Investigation of the performance of a simple rainfall disaggregation scheme using semi-distributed hydrological modelling of the Lee catchment, UK

Marie-Laure Segond, Howard S. Wheater and Christian Onof

ABSTRACT

A simple and practical spatial–temporal disaggregation scheme to convert observed daily rainfall to hourly data is presented, in which the observed sub-daily temporal profile available at one gauge is applied linearly to all sites over the catchment to reproduce the spatially varying daily totals. The performance of the methodology is evaluated using an event-based, semi-distributed, nonlinear hydrological rainfall–runoff model to test the suitability of the disaggregation scheme for UK conditions for catchment sizes of 80–1,000 km^2. The joint procedure is tested on the Lee catchment, UK, for five events from a 12 year period of data from 16 rain gauges and 12 flow stations. The disaggregation scheme generally performs extremely well in reproducing the simulated flow for the natural catchments, although, as expected, performance deteriorates for localized convective rainfall. However, some reduction in performance occurs when the catchments are artificially urbanised.

Key words | disaggregation, rainfall, runoff, semi-distributed modelling

Marie-Laure Segond (corresponding author)
Howard S. Wheater
Christian Onof
Department of Civil and Environmental Engineering,
Imperial College London,
Skempton Building,
London SW7 2AZ,
UK

Marie-Laure Segond (corresponding author)
Present address: Metnext,
17 rue de la banque,
F-75002 Paris,
France
E-mail: *marie-laure.segond@metnext.com*

INTRODUCTION

Commonly, in most developed and many developing countries, reasonably long daily rain gauge records are available to support hydrological analysis, while there are greater limitations on the number of sites and record lengths at the sub-daily scale. For instance, in the UK, there are about 4,500 daily rain gauges, but less than 10% of this number record at a sub-daily level (Met Office 2006). However, the catchment response time for many, if not most, basins studied in Europe is of the order of hours. Therefore sub-daily rainfall data as input to rainfall–runnof models are often more appropriate than daily data to accurately reproduce the flow variability. Hence there is a need for simulation methods that can generate spatial sub-daily rainfall sequences based on the typical availability of rainfall data. The development of techniques for rainfall disaggregation is currently of considerable interest. Indeed, these techniques provide rainfall data at finer temporal or spatial resolution while simultaneously providing multiple scale preservation of the stochastic structure of rainfall (Koutsoyiannis *et al.* 2003).

Various approaches to rainfall disaggregation from the daily to hourly time step can be found in the literature. These are based, for instance, on Poisson processes (Koutsoyiannis & Onof 2001), chaos theory (Sivakumar *et al.* 2001) or scale invariance (Schertzer & Lovejoy 1987; Over & Gupta 1996). However, few authors have combined the proposed disaggregation scheme with rainfall–runoff procedures. Among them, Socolofsky *et al.* (2001) described a methodology for disaggregation of daily catchment average rainfall to hourly data. The method breaks down observed daily precipitation at gauges inside the basin into storm intensity patterns by selecting samples of historical event statistics under the same climate regime from a nearby hourly gauge. The disaggregation scheme was tested with a continuous hydrological model applied to the 216 km^2 upper Charles River catchment (USA). It was found that

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river flow simulations based on daily gauges inside the basin disaggregated to hourly rainfall using a nearby gauge improved in comparison to those run using hourly rainfall from gauges outside the basin or those run with daily gauges only.

Franchini *et al.* (1996) and Maskey *et al.* (2004) observed that the appropriate characterisation of the temporal distribution of rainfall is necessary for hydrological modelling. Based on data from nine states in the US Midwest, Franchini *et al.* (1996) used a probabilistic disaggregation scheme to convert cumulative storm depths to hourly data and coupled it with an event-based rainfall–runoff model for estimation of annual exceedance probabilities of flood peaks. The authors observed a large variability of the flood peaks due to the variability of the temporal distribution of storm depths and variability in initial soil moisture conditions. In the context of real-time flood forecasting, Maskey *et al.* (2004) assessed rainfall uncertainty in rainfall–runoff modelling. They used temporal disaggregation of the precipitation over a 3 h period into sub-periods (1 h and 30 min) and allowed the uncertainty in both the temporal and spatial distributions of the rainfall to be accounted for. They applied various rainfall patterns over the catchment to assess the impact of rainfall distribution and varied the temporal pattern over the sub-basins to account for the spatial variation of rainfall. The disaggregated precipitation signal was then used as input to a rainfall–runoff routing model. Based on 60 h forecasts on a 1,744 km^2 catchment in Poland with nine sub-catchments ranging in size from 64 to 280 km^2, the authors concluded that the variation of temporal profiles over sub-basins was much less important than the need to represent the temporal structure at the large basin scale. They also observed only marginal differences when disaggregating into 30 min sub-periods instead of 1 h, which seems to indicate that an hourly time step is fine enough to model the streamflow for their application.

Finally, in a study on a 420 km^2 basin in New-Zealand, Woods & Sivapalan (1999) suggested that a rainfall representation described by an hourly spatially uniform temporal profile conditioned on storm averaged totals is appropriate for runoff production in humid temperate areas. Based on radar data, the authors argued that the spacetime rainfall field can be determined from a temporal profile of rainfall defined as the storm (space) averaged rainfall time series and scaled at any pixel location using a dimensionless rainfall space pattern.

We conclude that hourly data seem more appropriate than daily data for flow simulations in medium to large catchments of the order of, say, 100 to 2,000 km^2 (strict definition of scales is not possible due to the effects of other catchment characteristics) in humid temperate areas, and that the literature suggests that a single temporal profile of hourly rainfall may be adequate to represent the effects of temporal distribution over an area represented by several gauges. This was illustrated by Segond *et al.* (2006), who presented a methodology in which spatial variations of multisite daily rainfall are directly incorporated in a modelling framework using a Generalized Linear Model. Then the temporal profile of simulated hourly rainfall (using a single-site disaggregation procedure) of one of the sites is used to disaggregate the daily rainfall totals at the other sites to obtain multi-site sequences of hourly rainfall. They obtained satisfactory results in comparison to the observed rainfall time series. However, an important question remains concerning the subsequent effects on the runoff hydrograph. Hence this paper aims to test the suitability of the rainfall disaggregation scheme for rainfall–runoff modelling using a numerical investigation based on semi-distributed modelling of the upper catchment of the River Lee, just north of London, UK, which has a humid temperate climate. In a previous paper (Segond *et al.* 2007), the authors assessed the impact of spatial rainfall data on runoff generation using various rainfall estimators (full rain gauge network, subsets of the rain gauges and radar data) for catchment sizes of 80–1,000 km^2. Results showed a complex picture but overall it seemed that the rainfall spatial variability had a dominant effect on runoff generation. In this paper, the rainfall disaggregation procedure is assessed which, as discussed above, preserves the areal variation of daily rainfall but tests the suitability of a single temporal profile of hourly rainfall applied with linear scaling over the catchment.

The second section describes briefly the case-study area, the 1,040 km^2 Lee catchment, UK. The third section presents the methodology for rainfall disaggregation whereas the fourth section summarises the rainfall–runoff model calibration. Results of the joint rainfall and runoff procedure on rural and artificially urbanised basins are discussed in the fifth section. Finally, the conclusions are presented in the last section.

CASE-STUDY AREA

The upper catchment of the River Lee to Feildes Weir has a humid temperate climate with a mean annual rainfall of 632 mm; the elevation ranges from 20 to 250 masl. It is mainly rural, characterised by arable farming. However, the area has seen significant housing growth since the 1950s, with urban areas now covering 15% of the upper catchment. The upper catchment has six major subcatchments (the 150 km^2 Upper Lee, the 133 km^2 Mimram, the 175 km^2 Beane, the 136 km^2 Rib, the 80 km^2 Ash and the 280 km^2 Stort), which include a range of geology, land use and scales. Continuous sub-daily records from 16 rain gauges and 12 flow stations were provided by the Environment Agency of England and Wales for the period 1987–2002. In this investigation, hourly data are used. A map showing the catchment, the location of the rain gauges and flow stations is presented in Figure 1.

RAINFALL DISAGGREGATION METHODOLOGY

Segond *et al.* (2006) developed a simple approach to rainfall spatial–temporal disaggregation, based on the availability of daily observed or simulated rainfall at a network of sites and hourly rainfall at a representative gauge location, referred to as the master gauge. The resulting sub-daily time series is then applied to all other gauges over the catchment, referred to as the satellite gauges or satellite sites, linearly scaled to reproduce the correct spatially varying daily totals. This scheme was tested on 12 years of data from 21 rain gauges on the River Lee catchment and good results in terms of reproduction of standard properties of observed rainfall (1 h standard deviation, 1 h proportion of dry periods, 1 h coefficient of skewness and 1 h autocorrelation at lag 1 and 2 h) were obtained. It should be noted that, in applying our disaggregation method to a master gauge and using the same profile at the other gauges, we are in effect assuming that hourly spatial correlation is as high as daily spatial correlation.

The scheme is now illustrated on two contrasting events, representative of frontal and convective activities. The standard profile of observed hourly data of the master

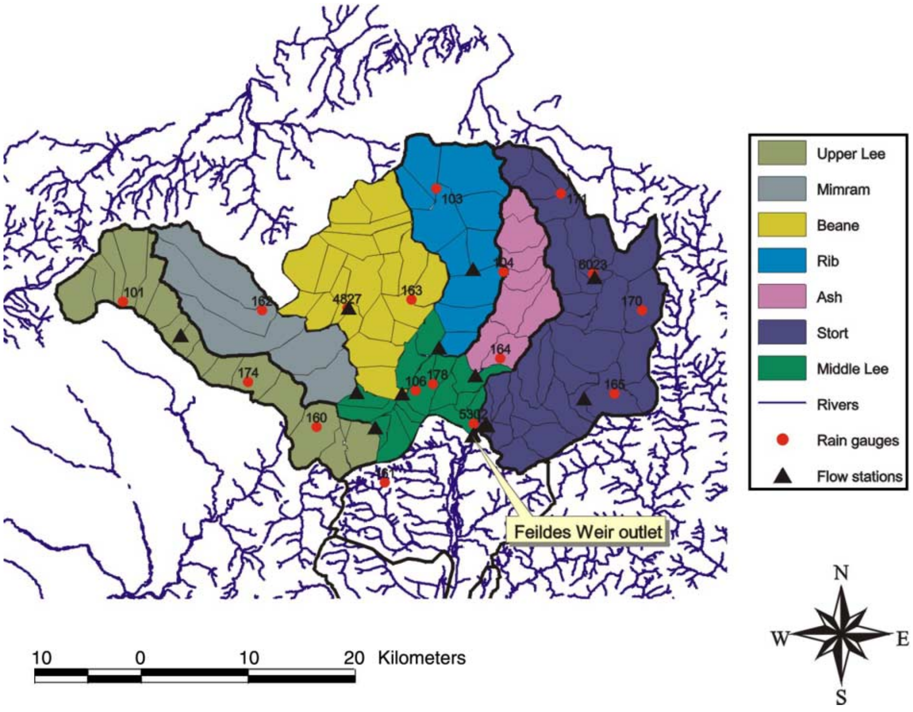

Figure 1 | Map of the Lee catchment showing the subcatchment subdivisions, rain gauge and flow station locations.

gauge (site 0163) is applied to the satellite sites and some simulated and observed profiles are presented in Figures 2 and 3 at gauges at distances ranging from 3 to 35 km from the master gauge. For the event of 3 February 1994, the modelled data reproduce well the observed series, except at site 0101. This site is on the edge of the Lee catchment, and this may indicate the limit of the application of a standard profile. The event of 3 February 1994 is representative of the usual model performance on this basin. However, exceptions exist, as illustrated by the more intense summer events of 30 July 2002 where the method shows some limitations (see Figure 3) as the rainfall is spatially highly variable.

It could be argued that this disaggregation scheme may not be adequate for rapidly moving storms. Therefore a visual inspection of an available radar archive was carried out, based on 12 years of 2 and 5 km data at 5 and 15 min temporal resolution, respectively, from the

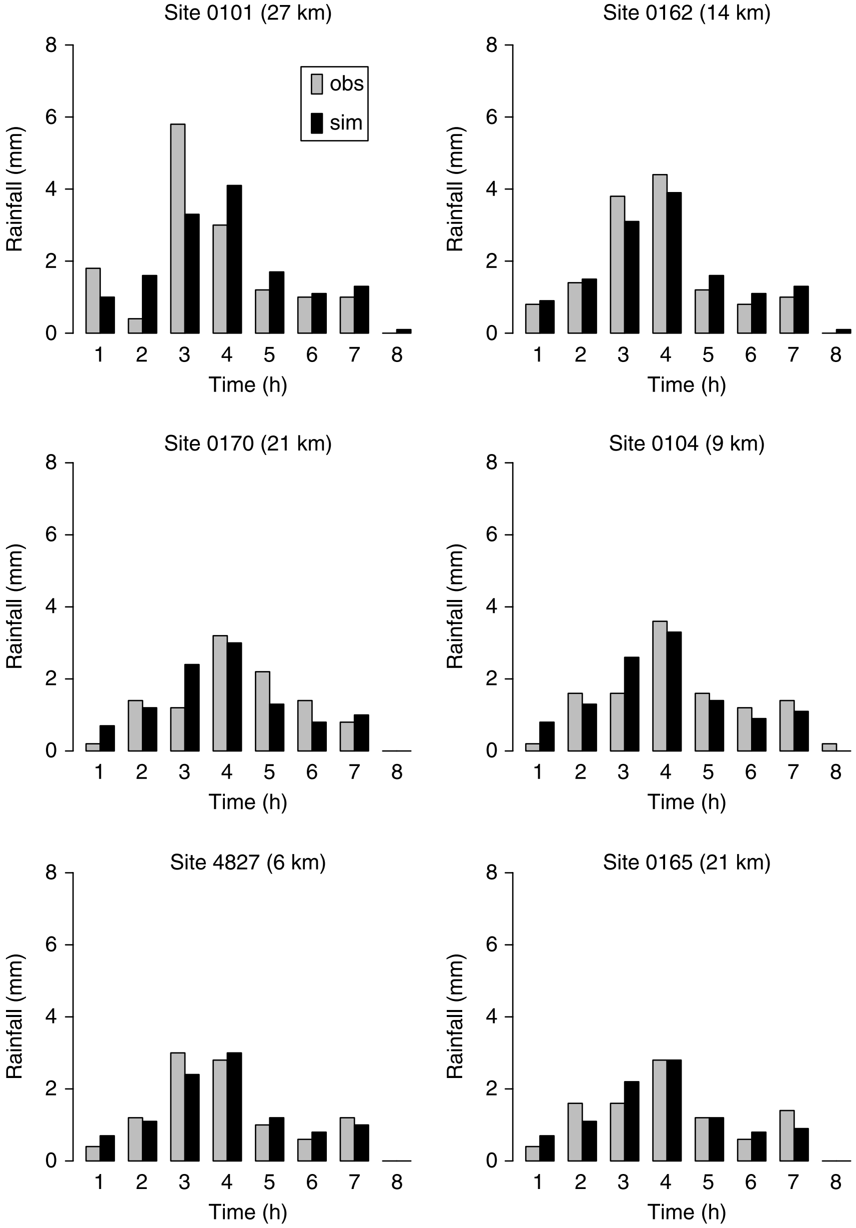

Figure 2 | Event of 3 February 1994—applying the observed profile of the master gauge to the satellite sites (distance to the master gauge is given in parentheses).

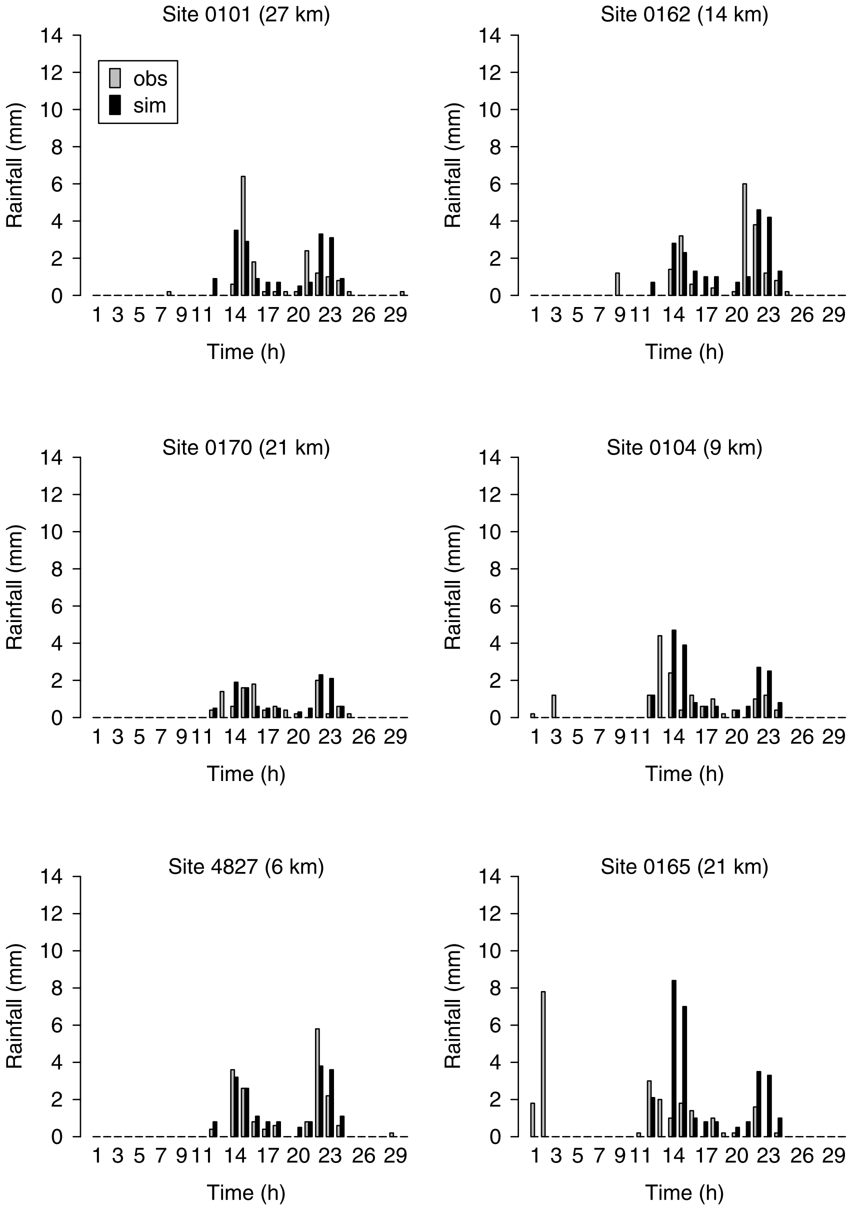

Figure 3 | Event of 30 July 2002—applying the observed profile of the master gauge to the satellite sites (distance to the master gauge is given in parentheses).

C band radar network located at Chenies, north-west of London. The radar covers the region of the Lee catchment and the data were also provided by the Environment Agency of England and Wales. Study of the radar archive revealed that the storm speed is relatively constant in this region, so that rapid storm movement was not a major concern. Further, at the large catchment scale, although the rainfall variability may increase, so does the integrating effect of the catchment (Segond *et al.* 2007) and therefore a detailed representation of rainfall may not be necessary. As illustrated in Figure 3, this scheme is too simple to model the behaviour of convective rainfall. However, as a first approach and in the context of flood management, we focus on winter rainfall, i.e. more widespread homogeneous frontal structures, and wet antecedent catchment conditions. The effects of the scheme on simulated runoff are now evaluated in this paper.

CALIBRATION OF THE UPPER CATCHMENT OF THE LEE

Here we use the semi-distributed rainfall–runoff modelling of the 1,040 km^2 catchment of the upper catchment of the Lee to Feildes Weir carried out by Segond *et al.* (2007) using the event-based hydrologic simulation model, RORB (Laurenson & Mein 1988). The six major subcatchments were first modelled independently. Then the combined flow from each subcatchment outlet was routed together to Feildes Weir to represent the whole catchment scale. It should be noted that the flow regime of the Stort is influenced by interaction between the river and the canalised Stort navigation, resulting in an erratic flowrate curve, thus making the calibration difficult at the Stort outlet, and to a lesser extent at Feildes Weir. The catchment discretisations can be seen in Figure 1.

For calibration purposes, spatially variable rainfall from the full rain gauge network (i.e. the observed hourly rainfall from all rain gauges) served as input and this rainfall descriptor is referred to as the reference rainfall. Since a relatively dense network of representative rain gauges is available, a simple method to derive the sub-areal precipitation was selected. Spatial interpolation was based on the Thiessen Polygon method; the hourly temporal pattern applied to each subarea was given by the nearest rain gauge. The simulated flow driven by the reference rainfall is referred to as the reference flow. Details of the calibration procedure can be found in Segond *et al.* (2007); a brief summary is given here.

The calibration of the rainfall–runoff model was based on a total of 28 events that span the whole dataset. Model parameter calibration and validation were based on three criteria: the reproduction of the peak outflow (Q_p), time to peak (T_p) and the well-known Nash–Sutcliffe efficiency (NSE) (Nash & Sutcliffe 1970), which is sensitive to hydrograph peak error. A relatively good fit was achieved for all tributaries with an NSE on average for all subcatchments and events of 0.88 and 0.89 in calibration and validation mode, respectively. This was considered a suitable performance basis to support the subsequent sensitivity analysis. Following validation of the individual subcatchments, they were incorporated into an integrated catchment model. Simulated runoff from each subcatchment was modelled independently, used as inflow to a middle Lee model and routed to generate the total runoff at the 1,040 km^2 catchment scale (Feildes model). A common set of events was defined in order to test the combined calibration at Feildes Weir. Due to data availability and the manual calibration procedure, these were limited to five individual storm events (Table 1) of medium to large rainfall depth. The largest rainfall event in the database, 11 October 1993, was included, leading to the highest peak flow. The others were taken at different times of the year, representative of frontal and convective rainfall and associated with high, medium and low flows. Overall, a reasonable fit is achieved with an NSE of 0.77 on average for all subcatchments and events. The individual NSE values can be found in Table 2.

JOINT TESTING OF THE RAINFALL DISAGGREGATION SCHEME WITH RAINFALL–RUNOFF PROCEDURES

As mentioned above, a spatially uniform temporal disaggregation of observed daily rainfall to hourly data is tested for hydrological applications. The sub-daily temporal profile of the master gauge 163, which is taken as the rain gauge

Table 1 | Characteristics of selected events (CV referred to the coefficient of variation in rainfall). Source: Segond *et al.* (2007)

Events	Duration (h)	Mean (mm)	CV (%)	Direct runoff (cumecs)
11 Oct 1993	65	62.7	16.9	109.1
3 Feb 1994	8	12.1	16.5	28.8
8 Jan 1996	19	20.3	14.3	30.7
16 May 1995	25	17.1	11.1	4.3
30 Jul 2002	30	21.4	42.7	4.2

Table 2 | Calibration results in terms of NSE. Source: Segond *et al.* (2007)

	Upper Lee	Mimram	Beane	Rib	Ash	Stort	Feildes
11 Oct 1993	0.92	0.55	0.54	0.96	0.94	0.75	0.84
3 Feb 1994	0.92	0.65	0.83	0.86	0.84	0.88	0.95
8 Jan 1996	0.94	0.64	0.97	0.85	0.97	0.88	0.87
16 May 1995	0.73	0.61	0.78	0.78	0.22	0.59	0.92
30 Jul 2002	0.61	0.84	0.92	0.51	0.73	0.23	0.88

Table 3 | NSE_{ref} for the disaggregation scheme applied to natural catchments

	Upper Lee	**Mimram**	**Beane**	**Rib**	**Ash**	**Stort**	**Feildes**
11 Oct 1993	0.99	0.98	0.98	0.99	0.98	0.98	0.97
3 Feb 1994	0.97	0.99	1.00	1.00	0.98	1.00	1.00
8 Jan 1996	0.98	0.99	1.00	1.00	1.00	0.96	0.99
16 May 1995	0.97	1.00	1.00	1.00	1.00	1.00	0.99
30 Jul 2002	0.92	0.96	0.95	0.99	0.99	0.98	0.96

closest to the centroid of the catchment, is applied to disaggregate the daily values at the satellite sites. Spatial interpolation using Thiessen polygons is applied. In comparison to the reference rainfall, this rainfall estimator conserves the volume and the areal variability of rainfall but uses a single temporal distribution of rainfall over the catchment. A modified definition of NSE is introduced at this stage to measure the performance of the simulated runoff from the disaggregation scheme in comparison to the reference flow:

$$\text{NSE}_{\text{ref}} = 1 - \frac{\sum_{i=1}^{M}(C_i - R_i)^2}{\sum_{i=1}^{M}(R_i - \bar{R})^2} \tag{1}$$

where C_i and R_i are the discharge calculated using the rainfall disaggregation scheme and the reference discharge with mean $\bar{R}$, respectively, at hour i. NSE_{ref} is used to eliminate model errors when comparing disaggregated rainfall to reference rainfall.

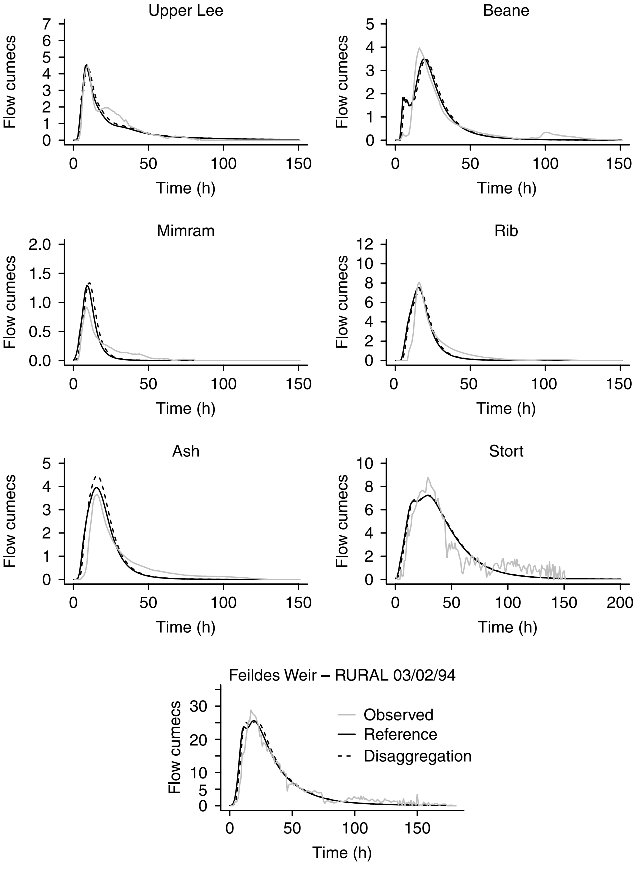

Figure 4 | Simulated flow using disaggregated rainfall on natural catchments for the event of 3 February 1994 (observed daily rainfall at all sites and hourly rainfall at master gauge, simulated hourly rainfall at other sites).

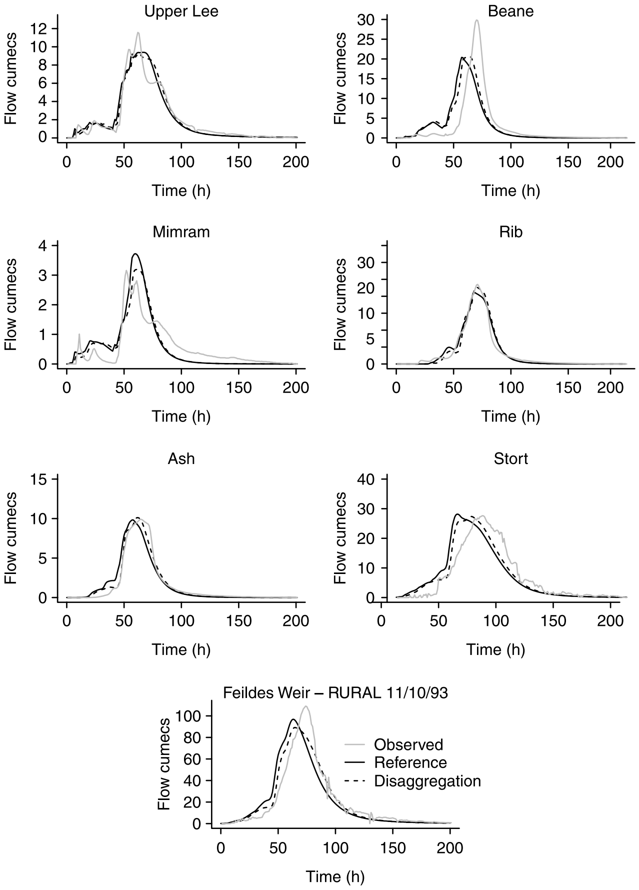

Figure 5 | Simulated flow using disaggregated rainfall on natural catchments for the event of 11 October 1993.

Results are first presented for the case of the natural basins. In a second experiment, the basins are artificially urbanised.

Results for rural catchments

Table 3 displays the NSE_{ref} results between the reference and simulated flow. Overall a close fit to the reference streamflow is obtained (NSE_{ref} about 1). The performance is slightly lower for the convective summer event of 30 July 2002 but still remains high ($NSE_{ref} > 0.92$). The comparison between the simulated and reference flows for a standard event and two contrasting events representative of extreme and convective rainfall are presented in Figures 4–6. In Figure 4, a good performance is observed between the reference and simulated hydrograph at all basin outlets for the standard event of 3 February 1994. A shift in the timing of the hydrograph is observed on the Ash, the Beane and the Stort for the extreme event of 11 October 1993, as illustrated in Figure 5. This is also observed in Figure 6 on the Ash, the Stort and Feildes Weir for the convective event of 30 July 2002. In addition, in the event of 16 May 1995, also representative of convective activity, the disaggregation rainfall estimator does not reproduce the double-peaked hydrograph on the Upper Lee, as shown in Figure 7. It should be noted that less difference is observed between the simulated and reference flows than between the reference and observed flows, which suggests that the impact of the modelling errors is higher than the errors in rainfall.

Table 4 summarises the model performance obtained using the disaggregation scheme on average for all events and subcatchments. Results are presented in terms of NSE_{ref} and are complemented by the percentage change in Q_p, T_p and V in comparison to the reference rainfall. Overall small variations are obtained for the case of the rural catchments. Since there is a trade-off between the rainfall variability and the integrating effect of the catchment, a simple disaggregation procedure can be applied with good modelling performance. This test reveals that, provided the areal variations of rainfall are preserved, a single temporal profile is adequate to model runoff on natural catchments

Results for urban catchments

In this subsection, we artificially turned the subcatchments into urban basins to explore the applicability of the disaggregation scheme on fast responding watersheds. The effect of urbanisation on runoff is due to (a) increase in impervious area which increases the amount of runoff and (b) hydraulic improvement of flow paths which speeds up the response. RORB handles (a) by changing

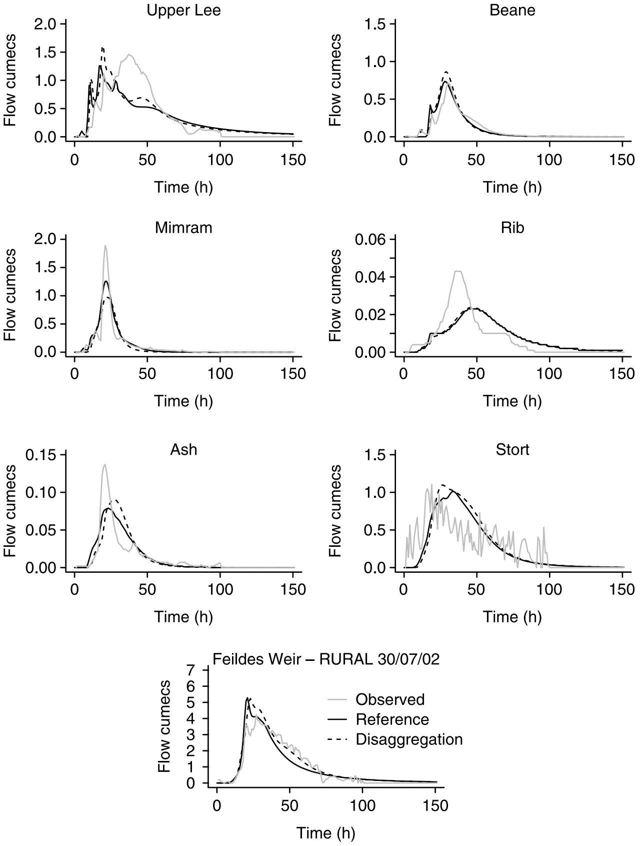

Figure 6 | Simulated flow using disaggregated rainfall on natural catchments for the event of 30 July 2002.

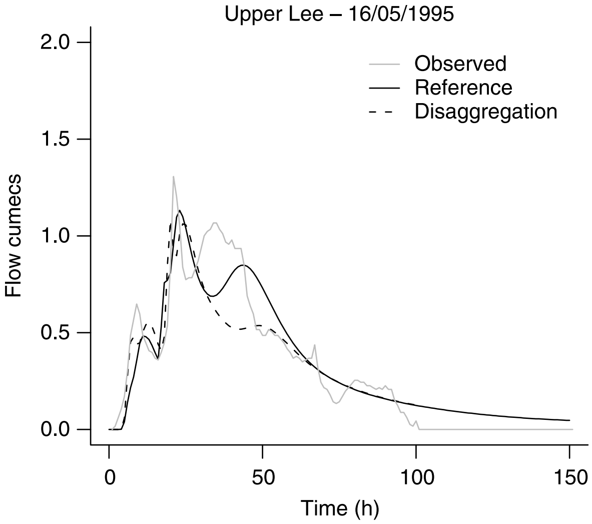

Figure 7 | Simulated flow using disaggregated rainfall on the Upper Lee for the event of 16 May 1995.

Table 4 | Summary performance on natural and urbanised catchments

	Rural	Urban
NSE_{ref}	0.98	0.94
Q_p (%)	6.6	9.0
T_p (%)	6.5	15.5
V (%)	4	4.1

the percentage of impervious area. The value input for each sub-area is the proportion of impervious surface which connects in some way to the drainage system. The hydraulic improvement (b) is dealt with using the Reach Type Flag in the model, which adjusts the hydraulic routing (Laurenson & Mein 1988). As in Segond *et al.* (2007), a fraction imperviousness of 30% was applied to all subareas and, with the exception of the Stort, by changing the reach type from Natural to Lined (or Piped) with a slope of 0.1% to ensure a faster response. The disaggregation scheme is tested and the simulated runoff is compared as before to the flow obtained with the reference rainfall. The comparisons between the simulated and reference flows for three contrasting events are presented in Figures 8–10.

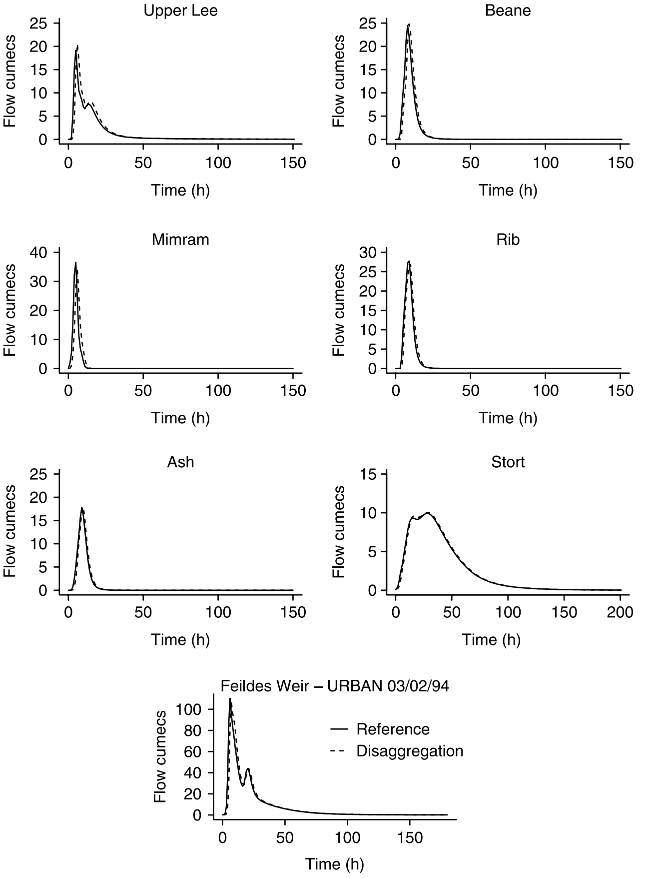

Figure 8 | Simulated flow using disaggregated rainfall on urbanised catchments for the event of 3 February 1994.

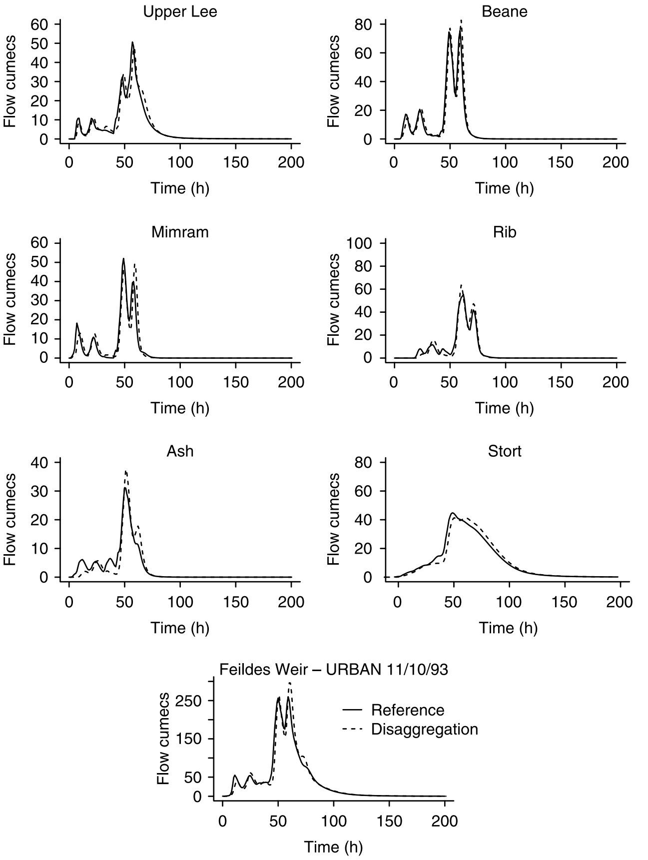

Figure 9 | Simulated flow using disaggregated rainfall on urbanised catchments for the event of 11 October 1993.

As seen in Table 5, the model performance remains high for the artificially urbanised basins with an NSE_{ref} of 0.94 on average for all events and subcatchments. Examining the results for the individual subcatchments, results show that the model performance is lower for the Mimram and the Ash on 30 July 2002 (NSE_{ref} of 0.71 and 0.33, respectively). In particular, the disaggregation rainfall estimator does not reproduce the double-peaked hydrograph on the Ash and lower performance at the catchment scale is also observed (NSE_{ref} of 0.88) for this event (see Figure 10). This indicates the limit of the disaggregation scheme which is not appropriate for temporally variable rainfall, as in the case of localised convective storms, when modelling fast-responding urban basins.

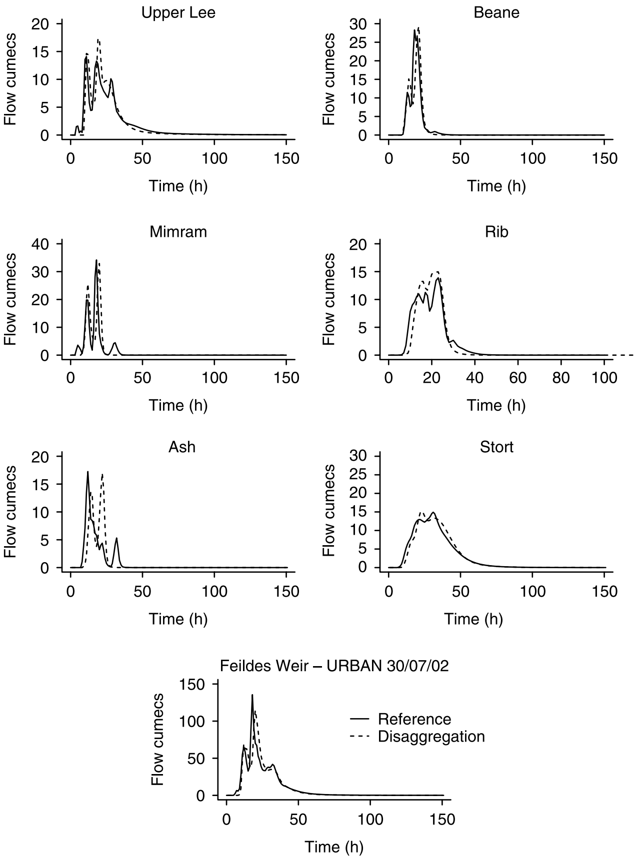

Figure 10 | Simulated flow using disaggregated rainfall on urbanised catchments for the event of 30 July 2002.

A summary of the model performance characteristics obtained on average for all catchments and events and for all rainfall representations on urbanised catchments is presented in Table 4. For the artificially urbanised basins, some degradation in performance occurs, especially for the reproduction of T_p (percentage change of 15.5% compared to 6.5% for the natural catchments), although the high performance is maintained (NSE_{ref} of 0.94 on average).

Table 5 | NSE_{ref} for the disaggregation scheme on urbanised catchments

	Upper Lee	Mimram	Beane	Rib	Ash	Stort	Feildes
11 Oct 1993	0.98	0.94	0.99	0.93	0.90	0.97	0.97
3 Feb 1994	0.98	0.98	1.00	0.99	0.99	1.00	1.00
8 Jan 1996	0.98	0.97	0.93	1.00	1.00	0.97	0.99
16 May 1995	0.93	0.83	0.96	0.96	0.97	0.99	0.96
30 Jul 2002	0.92	0.71	0.93	0.88	0.33	0.98	0.88

CONCLUSIONS

The methodology for disaggregation of observed daily rainfall to hourly information was tested with respect to simulated runoff response. Using this scheme, the spatial pattern of daily rainfall is preserved, but a single subdaily temporal profile of rainfall is applied uniformly in space. For the natural catchments, a close fit ($NSE_{ref} > 0.92$) between the simulated flow and the reference flow is obtained, suggesting that the damping effect of the catchments compensates for the lack of rainfall temporal variability at sub-daily scale in space. However, as might be expected, some deterioration in performance occurred when the catchments were artificially urbanised: the lowest NSE_{ref} recorded is 0.33, the peak flow performance is somewhat decreased and larger errors in the timing of the peak are observed (15.5%). This suggests that a scheme accounting for the spatial variations of temporal rainfall is required to model adequately the behaviour of urban basins. This is in agreement with the findings from the literature which recommend fine spatial and temporal resolution of the order of kilometres and minutes (Berne *et al.* 2004) for the modelling of urban catchments. Further, in some cases, it was observed that double-peaked hydrographs were not adequately reproduced both for rural and urbanised basins.

Overall, when there is a lack of available rainfall data at sub-daily time scale, this simple disaggregation scheme conditioned on real or simulated daily rainfall can provide a useful alternative. The main limitations concern the unsuitability of the method for highly urbanised basins and convective rainfall and the method is applicable only for a limited spatial extent. The maximum spatial extent to which this method can be applied will depend upon the spatial correlation structure: the assumption that hourly spatial correlation is close to daily spatial correlation becomes less tenable as the inter-gauge distance gets larger.

Radar data can be used to estimate hourly rainfall in convective events; however, long sequences of homogeneous radar data are not always available. The procedure presented here can be readily implemented, recommended with some confidence for frontal rainfall in the case of rural catchments up to about 1,000 km^2 and is expected to have applicability to regions with a similar climatic regime.

The method proved to be suitable on an event basis; possible extension of this work involves testing the rainfall methodology with continuous hydrological simulations.

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