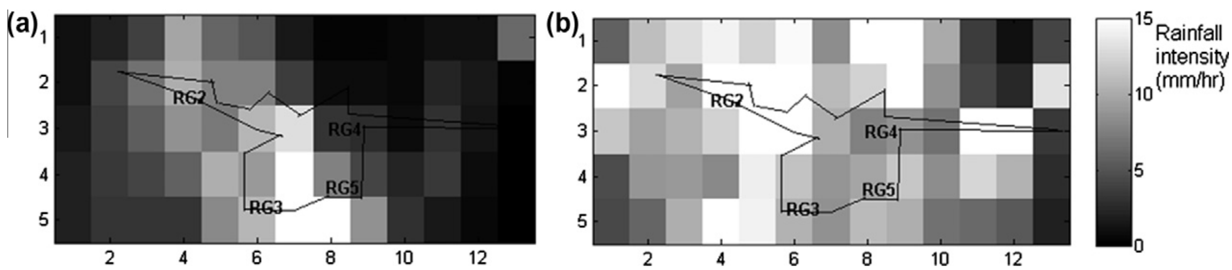

Fig. 7. Radar rainfall intensities in relation to the urban area and rain gauge locations, 1st July 2008, (a) 20:00 and (b) 20:05.

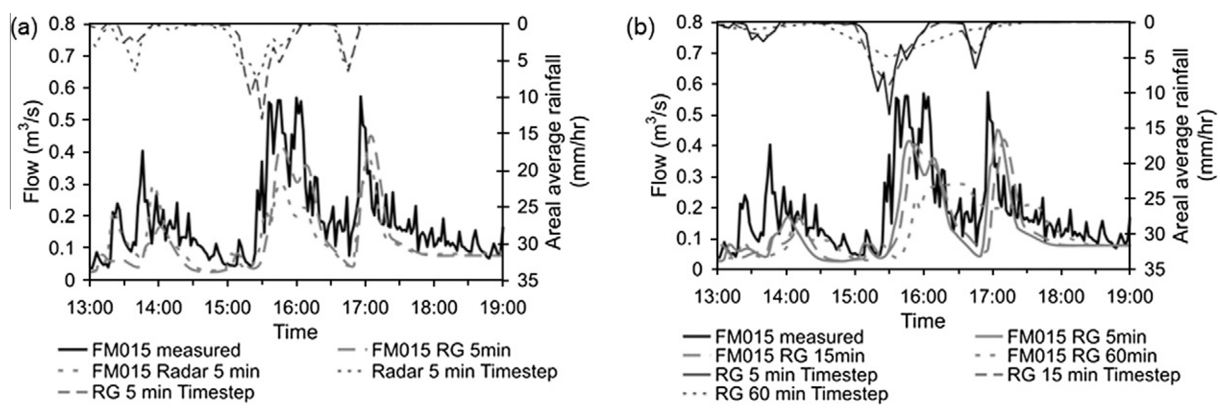

Fig. 8. Comparisons of simulated flows, plotted with measured flows and areal average rainfall for Event H (7th July 2008), (a) 5 min rainfall from radar and rain gauge. (b) 5, 15 and 60 min rainfall from rain gauge.

Fig. 8b shows the effect of reducing the time resolution of the rain gauge data input to the model. As the rainfall cells are longer lasting than event G, reducing the time resolution to 15 min has a smaller effect on the peak rainfall intensity, and therefore a small effect on the predicted flow. Further reducing the rainfall time resolution to 60 min effects a significant reduction in the peak rainfall intensity and the predicted flow, the peak of which is appreciably later. Scatter plots comparing the predicted flows against the measured flows (not shown) indicated the same trend seen for event G, the maximum simulated flows only being reduced slightly for the 15 min resolution rainfall data, but reaching a plateau below 0.3 m^3/s when the rainfall resolution is reduced to 60 min.

5. Discussion

The radar data did not show a systematic bias when compared with the rain gauge data; rather there are inherent uncertainties in both rainfall estimates, the magnitude of which varied on an event by event basis, as shown by Figs. 2–4. The detailed analysis of events G and H illustrate how uncertainty in rainfall estimates can significantly influence simulated sewer flows, especially peak flows which are of key importance for understanding flooding and CSO spills. Both the time and space resolution of the rainfall measurements was shown to be important, at the single flow monitor location studied in detail as well as in the scatter plots combining data from multiple flow monitor locations. For the case study site and for the events studied, the reduction of the rainfall resolution to 15 min resulted in some reduction in peak flows and CSO spill volumes, but the reduction to 1 h resolution drastically reduced peak flows and CSO spill volumes. At all time scales studied, there remains a considerable difference between peak flows as well as CSO spill volumes simulated using either the rain gauge data or the radar data, as shown by Table 3 and Figs. 5, 6 and 8. This is expected to be due to the fact that the sub-catchments contributing to the flows in the sewer system range in size between 0.1 and 300 hectares; hence spatial representativeness errors (as defined by Kitchen and Blackall [20]), due the input of rain gauge data collected at 4 locations or radar data recorded at 25 locations, are translated to differences in simulated flow peaks.

Finally the rainfall runoff and hydrodynamic sewer flow model itself is also acknowledged to include some inaccuracies due to the complexity of runoff processes from urban surfaces, the limited degree to which it is commercially feasible to calibrate models and the simplification assumptions made during the model build [38]. It should also not be forgotten that, while providing a good indication, measured sewer flows also contain potential inaccuracies, a full account of which are detailed in [41].

The results presented in this paper concur with [4] in that a combination of radar and rain gauge data are required to provide the best spatial estimate of rainfall. There are various pathways which may be taken to obtain the best prediction of sewer flows, given the uncertainty of rainfall measurements, especially at small urban scales. A number of studies describing ways of dealing with uncertainty and how uncertainty propagates from atmospheric to hydrological modelling are described by Rossa et al. [42]. A way to propagate uncertainty in rainfall measurements/forecasts could be the use of ensemble quantitative precipitation estimation (QPE) and/or the use of ensemble quantitative precipitation forecasts (QPF) with recent studies described by Schröter et al. [43] and Liguori et al. [44]. This paper has only considered rainfall measurements which are widely available within the UK, uncertainty in rainfall measurements may be reduced by using alternative types of rainfall measurements, such as microwave links or the use of local area weather radar and also by combining the different types of rainfall measurements, as described by Grum et al. [45,46].

Furthermore, for urban drainage management purposes, indicators informing on the expected level of accuracy of both radar and rain gauge data need to be developed that can be analysed at real time, as described in [6,47,48] to then allow an indication of the accuracy of sewer flow predictions. The events analysed in this paper illustrate that errors and uncertainty in the rainfall data can have a considerable influence on sewer flow simulations. The outputs of this research highlight that there will be significant uncertainties associated with the simulation of sewer flow from rainfall estimates in near real time as well as the prediction of sewer flows using quantitative rainfall forecasts.

6. Conclusions

A detailed study into the differences between rainfall measurement by radar and rain gauge has been described, and the impact of these differences when these data are used as an input for sewer flow simulations has been analysed. A hydrodynamic model was used for simulating runoff and sewer flows corresponding to a selection of storm events, both radar rainfall and rain gauge data were input to the model, and the simulation results were compared with measured sewer flows. Although the hydrodynamic model showed a tendency to under-estimate the flow peaks for the larger events, comparison of the flow peaks simulated using radar or rain gauge data with measured flow peaks in the sewer system provided a valuable insight into the effect of rainfall measurement technique and the effect of spatial variability of rainfall at the scale of a relatively small urban catchment. On the small spatial and temporal scales of the hydrodynamic model, the spatial representativeness error in the rainfall estimates translated to considerable differences in simulated flow peaks. The results highlight that there were very significant differences in predicted CSO spill volumes and in the prediction of the peak flow rates within the sewer system. For managing spills from sewer systems and predicting flooding in urban areas, the magnitude and timing of flow peaks is of principal concern. The events studied in this paper illustrated the difficulty in accurately simulating the occurrence of sewer flow peaks, especially when the rainfall is highly spatially varied.

It is concluded that, to ensure optimum accuracy of peak flow predictions, it is necessary to use rainfall data which has both high spatial and temporal resolution. The use of more than one measurement technique could result in improvements in rainfall estimate accuracy, and hence the accuracy of predicted sewer flows. It is envisaged that ensemble QPE and/or QPF will be necessary to account for the uncertainty inherent in all rainfall measurement methods used for urban drainage applications.

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References

[1] Council Directive (EC) 2000/60/EC of 23 October 2000. Establishing A Framework For Community Action In The Field Of Water Policy. [cited 2011 Aug 16]. Available from: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0060:20011216:EN:PDF>.
[2] Council Directive (EC) 2007/60/EC of 23 October 2007 on the assessment and management of flood risks. [cited 2011 Aug 16]. Available from: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:288:0027:0034:EN:PDF>.
[3] Flood and Water Management Act of 2010. [cited 2011 Aug 16]. Available from: <http://www.legislation.gov.uk/ukpga/2010/29/contents>.
[4] Einfalt T, Arnbjerg-Nielsen K, Golz C, Jensen N-E, Quirmbach M, Vaes G, Vieux B. Towards a roadmap for use of radar rainfall data in urban drainage. J Hydrol 2004;299:186–202.
[5] Vieux BE, Vieux JE. Statistical evaluation of a radar rainfall system for sewer system management. Atmos Res 2005;77:322–36.
[6] Krämer S, Verworn H. Improved radar data processing algorithms for quantitative rainfall estimation in real time. Water Sci Technol 2009;60:175–84.
[7] Krämer S, Fuchs L, Verworn H. Aspects of radar rainfall forecasts and their effectiveness for real time control – the example of the sewer system of the City of Vienna. In: Proceedings of the 7th international conference on urban drainage modelling and the 4th international conference on water sensitive urban design; 2006 Apr. 3–7; Melbourne, Australia. Melbourne; 2006. p. 1187–94.
[8] Schilling W. Rainfall data for urban hydrology: what do we need? Atmos Res 1991;27(1-3):5–21.
[9] Verworn HR. Hydrological relevance of radar rainfall data. In: Cluckie ID, Collier CG, editors. Hydrological applications of weather radar. Chichester: Ellis Horwood; 1991. p. 531–40.
[10] Berne A, Delrieu G, Creutin J-D, Obled C. Temporal and spatial resolution of rainfall measurements required for urban hydrology. J Hydrol 2004;299:166–79.
[11] Upton GJG, Rahimi AR. On-line detection of errors in tipping bucket rain gauges. J Hydrol 2003;278:197–212.
[12] Ciach GJ. Local random errors in tipping-bucket rain gauge measurements. J Atmos Ocean Tech 2003;20:752–9.
[13] Habib E, Krajewski, WF Kruger A. Sampling errors of fine resolution tipping-bucket rain gauge measurements. J Hydrol Eng 2001;6(2):159–66.
[14] Krajewski WF, Villarini G, Smith JA. Radar-rainfall uncertainties – where are we after thirty years of effort. Bull Am Meteorol Soc 2010;91(1):87–94.
[15] Villarini G, Krajewski WF. Review of the different sources of uncertainty in single polarisation radar-based estimates of rainfall. Surv Geophys 2010;31:107–29.
[16] Harrison DL, Driscoll SJ, Kitchen M. Improving precipitation estimates from weather radar using quality control and correction techniques. Meteorol Appl 2000;6:135–44.
[17] Met Office. Fact Sheet 15, Weather Radar, 2010. [cited 2011 Aug 16]. Available from: <http://www.metoffice.gov.uk/media/pdf/o/c/fact_sheet_No._15.pdf>.

[18] Harrison DL, Scovell RW, Kitchen M. High-resolution precipitation estimates for hydrological uses. Proc Inst Civ Eng – Water Manag 2009;162(WM2):125–35.
[19] Golding B. Nimrod: a system for generating automated very short range forecasts. Meteorol Appl 1998;5:1–16.
[20] Kitchen M, Blackall RM. Representativeness errors in comparisons between radar and gauge measurements of rainfall. J Hydrol 1992;134(1–4):13–33.
[21] Villarini G, Krajewski WF. Empirically-based modeling of spatial sampling uncertainties associated with rainfall measurements by rain gauges. Adv Water Res 2008;31(7):1015–23.
[22] Fabry F, Bellon A, Duncan MR, Austin GL. High resolution rainfall measurements by radar for very small basins: the sampling problem re-examined. J Hydrol 1994;161:415–28.
[23] Collier CG. The impact of wind drift on the utility of very high spatial resolution radar data over urban areas. Phys Chem Earth (B) 1999;24(8):889–93.
[24] Tilford KA, Fox NI, Collier CG. Application of weather radar data for urban hydrology. Meteorol Appl 2002;9:95–104.
[25] Jessen M, Einfalt T, Stoffer A, Mehlig B. Analysis of heavy rainfall events in North Rhine–Westphalia with radar and rain gauge data. Atmos Res 2005;77:337–46.
[26] Wood SJ, Jones DA, Moore RJ. Static and dynamic calibration of radar data for hydrological use. Hydrol Earth Syst Sci 2000;4(4):545–54.
[27] Jensen NE, Pedersen L. Spatial variability of rainfall: variations within a single radar pixel. Atmos Res 2005;77:269–77.
[28] Vieux BE, Bedient PB. Assessing urban hydrologic prediction accuracy through event reconstruction. J Hydrol 2004;299:217–36.
[29] Zhu D, Park J, Rico-Ramirez M, Cluckie I. Sensitivity analysis of a distributed hydrological model for the Upper Medway catchment using point and radar-based rainfall data. In: Proceedings of BHS 10th National Hydrology Symposium; 2008; Exeter. [cited 2011 Aug 16]. Available from: <http://www.hydrology.org.uk/Publications/exeter/24.pdf>.
[30] Collier CG. On the propagation of uncertainty in weather radar estimates of rainfall through hydrological models. Meteorol Appl 2009;16(1):35–40.
[31] Smith JA, Miller A, Baeck ML, Nelson PA, Fisher GT, Meierdiercks KL. Extraordinary flood response of a small urban watershed to short-duration convective rainfall. J Hydrometeorol 2005;6(5):599–617.
[32] Smith JA, Baeck ML, Meierdiercks KL, Miller AJ, Krajewski WF. Radar rainfall estimation for flash flood forecasting in small urban watersheds. Adv Water Res 2007;30:2087–97.
[33] Villarini G, Smith JA, Baeck ML, Sturdevant-Rees P, Krajewski WF. Radar analyses of extreme rainfall and flooding in urban drainage basins. J Hydrol 2010;381(3–4):266–86.
[34] Quirmbach M, Schultz GA. Comparison of rain gauge and radar data as input to an urban drainage rainfall–runoff model. Water Sci Technol 2002;45(2):27–33.
[35] Packman J. New Hydrology model. Proceedings of WaPUG spring meeting 1990. [cited 2010 Jul 1]. Available from: <http://www.ciwem.org/groups/wapug/SP1990.PAPER01.pdf>.
[36] Department Of The Environment/National Water Council. The Wallingford Procedure for Design and Analysis of Urban Storm Drainage. Standing Technical Committee Report No.28. Wallingford, UK; Hydraulics Research Ltd; 1981. ISBN 0 901090 27 1.
[37] Sarginson EJ, Nussey BB. The explicit computation of urban runoff. In: Featherstone RE, James A. editors. Urban drainage systems: proceedings of the first international seminar; Southampton, England; 1982. ISBN: 0273085964.
[38] WaPUG. Code of practice for the hydraulic modelling of sewer systems. 2002. [cited 2011 Aug 16]. Available from: <http://www.ciwem.org/media/44426/Modelling_COP_Ver_03.pdf>.
[39] Dempsey P, UK Met Office. Personal communication. [4thApril2009].
[40] Edwards BF, Wilder JW, Scime EE. Dynamics of falling rain drops. Eur J Phys 2001;22:113–8.
[41] WRc. A guide to short term flow surveys of sewer systems. Swindon: WRc Engineering; 1987.
[42] Rossa A, Liechti K, Zappa M, Bruen M, Germann U, Haase, et al. The COST 731 action: a review on uncertainty propagation in advanced hydro-meteorological forecast systems. Atmos Res 2011;100:150–67.
[43] Schröter K, Llort X, Velasco-Forero C, Ostrowski M, Sempere-Torres D. Implications of radar rainfall estimates using uncertainty on distributed hydrological model predictions. Atmos Res 2011;100:237–45.
[44] Liguori S, Rico-Ramirez MA, Schellart ANA, Saul AJ. Using probabilistic radar rainfall nowcasts and NWP forecasts for flow prediction in urban catchments. Atmos Res; in press. doi: 10.1016/j.atmosres.2011.05.004.
[45] Grum M, Kraemer S, Verworn H-R, Redder A. Combined use of point rain gauges, radar, microwave link and level measurements in urban hydrological modeling. Atmos Res 2005;77(1–4):313–21.
[46] Grum M, Harremoës P, Linde JJ. Assimilating a multitude of rainfall and runoff data using a stochastic state space modelling approach. In: Strecker EW, Huber WC, editors. Proceedings of 9th international conference on Urban drainage; 2002 Sep. 8–13; Portland, USA. Portland: GeoSyntec Consultants; 2002.
[47] Fabry F, Seed AW. Quantifying and predicting the accuracy of radar-based quantitative precipitation forecasts. Adv Water Res 2009;32:1043–9.
[48] Rico-Ramirez MA, Cluckie I. Classification of ground clutter and anomalous propagation using dual-polarization weather radar. IEEE Trans Geosci Remote Sens 2008;46(7):1892–904.