Assessment of a 1-hour gridded precipitation dataset to drive a hydrological model: a case study of the summer 2007 floods in the Upper Severn, UK

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ABSTRACT

In this study a gridded hourly 1-km precipitation dataset for a meso-scale catchment (4,062 km^2) of the Upper Severn River, UK was constructed using rainfall radar data to disaggregate a daily precipitation (rain gauge) dataset. The dataset was compared to an hourly precipitation dataset created entirely from rainfall radar data. Results found that when assessed against gauge readings and as input to the Lisflood-RR hydrological model, the rain gauge/radar disaggregated dataset performed the best suggesting that this simple method of combining rainfall radar data with rain gauge readings can provide temporally detailed precipitation datasets for calibrating hydrological models.

Key words | disaggregation, gauge, hydrological modelling, precipitation, radar, Severn Uplands

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INTRODUCTION

The timeliness and accuracy of flood warnings are important in order to minimise damage to property and loss of life (Pappenberger *et al.* 2008). The use of numerical weather prediction techniques to forecast when and where precipitation will occur can extend the forecast lead times from hours to days (Golding 2000; Pappenberger *et al.* 2008; He *et al.* 2009). However, the extent and location of flooding will not be known unless the response of the river catchments to precipitation can be modelled accurately. Peak discharges during flash floods are often maintained only for hours (Kobold & Brilly 2006) suggesting that calibrating and validating hydrological models with sub-daily time-steps will bring improvements to flood forecasts. The high sensitivity of hydrological models to precipitation (Singh 1997; Kobold & Brilly 2006) means an accurate, sub-daily precipitation dataset for the catchment should be provided as input to the models (Cole & Moore 2008). Whilst the network of daily recording rain gauges across the UK may give a sufficiently spatially detailed estimate of daily precipitation (Cole & Moore 2008), the network of hourly recording rain gauges is too sparse in many places to give a reliable spatial estimation of hourly rainfall for the purposes of hydrological modelling (Lewis & Harrison 2007).

The first recorded use of radar to observe precipitation was 20 February 1941, when a shower was tracked by radar located on the English coast (Atlas 1964). In the early 1950s, the UK Met Office began investigating the

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usefulness of radar for detecting precipitation and in 1955 the first radar was installed for use by weather forecasters (Met Office 2009). It was in the late 1960s and early 1970s, with the increase in available computing power, that meteorologists started to realise the true potential of weather radar, both for short-term forecasts (Austin & Bellon 1974) and estimation of precipitation amounts when combined with rain gauge readings (Wilson 1970). Radar operate by analysing the qualities of electromagnetic pulses reflected by a target (Met Office 2009). Considerable information about the target can be derived from the nature of the echo of the pulse: the magnitude of the echo gives information about the size of the target; the distance to the target can be calculated from the time it takes for the echo to return; the angular location is known from the direction the radar is pointing when the echo is received; even the velocity of the target can be found from a shift in frequency of the echo due to the Doppler effect (Skolnik 2001). However, it is far from straightforward identifying the presence and quantity of precipitation and there are a number of well known sources of error that have dogged radar meteorology since its inception (see for example Probert-Jones 1962; Collier *et al.* 1983; Collier 1986; Harrison *et al.* 2000) and continue to cause large systematic errors and inaccuracies in the present (Cole & Moore 2008; Collier 2009; Villarini & Krajewski 2010; Zhang & Qi 2010). Radar can provide ‘snapshots’ with 1–5 km^2 resolution, typically every five minutes, of precipitation over an area of several hundred square kilometres (Wood *et al.* 2000). This is far more spatial and temporal detail than a gauge network normally provides: an attractive prospect to a hydrological modeller. However, the frequent errors and large inaccuracies that mar radar precipitation estimates mean combining radar data with rain gauge readings has been a common strategy for several decades (Wilson 1970; Haberlandt 2007), and these combined data have been studied as input to hydrological models for some time (Collier & Knowles 1986; Collier 2009). The use of rainfall radar data as input to hydrological models in an operational context has been limited in the UK (Moore *et al.* 2004), but recent research into the quality of rainfall radar estimations (Rossa *et al.* 2010) and methods of dealing with the associated uncertainty (Szturc *et al.* 2008; Germann *et al.* 2009) suggest the acceptance of radar data for flood forecasting is increasing. Biggs & Atkinson (2010b) simulated an extreme hydrological event spanning November–December 2006 for part of the River Severn catchment using HEC-HMS as a hydrological model. They employed universal cokriging to geostatically interpolate gauge data with radar and elevation and found that simulations run using gauge-corrected radar precipitation measurements compared favourably to simulations run using rain gauge-only measurements when the time-steps of the rain gauge data were greater than 1 hour. In addition, Cole & Moore (2008, 2009) assessed the use of rainfall radar for precipitation input to the G2G model (Bell *et al.* 2007). Whereas gauge-adjusted radar data perform better than radar data alone, there is generally no benefit to using gauge-adjusted radar over rain gauge-only interpolated precipitation data as long as there are a sufficient number of high temporal resolution gauges (Cole *et al.* 2010). In addition, large transient errors in the radar data can persist in the gauge-adjusted dataset (Cole & Moore 2009). However, the density of sub-daily rain gauges varies across the UK with high elevations in mountainous terrain being particularly poorly represented (Cole *et al.* 2010). It is catchments in these locations that are most sensitive to the temporal variation of the precipitation (Biggs & Atkinson 2010b) and much research has been performed to establish the value that the high spatial and temporal radar precipitation estimates bring in improving flood simulation for these sorts of catchments (Harrold *et al.* 1974; Collier & Knowles 1986; Anquetin *et al.* 2010). Using radar data to disaggregate readings from a network of daily rain-gauges can provide a more accurate, temporally detailed precipitation dataset for mountainous catchments and since the precipitation quantities from the rain gauge network are retained, the influence of any large transient errors in the rainfall radar data are minimised. This method is analogous to that used by Harrold *et al.* (1974) who used a radar-derived pattern to add spatial detail to a precipitation dataset from a sparse network of hourly rain gauges. Here the radar data are used to give temporal detail to a fairly dense network of daily raingauges.

In this study a relatively simple way of combining gauge and radar precipitation readings was used to prepare an hourly precipitation dataset which was compared against a radar-only dataset. The study area covers the catchment of the Upper Severn River in the UK, October 2006 to

December 2007. Both datasets were used as input to drive the LISFLOOD-RR hydrological model (van der Knijff *et al.* 2010) for the catchment; simulated discharge values were compared against observed values from two gauging stations in the Upper Severn. The main purpose of this paper is to explore how the relative performances of hourly data can help to inform researchers in the merits of using rainfall radar data for hydrological modelling with hourly or sub-hourly time-steps. The paper is organised as follows. First the study area and datasets are presented followed by a description of the methods of data preparation and hydrological modelling. The results are then presented and discussed, and finally a conclusion is given.

STUDY AREA AND DATA

Study site

The Upper Severn catchment (Severn upstream of Bridgnorth) is approximately 4,062 km^2 (Figure 1) and has been used in a number of previous hydrological studies (e.g. He *et al.* 2009; Biggs & Atkinson 2010b) because of the large quantity of available observational data and the relatively small catchment area. The soil type is predominantly loosely packed peat with agriculture and urban areas taking up approximately 50 and 3% of land area, respectively (He *et al.* 2009). The topography varies from mountainous in the west to downstream alluvial floodplains in the east (Biggs & Atkinson 2010a). Precipitation varies throughout the catchment from approximately 1,600 mm year^{-1} in the west to less than 700 mm year^{-1} further east (Environment Agency 2005). During June and July 2007, unusual weather patterns caused a period of very heavy rainfall over much of the UK resulting in widespread inundation in many areas including the River Severn (Marsh & Hannaford 2007).

Precipitation data

All rain gauge data used in this study came from the Met Office's MIDAS stations (MIDAS 2010). A total of 136 gauges were used for the study area, with complete sets of observations for 2007 available for comparison. The daily rain gauge readings from the MIDAS stations are accumulations of rainfall over the preceding 24 h period and the readings are taken at 09:00 UTC.

A 1 km gridded precipitation dataset from the Environment Agency (2008) of England and Wales is used over the entire study area. This is the same dataset used by He *et al.* (2009) and is referred to as 'EA daily gridded data' for the rest of this paper. The dataset was produced by applying a triangular planes based methodology (Jones 1983) to create a spatial interpolation of the daily rain gauge readings from Met Office MIDAS data (Environment Agency 2008).

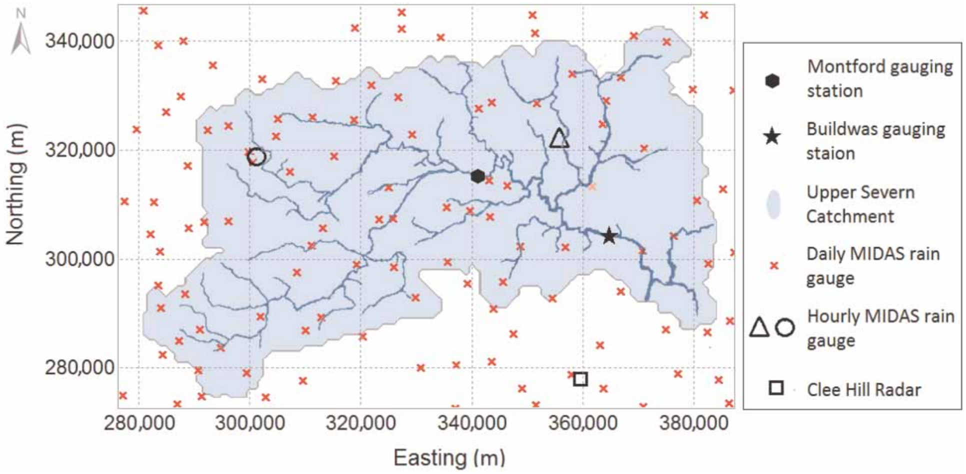


Figure 1 | Schematic of the area covered by EA daily gridded precipitation data (Environment Agency 2008) and the catchment of the Upper Severn River, UK. Also shown are the locations of (i) river gauges used in this study (solid hexagon, Montford; solid star, Buildwas), (ii) daily MIDAS rain gauges (crosses); (iii) hourly MIDAS rain gauges (unfilled circle, station 425000, Lake Vyrnwy 2, Powys (North), Wales, UK, SY10 0; unfilled triangle, station 433709, Shawbury, Shropshire, UK, SY4 4); and (iv) the rainfall radar (unfilled square) located at Clee Hill, Titterstone Clee, Ludlow, Shropshire, UK (359485E, 277940N). Rain gauge data from BADC (2010a) and rainfall radar data from Met Office (2009).

The EA daily gridded data used covered the period 1961–2007 with a 8,214 km^2 spatial coverage from 277000E to 387000E, 273000N to 346000N (Figure 1) and each day covers a 24 h period starting at 09:00 UTC.

The Met Office (2010) operates a network of 16 weather radar in the UK with data from a further two radars in the Republic of Ireland provided by Met Éireann. Since 1996 the Met Office has operated an automated system called NIMROD that produces estimates and short-range forecasts of precipitation, cloud and visibility (Golding 1998). Radar data from the network of weather radar provide the basis for the precipitation analysis and forecasting, but the data first undergo considerable processing, applying several physically based corrections (Cole & Moore 2008). Although the NIMROD data used here were from a composite rainfall radar dataset, the radar at Clee Hill (Titterstone Clee, Ludlow, Shropshire, UK) (Met Office 2009) is located in the study area at 359485E, 277940N, close to the Upper Severn River catchment (Figure 1). Consequently the radar data for the study area were predominantly based on output from the Clee Hill radar. The NIMROD rainfall data were provided as a 1 km gridded dataset covering the rectangle formed by the coordinates −405000E, −625000N and 132000E, 155000N (an area of 3.75×10^6 km^2). Snapshots were provided at 5 min intervals, giving 288 snapshots per day.

Observed discharge data for these river gauging stations at Montford and Buildwas (Figure 1) were provided by the UK Environment Agency Midlands region (Environment Agency 2010). The observed discharge data were supplied as instantaneous, snapshot readings taken every 15 min, so the hourly observed discharge estimates were calculated as the average of the four snapshots for the hour. All spatial coordinates in this paper use the numeric format of the British national grid (BNG) reference system devised by the Ordnance Survey (2008).

METHODS

Preparation of hourly precipitation maps

Two sets of hourly precipitation maps were used in this study. The first dataset is based entirely on data from the NIMROD rainfall radar. A subset of the NIMROD rainfall data were selected to cover the entire Upper Severn catchment. If data were missing for a part of the hour, the hourly precipitation was calculated from an average of the snapshots that were available. If no snapshots were available for a given hour, the data were marked as missing and the precipitation was assumed to be zero for that hour.

The second dataset, referred to as the ‘EA disaggregated dataset’, started with the EA daily gridded data described above which were then disaggregated using the NIMROD rainfall radar data to form an hourly dataset (described below). In this way the daily precipitation totals from the EA daily gridded data were retained but the higher temporal resolution of the radar data was exploited to produce the hourly dataset. This method is similar to that employed by Wüest et al. (2009).

Once the NIMROD rainfall radar data had been translated to fit the EA gridded data cells, the calculation to arrive at the hourly precipitation P at a location x, y (1 km grid square) and time t (hour of day) was as follows:

$$P(x,y,t) = P_{\mathrm{EA}}(x,y)\frac{P_N(x,y,t)}{\Sigma_{t=1}^{24} P_N(x,y,t)} \tag{1}$$

where P_{EA} is the daily precipitation from the EA gridded data and P_N is the hourly precipitation from the NIMROD rainfall radar data. The EA gridded dataset was supplied with no missing data, but there were missing data from the NIMROD rainfall radar dataset, described later. If, for any grid square, the entire day was missing from the NIMROD data, then the EA gridded precipitation was divided equally among the 24 h for that day. For days with partially missing datasets, it was assumed there was no rainfall during the missing hours.

Quality control of the data

In addition to missing data, inconsistencies between the EA daily gridded and NIMROD hourly rainfall radar datasets needed to be addressed. These occurred when the daily precipitation recorded for a grid square was non-zero in one dataset, but zero in the other. For the cases where the EA daily gridded data was 0 mm but the NIMROD data was above a minimum threshold of 0.5 mm over the day, the precipitation was assumed to be 0 mm for the full day. For the opposite case, the non-zero EA daily gridded precipitation data were divided equally among the 24 h for that day.

All cases of errors and inconsistencies were logged and recorded. For 2007, 2 complete days were missing from the NIMROD rainfall radar data: 09:00 UTC on 15 July to 09:00 UTC on 16 July and 09:00 UTC on 1 December to 09:00 UTC on 2 December. For these days it was assumed the EA daily gridded precipitation was spread out evenly over the 24 h period. The ratio of occurrences of inconsistent data between the datasets was 2.5%. As an additional measure of the level of inconsistency, the sum of the non-zero precipitation readings in the EA daily gridded data that were matched by zero readings in the NIMROD data and vice versa were compared to the total precipitation for the Upper Severn study area. It was found that the mismatching precipitation for 2007 was 0.6% of the total precipitation recorded in the EA daily gridded dataset. This suggested that the inconsistencies were more likely to occur at periods of light precipitation so they were likely not to have a significant effect on hydrological models.

As a scalar measure of the difference between the rain gauge and NIMROD rainfall radar accumulations, the mean absolute error (*MAE*) was used (Wilks 2006),

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |P_{RG_i} - P_{N_i}| \tag{2}$$

where P_{RG_i} and P_{N_i} represent the daily time series of the daily precipitation estimates from the rain gauge and NIMROD rainfall radar respectively, and n is the number of values. A $MAE = 0$ indicates perfect correlation between the two datasets, and the *MAE* value increases as the discrepancies between the two time series increases. The *MAE* was used here in preference to the root mean square error because the *MAE* is less sensitive to large errors caused by extreme values (Wilks 2006).

River discharge simulation using LISFLOOD-RR

LISFLOOD-RR is a spatially distributed, geographic information system (GIS)-based, rainfall-runoff-routing model implemented using the PCRaster Dynamic Modelling language (Karssenberg 2002). The model forms the core of the (pre)operational European Flood Alert System (EFAS) (Thielen *et al.* 2009) and has been used previously in flood forecasting research (e.g. Gouweleeuw *et al.* 2005; He *et al.* 2009). Here it is implemented at a 1 km^2 resolution for use in the assessment of the accuracy of the hourly precipitation datasets.

The NIMROD rainfall radar and EA disaggregated datasets were used as input to the LISFLOOD-RR hydrological model. The simulated discharge figures from the model run were then compared against observed discharge to give an indication as to which dataset provided the best estimate of precipitation over the catchment. With the exception of precipitation, all the maps and model parameters used in this study were the same as those used by He *et al.* (2009).

It is important to note that the variations of simulated and observed discharge could be caused by a number of factors other than inaccurate representation of precipitation. The performance of the model is likely to be a significant factor. Whilst the LISFLOOD-RR model is known to perform well when properly calibrated and supplied with accurate input maps (van der Knijff *et al.* 2010), hourly time-step maps for temperature, evapotranspiration and evaporation were not available so daily maps for these variables were used. In addition, the parameters selected were based on a model calibration for 6-hr time-steps (see He *et al.* 2009 for a description of the calibration process).

The LISFLOOD-RR model was run using the NIMROD rainfall radar and EA disaggregated precipitation datasets with hourly time-steps for the period from 1 October 2006 to 31 December 2007. The model output was the hourly simulated discharge on 31 points on the upper reaches of the River Severn, two of the simulated discharge points correspond to the gauging stations located at Montford (Shropshire, UK) and Buildwas (Shropshire, UK) (Figure 1). The period from 1 October 2006 to 31 December 2006 was taken as a model warm up; consequently the results from this period were not included in the analysis. The Nash-Sutcliffe efficiency index (*NS*) (Nash & Sutcliffe 1970) and the observed and simulated mean discharge ($\overline{Q_{\text{obs}}}$ and $\overline{Q_{\text{sim}}}$) figures were calculated for both simulations to assess the performance of the model and the precipitation maps. A *NS* value close to 1 denotes a good simulation, whereas values below 0 denote that the model performs worse than the climatological mean.

RESULTS

Example of comparing individual daily rain gauge readings with rainfall radar data

The typical differences between MIDAS and radar can be demonstrated by specifically comparing the daily rain gauge readings from MIDAS station 424242 and the daily accumulations of precipitation estimates from the corresponding 1 km grid square in the NIMROD rainfall radar dataset (Figure 2). The mean precipitation in 2007 for the rain gauge at MIDAS station 424242 was $\overline{P_{RG}} = 2.73$ mm day^{-1}. The mean daily precipitation in 2007 for the NIMROD data from the 1 km × 1 km grid square centred

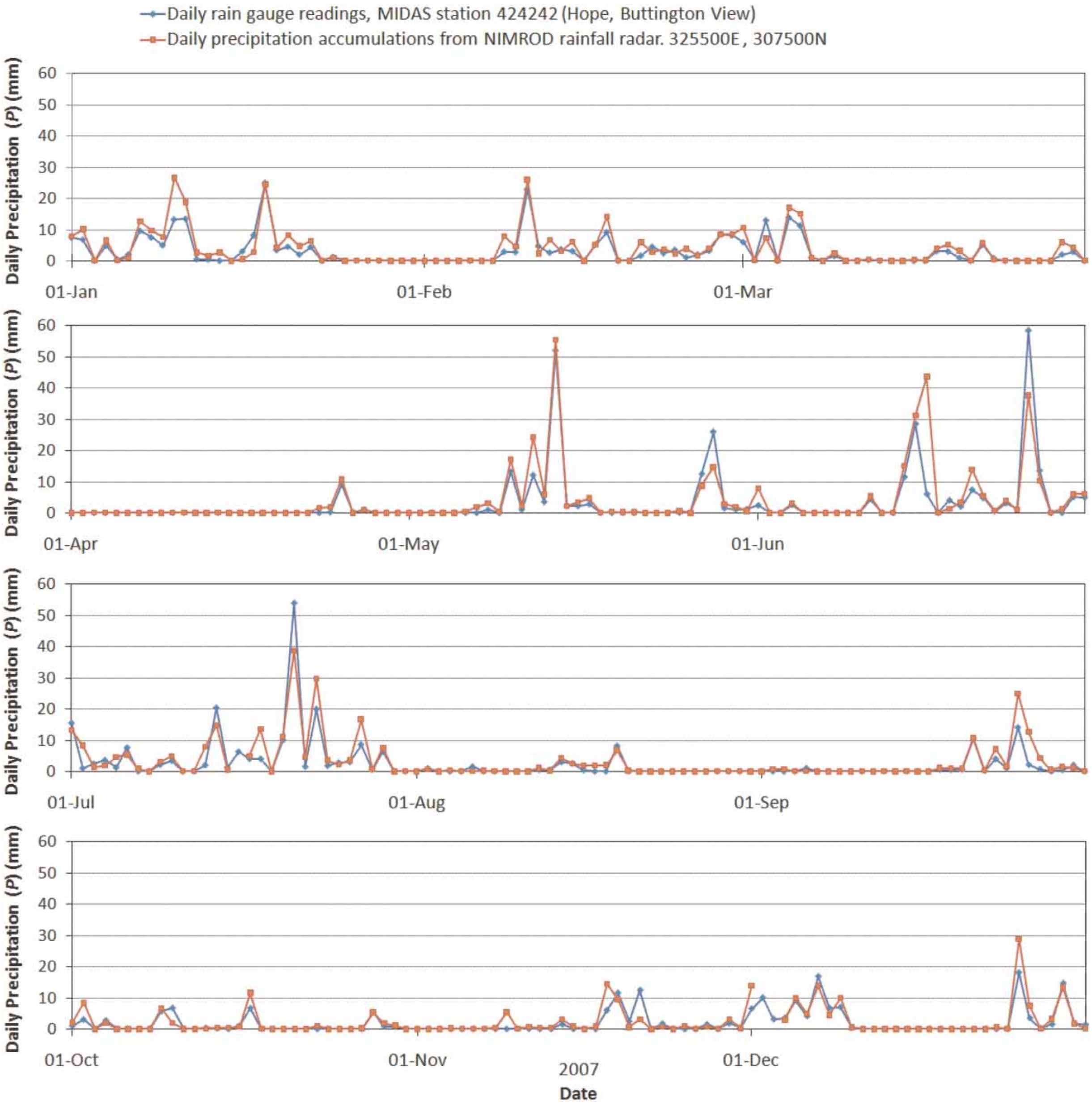


Figure 2 | Daily precipitation for 2007 from MIDAS station 424242 (Hope, Buttington View 325900E, 307400N) (readings taken at 09:00 UTC) (P_{RG}) and NIMROD radar data daily accumulations (09:00 UTC to 08:55 UTC) from 1 km grid square centred on 325500E, 307500N (P_N). NIMROD data were missing for 16 July, 2 December and 3 December 2007. Data from BADC (2010b).

on 325500E, 307500N was $\overline{P_N} = 3.40$ mm day^{-1}. Excluded were 16 July, 2 December and 3 December (2007) when few or no NIMROD radar data are available.

For the year 2007, using Equation (2) with the daily rain gauge readings from MIDAS station 424242 and the daily accumulations of precipitation estimates from the corresponding location in the NIMROD rainfall radar dataset gives a value of $MAE = 1.40$ mm day^{-1}. Composite images from the NIMROD rainfall radar for 15 and 24 June 2007 show intense convective rainfall over the study area on both days which may explain the sizeable difference between rain gauge and radar estimates. Note that daily rain gauge readings are accumulations over the preceding 24 h and the readings are taken at 09:00 UTC (BADC 2009), so the value for 16 June is a measure of the precipitation accumulated between 09:00 UTC on 15 June and 08:55 UTC on 16 June.

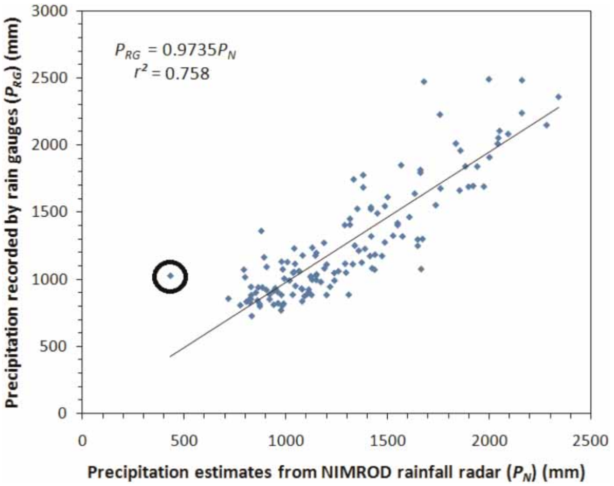


Figure 3 | Comparison between NIMROD rainfall radar accumulations (P_N) and MIDAS daily rain gauge readings (P_{RG}) for 2007 for the Upper Severn Area, UK. Data from BADC (2010b). The outlier, circled, is the rain gauge at MIDAS station 440885 (Brampton Bryan, 337100E, 272600N).

Comparisons of rainfall radar data against multiple daily rain gauges

Figure 3 shows the comparison between accumulated precipitation for 2007 for daily rain gauges in the Upper Severn study area and the estimates of precipitation accumulation from the NIMROD radar data from the 1 km grid squares where the rain gauges are located. Included were rain gauges that had a full year of valid readings. Excluded were those periods of time when few or no NIMROD data are available: 09:00 UTC 15 July to 08:55 UTC 16 July; 09:00 UTC 1 December to 08:55 UTC 3 December.

The gradient of the line of least-squares fit to the scatter plot between the precipitation sources is close to one and the Pearson product-moment correlation coefficient is $r^2 = 0.758$ (Figure 3). The low readings of the outlier gauge circled in Figures 3 and 4 are likely caused by occultation of the radar beam by an air-traffic control radar located near to the rainfall radar.

Comparison of hourly rain gauge readings with the NIMROD rainfall radar and EA disaggregated datasets

Figure 5 shows correlations between the two MIDAS hourly rain gauges in the study area and the NIMROD rainfall radar data from the 1 km grid squares that contain the location of the rain gauges. As well as comparing how the correlations of precipitation estimates vary between the two hourly rain gauges, Figure 5 shows the variation in precipitation correlation between a summer month (July 2007, Figure 5(a) and (b)) and a winter month (December 2007, Figure 5(c) and (d)). Figure 6 is similar to Figure 5 but it uses data from the EA disaggregated hourly precipitation dataset instead of the NIMROD rainfall radar dataset.

The correlations between the hourly rain gauge readings and the NIMROD radar data were weaker than the correlations between the hourly rain gauge figures and the EA disaggregated hourly precipitation data (Figures 6 and 7). The Pearson product-moment correlation coefficient as a measure of covariance was not suitable here due to the preponderance of data points near or on the origin in Figures 6 and 7. In addition, the Pearson product-moment correlation coefficient is not resistant since it can be highly sensitive to outlying point pairs (Wilks 2006). So the relatively small number of data points with high precipitation readings in Figures 6 and 7 will have a disproportionate influence on the correlation coefficient.

In preference to the Pearson product-moment correlation coefficient, the mean absolute difference (MAE) (Equation (2)) is used to give a measure of the correlation between the rain gauge readings and the two hourly rainfall

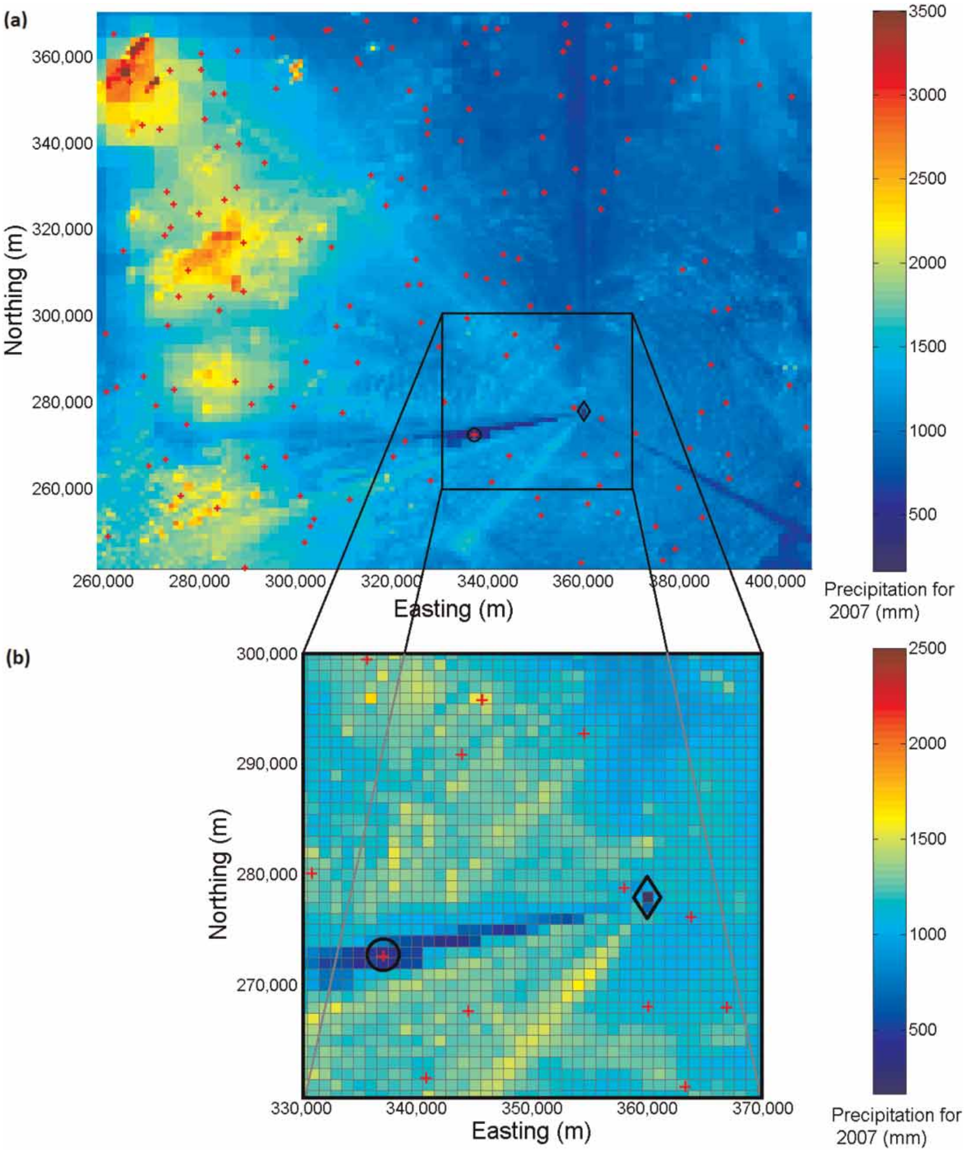


Figure 4 | Accumulation of precipitation over the Upper Severn study area from NIMROD rainfall radar for 2007. The locations of the daily MIDAS rain gauges are marked (+). The rain gauge circled is located at MIDAS station 440885 (Brampton Bryan, 337100E, 272600N), this corresponds to the outlier circled in Figure 3. Clee Hill radar (◊ diamond) is located at 359485E, 277940N (Met Office 2009). Pixel size is 1 km^2.

datasets (Table 1). Only data points where non-zero precipitation was recorded by one or both of the time series were used.

The *MAE* values for the hourly rain gauge at MIDAS station 425000 (Lake Vyrnwy 2, Powys (North), Wales, UK, SY10 0) were generally higher than those for the hourly rain gauge at MIDAS station 433709 (Table 1). Possible reasons for this were suggested by the location of MIDAS station 425000 to the west of the study area. Here the average precipitation is higher (Environment Agency 2005) and the terrain mountainous which is likely to limit radar visibility (Wüest *et al.* 2009) and introduce more errors in the radar readings caused by orographically enhanced rainfall (Biggs *et al.* 2008). In addition, the resolution of the radar data is lower for the area around MIDAS station 425000 because it is geographically further than MIDAS station 433709 from the nearest rainfall radar, located at Clee Hill (71.2 and 44.4 km, respectively).

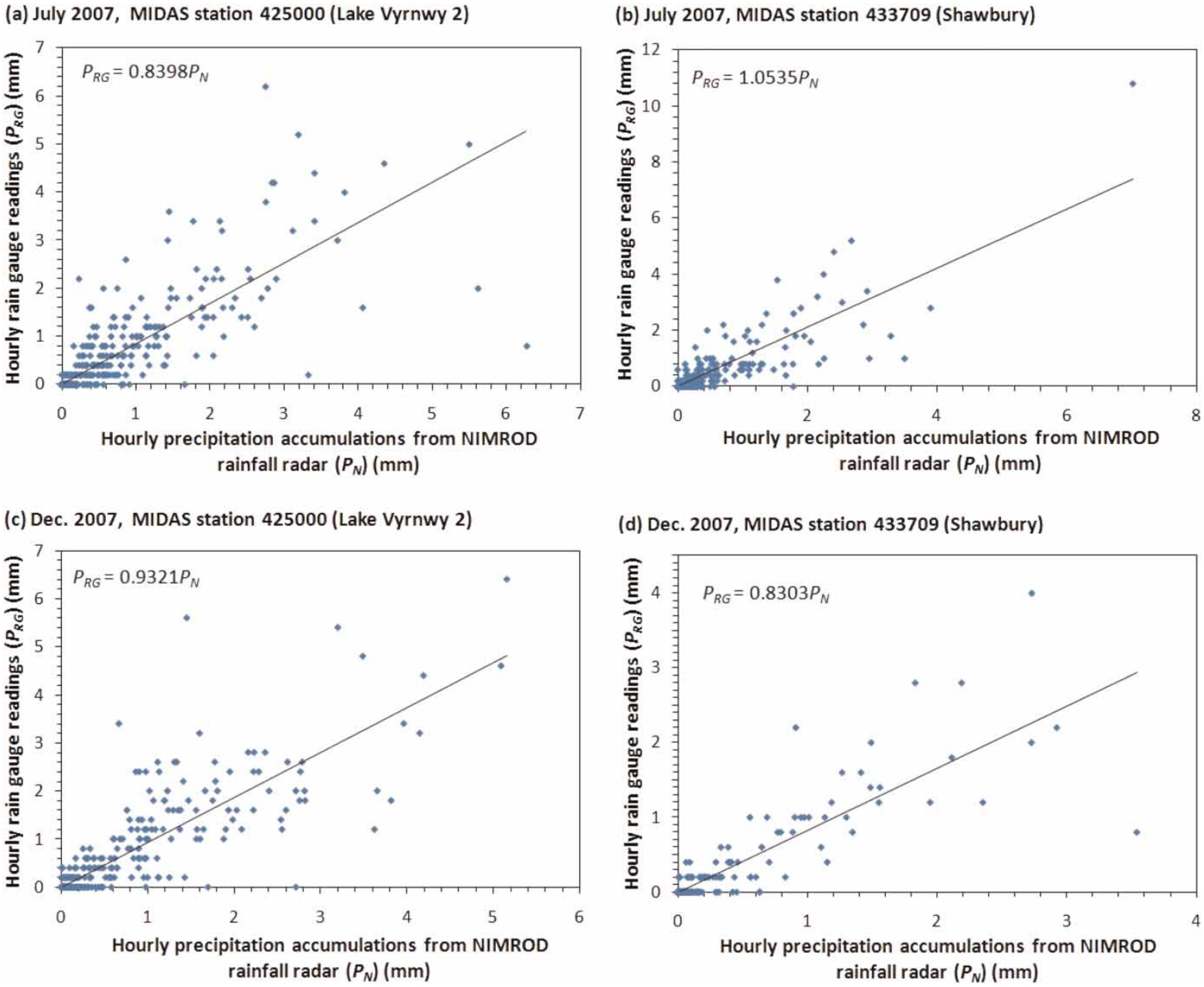


Figure 5 | Comparison between NIMROD rainfall radar hourly accumulations (P_N) and MIDAS hourly rain gauge readings (P_{RG}) covering the periods (a & b) July 2007 and (c & d) December 2007. (a & c) MIDAS station 425000 (Lake Vyrnwy 2, 301200E, 318700N), NIMROD radar data from grid square centred on 301500E, 318500N. (b & d) MIDAS station 433709 (Shawbury, 355300E, 322100N), NIMROD radar data from grid square centred on 355500E, 322500N. Rain gauge data from MIDAS (2010).

Table 1 also shows the combined *MAE* values (i.e. both July and December for both stations) were approximately 18% lower for the EA disaggregated dataset ($MAE = 0.345$ mm day^{-1}) than for the NIMROD rainfall radar dataset ($MAE = 0.421$ mm day^{-1}). This suggests there was a significantly better correlation between the local hourly MIDAS stations and the EA disaggregated dataset than the NIMROD rainfall radar dataset.

The NIMROD rainfall radar and EA disaggregated datasets were compared to time series from hourly rain gauges (425000, 433709) spanning a shorter time period (19–29 July 2007) that contains instances of intense rainfall (Figure 7). This time series spans the heavy July 2007 rainfall responsible for flooding in the study area. Both datasets exhibited a good correspondence in the timing of the peaks in precipitation rate, but the amplitude of the peaks was represented more closely by the EA disaggregated dataset for both rain gauges. It should be noted that the there is a spatial discrepancy between the two datasets, and that this discrepancy is likely to be higher during convective precipitation.

Overall, the EA disaggregated hourly dataset compared favourably against the NIMROD rainfall radar hourly dataset when the two are evaluated using data from the two hourly rain gauges in the study area. This result is expected, because the precipitation quantities used to form the EA

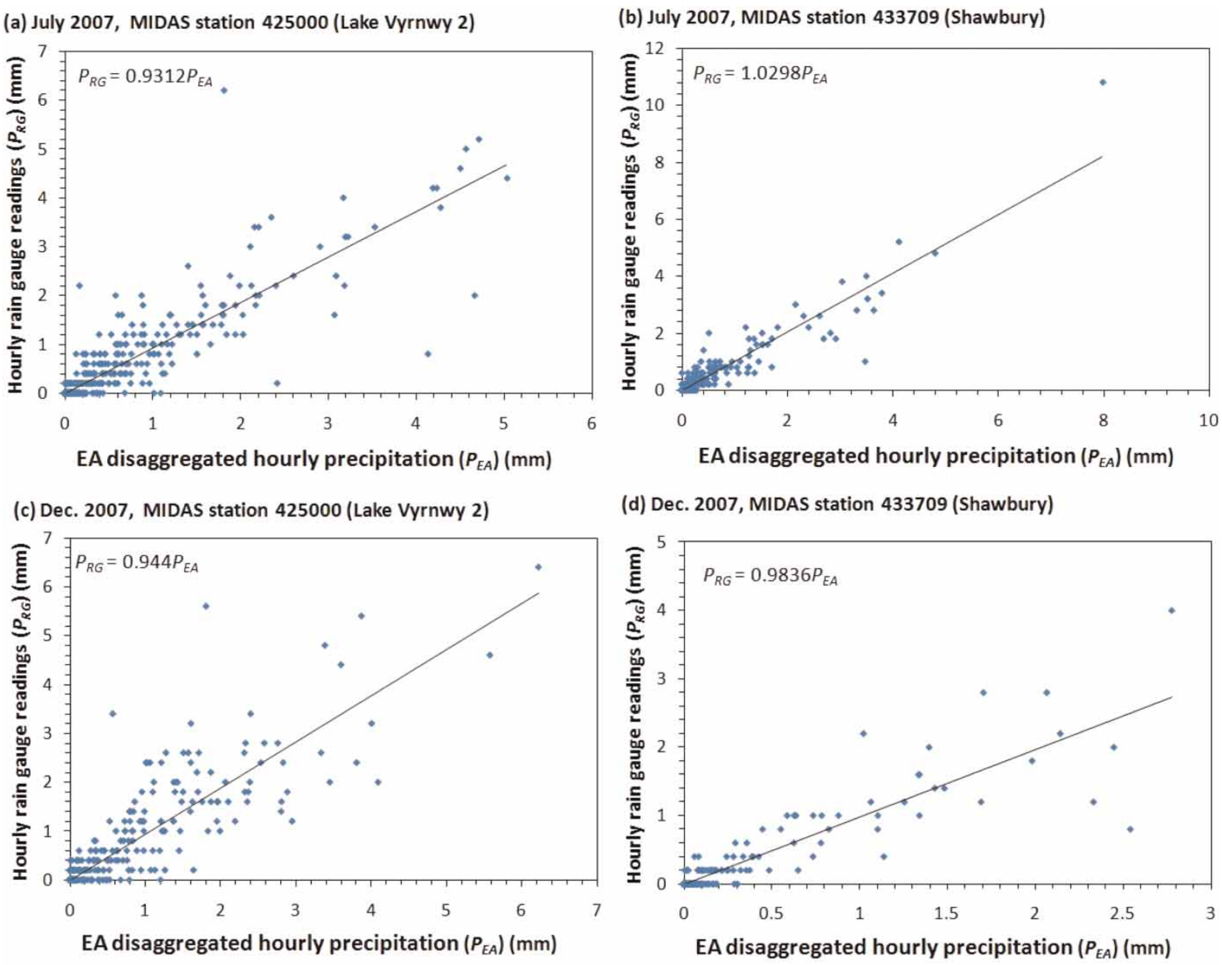


Figure 6 | Comparison between EA disaggregated hourly precipitation (P_{EA}) and MIDAS hourly rain gauge readings (P_{RG}) for (a & b) July 2007 and (c & d) December 2007. (a & c) MIDAS station 425000 (Lake Vyrnwy 2, 301200E, 318700N), EA disaggregated data from grid square centred on 301000E, 319000N. (b & d) MIDAS station 433709 (Shawbury, 355300E, 322100N), EA disaggregated data from grid square centred on 355000E, 322000N. Rain gauge data from MIDAS (2010).

disaggregated dataset were originally derived from MIDAS station data which would include stations 425000 and 433709 suggesting a self-referential aspect to the comparisons made in Figures 6 and 7. Since neither rain gauge or radar precipitation measurements can be taken as 'truth' (Ciach 2002; Biggs *et al*. 2008), a more meaningful evaluation of the precipitation datasets may be achieved through their application in a hydrological model.

Application of the hourly precipitation datasets in a hydrological model

Simulated discharge for both hourly precipitation datasets was compared to the observed discharge at the Buildwas and Montford gauging stations (Figure 8). The amplitudes of the peak flows were often poorly simulated and in particular the June and July flood events were not represented well at either gauging station by either simulation (Figure 8).

Simulations run using the EA disaggregated precipitation maps consistently performed better than those run using the NIMROD rainfall radar precipitation maps (Table 2). For example, the *NS* value for the full year simulation results at the Montford gauging station run using the EA disaggregated precipitation dataset was 0.855 compared to 0.802 using the NIMROD radar dataset. The model also performed better during winter than summer for both sets of precipitation maps, this was

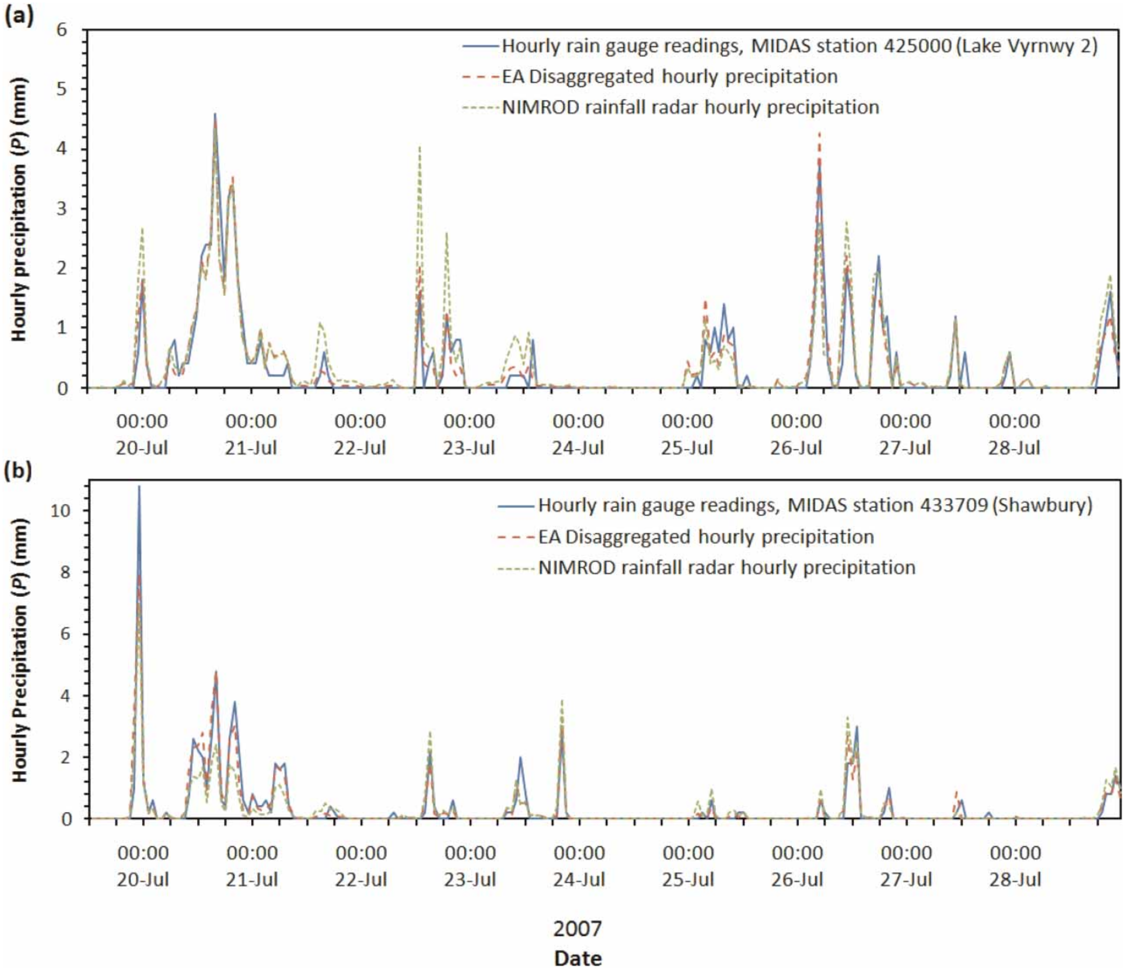


Figure 7 | Time series of hourly precipitation (*P*) from (a) MIDAS station 425000 (Lake Vyrnwy 2 E: 301,200 N: 318,700), EA disaggregated data from grid square centred on E: 301,000 N: 319,000, NIMROD radar data from grid square centred on 301500E, 318500N and (b) MIDAS station 433709 (Shawbury 355300E, 322100N), EA disaggregated data from grid square centred on 355000E, 322000N, NIMROD radar data from grid square centred on 355500E, 322500N. Rain gauge data from MIDAS (2010).

due to the poor representation of the heavy rainfall in June and July.

For variables such as discharge, which only take positive values, the standard deviation is often proportional to the mean, so it is useful to describe the variability of a time series in relative terms using the coefficient of variation (C_V) which is the ratio of the standard deviation to the mean (von Storch & Zwiers 1999). In this study $\overline{Q_{obs}}$ is consistently lower than $\overline{Q_{sim}}$ for all periods analysed (except for the June and July flood event), so C_V was used to compare the temporal variability of the observed and simulated time series (Table 3). Results suggested that, of the two simulated time series, the variability of the simulation using the EA disaggregated precipitation dataset was closest to the variability of the observed discharges. Additionally, the variability of the simulated time series was lower than the variability of the observed time series. This was in agreement with the frequency densities of discharge (Figure 9), which show the number of occurrences of hourly discharge within a given range (bin) divided by the bin size. The evident underrepresentation in Figure 9 of peaks of discharge and low flow by the simulations suggested a bias away from high and low flows, which in turn suggests low coefficients of variation (Figure 9).

Table 1 | Mean absolute error (*MAE*) (Equation (2)) values for NIMROD hourly radar and EA disaggregated hourly precipitation datasets and readings from hourly rain gauge readings from two MIDAS stations (425000, Lake Vyrnwy 2, 301200E, 318700N and 433709, Shawbury, 355300E 322100N). Rain gauge data from MIDAS (2010)

Precipitation dataset	Period	MIDAS station	*MAE* (mm day^{-1})
NIMROD rainfall radar	July 2007	425000	0.425
		433709	0.445
	December 2007	425000	0.463
		433709	0.276
	July & December 2007	425000	0.441
		433709	0.383
		425000 & 433709	0.421
EA disaggregated	July 2007	425000	0.335
		433709	0.281
	December 2007	425000	0.448
		433709	0.251
	July & December 2007	425000	0.384
		433709	0.271
		425000 & 433709	0.345

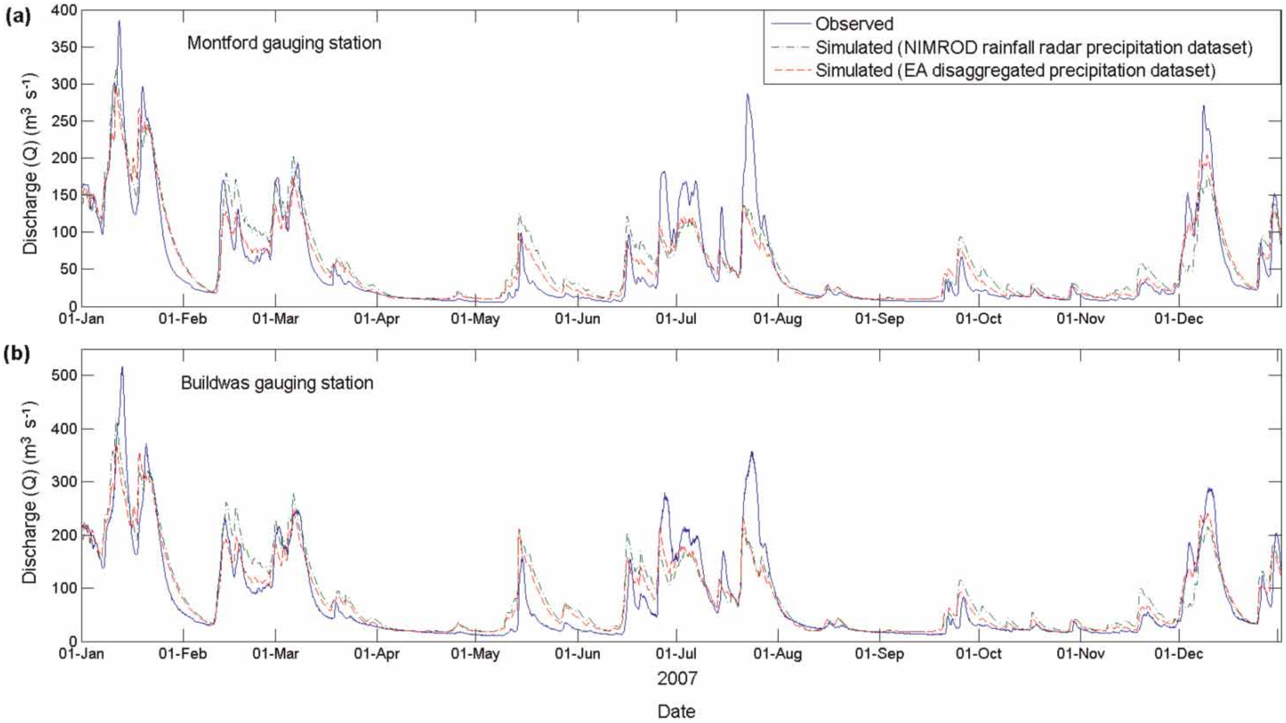


Figure 8 | Observed and simulated discharge (*Q*) for 2007 at (a) Montford and (b) Buildwas gauging stations on the upper reaches of the River Severn, UK. The simulation was performed using the LISFLOOD-RR hydrological model with the NIMROD rainfall radar and EA disaggregated hourly precipitation maps.

Table 2 | Observed mean discharge ($\overline{Q_{obs}}$), simulated mean discharge ($\overline{Q_{sim}}$) and Nash-Sutcliffe model efficiency index (*NS*) values for the Upper Severn LISFLOOD-RR model simulations using the NIMROD rainfall radar and EA disaggregated hourly precipitation maps

Period	Gauging station	Precipitation dataset	$\overline{Q_{obs}}$ (m^3 s^{-1})	$\overline{Q_{sim}}$ (m^3 s^{-1})	*NS*
2007 (entire year)	Montford	NIMROD rainfall radar	53.43	59.96	0.802
		EA disaggregated		55.32	0.855
	Buildwas	NIMROD rainfall radar	77.44	86.83	0.787
		EA disaggregated		81.07	0.844
January, February, March, October, November, December 2007 (winter)	Montford	NIMROD rainfall radar	70.95	80.45	0.857
		EA disaggregated		75.17	0.906
	Buildwas	NIMROD rainfall radar	98.17	111.22	0.847
		EA disaggregated		102.77	0.892
April, May, June, July, August, September 2007 (summer)	Montford	NIMROD rainfall radar	36.01	39.59	0.631
		EA disaggregated		35.59	0.706
	Buildwas	NIMROD rainfall radar	56.80	62.58	0.641
		EA disaggregated		59.49	0.731
1 June to 31 July 2007 (June and July floods)	Montford	NIMROD rainfall radar	77.27	67.30	0.551
		EA disaggregated		62.16	0.585
	Buildwas	NIMROD rainfall radar	118.48	106.27	0.534
		EA disaggregated		103.90	0.629

Table 3 | Coefficient of variation (C_V) values for 2007 time series of observed discharge readings and for the LISFLOOD-RR model simulations using the NIMROD rainfall radar and EA disaggregated hourly precipitation maps

Gauging station	C_V observed	Precipitation dataset	C_V simulated
Montford	1.215	NIMROD rainfall radar	0.942
		EA disaggregated	0.991
Buildwas	1.099	NIMROD rainfall radar	0.866
		EA disaggregated	0.887

DISCUSSION

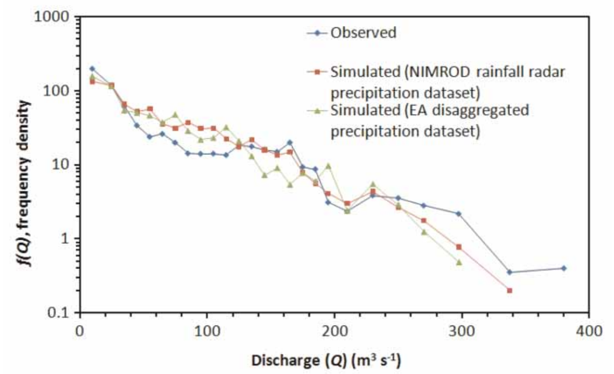
Comparing radar and rain gauge measurements of precipitation

The evaluation of the two hourly precipitation datasets indicated that the EA disaggregated performed better than the NIMROD rainfall radar dataset. This suggests that, in spite of the various quality control and correction procedures (Cole & Moore 2008), the precipitation estimates from the NIMROD rainfall radar network still lack quantitative accuracy of a rain gauge network, a result that has been established in many previous studies (see for example Collier 1989).

It has been established since the early days of weather radar that the discrepancy between rain gauge and radar precipitation readings is likely to be high when the spatial variability of precipitation is high (Wilson 1970). This situation occurs more frequently in the summer when convective rainfall is more likely (Dai 2001). The 2 days with the largest differences between rain gauge readings and radar estimates both occur in the summer (Figure 2): 16 June (radar estimate higher by 37.6 mm day^{-1}) and 25 June (rain gauge reading higher by 20.8 mm day^{-1}).

Occultation of the radar beam caused by a ground-based obstacle close to the Clee Hill rainfall radar was identified as a specific source of error in the radar precipitation estimates. But this is just one straightforward example of the many sources of inaccuracy in radar-based rainfall estimates. These sources of error and inaccuracy are generally well known, and there exist many previous studies comparing rain gauge and radar quantitative precipitation estimates to ascertain, for example, how the difference between radar and rain gauge readings varies with altitude, mean annual

(a) Montford gauging station



(b) Buildwas gauging station

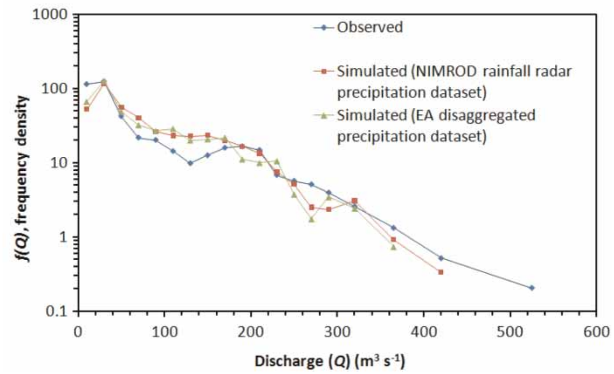


Figure 9 | Frequency densities (number of occurrences of hourly discharge within a given range (bin) divided by the bin size) of the observed and simulated discharges (*Q*) for 2007 at (a) Montford and (b) Buildwas gauging stations on the upper reaches of the River Severn.

precipitation and distance from the radar site (see for example Harrison *et al.* 2000; Collier 2009; Villarini & Krajewski 2010). An opportunity for further research with the datasets created in this study is to extend the study period beyond 2007 to highlight the extent of improvements to the long range resolution of the radar data as a result of the introduction of an improved compositing methodology introduced in mid-November 2007 (Harrison *et al.* 2009). Furthermore, developments in implementing radar ensembles and probabilistic forecasting and blending may seek to better encompass the uncertainty in using radar data in this way.

Hydrological modelling

Applying radar precipitation data in hydrological models has long been an established method of estimating the quality of the data (Collier & Knowles 1986; Collier 2009). Whilst the application of the precipitation datasets in a hydrological model provided useful additional information on their relative merits, it is not, in itself a measure of their absolute accuracy. There are some comparable studies that help to give this research some context: Biggs *et al.* (2008) use HEC-HMS, a one dimensional rainfall-runoff model, to simulate the summer 2007 flooding events on the Severn Uplands using a rain gauge interpolated precipitation dataset and rainfall estimates from the NIMROD system. For the period 1 June to 31 July 2007, they quote *NS* scores of 0.578 and 0.197 at the Montford gauging station for the rain gauge and radar derived datasets respectively (Biggs *et al.* 2008). These can be compared to the *NS* values in Table 2 of 0.551 and 0.585 for the output of the simulations at Montford for the same period in this study; however, we highlight that the two studies employed very different hydrological models and calibration techniques. The results presented here also concur with the results from Biggs & Atkinson (2010b).

SUMMARY AND CONCLUSION

This study evaluated two hourly precipitation datasets for the catchment of the Upper Severn River for the year 2007. The first dataset, referred to as the NIMROD rainfall radar dataset, was created entirely from the output of the UK Met Office's rainfall radar network (Met Office 2010). The second dataset used a 1 km gridded daily precipitation dataset based on readings from a network of rain gauges that was disaggregated using the output of the rainfall radar network to form an hourly dataset referred to as the EA disaggregated dataset.

The datasets were evaluated against daily and hourly rain gauge readings in the Upper Severn study area by comparing precipitation accumulations and time series. Discrepancies between gauge and radar derived data were examined and suggestions made for the causes of the differences. The EA disaggregated dataset correlated more strongly with the hourly rain gauge readings, showing approximately 18% less deviation from the gauge readings than the NIMROD rainfall radar dataset.

In order to assess which dataset provided the best representation of precipitation across the whole catchment, simulations were run using the LISFLOOD-RR hydrological model using the hourly precipitation datasets as model input. The discharge figures simulated by the model were compared with observed discharge readings from two gauging stations on the River Severn. The model outputs were assessed using Nash-Sutcliffe efficiency index scores, coefficients of variation and frequency densities. The model runs using the EA disaggregated datasets as model input performed better in all assessments.

The results of this study strongly suggested that the hourly precipitation dataset derived entirely from NIMROD rainfall radar data is not as good a representation of precipitation over the study area as the EA disaggregated dataset which retains the daily precipitation totals derived from a network of rain gauges but exploits the higher temporal resolution of the rainfall radar. This is in agreement with several recent studies in the UK using NIMROD radar data which show that inaccuracies and large transient errors in radar data mean flood forecasts from gauge adjusted radar do not consistently outperform gauge-only forecasts (Cole & Moore 2008, 2009; Biggs & Atkinson 2010b). However, this study has shown how rainfall radar data can be used to provide temporal detail to daily rain gauge precipitation datasets in areas where data from sub-daily rain gauges in unavailable or sparse (high elevation, mountainous areas). Importantly, it is these areas that are most likely to contain catchments liable to flash flooding, where the performance of distributed hydrological models will benefit most from hourly or sub-hourly precipitation datasets. Whilst precipitation datasets based on daily rain gauge readings cannot be applied directly in flood forecasting, they can be used to improve the calibration and validation of rainfall-runoff models that can then be driven operationally by sub-daily precipitation forecasts from numerical weather predictions.

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