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The Significance of Spatial Variability of Rainfall on Runoff

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Abstract: A key issue in rainfall-runoff modelling is to assess the importance of the spatial representation of rainfall on streamflow generation. Distributed models have the potential to represent the effects of spatially variable inputs such as rainfall making them an appropriate tool to investigate the role of spatial rainfall on runoff. This paper explores the importance of spatial rainfall representation for rainfall-runoff modelling as a function of catchment scale and type. The study investigated the effect of catchment scale and type using 9 gauged catchments ranging in size from 30 to 1040 km². Regional relationships between known catchment characteristics and model parameters have been developed to overcome the task of estimating model parameter values at ungauged subcatchments. The results indicate the importance of considering the effect of spatial rainfall in most of the catchments with the significance of spatial effects increasing at small spatial scales. Finally, the importance of spatial variability is enhanced when impermeable areas are investigated.

Keywords: Spatial rainfall; Calibration; Semi-distributed modelling; Rainfall-runoff models.

1. INTRODUCTION

One question that arises in rainfall-runoff studies is: “How important is the spatial nature of rainfall to runoff response?” In a recent review, Singh [1997] concluded that the significance of spatial rainfall varies as a function of catchment rainfall properties, catchment scale and type and antecedent conditions. Much effort has further been devoted to gain a better understanding of the role of spatial rainfall on runoff [Bell and Moore, 2000, Smith et al., 2004, Segond et al., 2007] concluding that the spatial rainfall can influence considerably the volume of runoff, peak runoff and time to peak. However, although the literature on the relationship between spatial rainfall and runoff generation is extensive, results have been contrasting and sometimes contradictory.

Hydrological models can be classified based on the spatial variation of inputs such as rainfall and model parameters into: (a) lumped; and (b) distributed [Beven, 2001]. Spatially distributed models, compared to lumped, have the potential to represent the effects of spatially variable inputs making them an appropriate tool to investigate the role of spatial rainfall on streamflow estimation [Arnaud et al., 2002, Tetzlaff and Uhlenbrook, 2005]. However, calibration of distributed models is rarely a straightforward task, due to the large number of parameter values that may need to be estimated [Carpenter and Georgakakos, 2006]. A variety of distributed model calibration strategies have been suggested to take into account the spatial heterogeneity of model parameters; most of these involve applying a priori parameter estimates based on regionalisation approaches [Wagener and Wheater, 2006].

This paper presents the initial results of a study on the significance of spatial rainfall on runoff, considering 8 years of hourly historic data from 9 flow gauges within the Upper Lee catchment, UK. From the 8 years, five storm events were analysed in detail. For each of these events, the simulated hydrograph response using three representations of the
spatial variability of the rainfall data (i.e. averaging over four different spatial scales) was investigated. The paper also presents a simple approach to calibrating a distributed model.

2. REVIEW OF THE INFLUENCE OF SPATIAL RAINFALL ON STREAMFLOW

The picture obtained from the literature is that the spatial nature of rainfall is a significant factor controlling runoff response. However, this effect is likely to be less clear-cut when humid temperate catchments are investigated, due to the trade-off between the impact of spatial variability of rainfall and dampening and filtering effect of the catchment [Smith et al., 2004, Segond et al., 2007].

The suitable spatial resolution of rainfall measurements for hydrological purposes is linked to the size of the catchment with the importance of spatial rainfall decreasing at bigger catchment scales [Woods and Sivapalan, 1999]. For small (< 100 km²) and medium to large (100-2000 km²) catchments, the spatial resolution of rainfall is important and more precise areal rainfall estimates are required [Arnaud et al., 2002]. Studies show that as the scale increases, the catchment response time distribution becomes the dominant factor governing the runoff generation [Bell and Moore, 2000].

Effects of spatial rainfall are also likely to vary depending on the effect of antecedent catchment conditions [Singh, 1997]. In general, good runoff predictions are obtained with spatially averaged rainfall input under wet conditions. However, for dry catchment conditions, the runoff prediction errors are seen to be considerably higher than for the wet conditions [Arnaud et al., 2002]. This result suggests that there is an interaction between the spatial rainfall and the spatial distribution of soil moisture which controls runoff prediction.

The proportion of rainfall becoming direct runoff is also controlled by the permeability of the catchment and can mask the impact of spatial rainfall [Tetzlaff and Uhlenbrook, 2005]. On pervious catchment areas, rainfall variations are damped by the integrating reaction of the catchment, whereas on impervious areas a high proportion of precipitation becomes effective rainfall. Impervious catchments are fast responding and studies showed that a high density rain gauge network is required for runoff modelling [Berne et al., 2004].

Urbanisation has a great effect on runoff generation. Regarding the significance of spatial rainfall on runoff taking into account that the land use is urban, the conclusion is that small urban catchments require very dense rain gauge networks and weather radar data are an interesting alternative [Dodov and Foufoula-Georgiou, 2005].

Additionally, the runoff response is sensitive to the rainfall type [Koren et al., 1999]. Knowledge of spatial rainfall is important in rainfall-runoff modelling especially when simulating extreme events in the summer [Bell and Moore, 2000]. The error in runoff simulation is decreased for convective rainfall events when spatially high resolution data are applied. However for single frontal events with a longer duration, the spatial distribution of rainfall has less influence on mean catchment rainfall because the low variability of these type of events [Arnaud et al., 2002].

The importance of spatial rainfall is dependent upon the rainfall-runoff modelling strategy. A fine model discretisation is preferable to avoid loss of rainfall information due to averaging at too large scale [Koren et al., 1999]. Although studies found that large errors may arise when a lumped instead of a distributed model is applied to the catchment, the use of the latter type of models introduces large uncertainties in model parameters due to the spatial variability of rainfall [Chaubey et al., 1999].

3. CATCHMENT DESCRIPTION

The significance of spatial rainfall variability was assessed using observed data from the 1040 km² Upper Lee catchment (Fig. 1) in the Thames region, UK. The catchment is characterised as humid temperate with mean annual precipitation of 632 mm, while the elevation varies between 20 and 250 meters above UK ordnance datum.
Historical hourly flow and rainfall data were provided by the Environment Agency of England and Wales for the period 1991-1998. The location of the flow stations and raingauges can be found in Fig. 1. In the current analysis only the following gauged catchments are used: Water Hall (150 km²), Stevenage (31), Hertford (176), Griggs Bridge (50), Wadesmill (136), Mardock (79), Sheering (55), Glen Faba (278), and Feildes Weir (1040).

The 150 km² Upper Lee subcatchment has a flow gauge in Luton Hoo and Water Hall. The Upper Lee at Luton Hoo is mainly chalk with high permeability. Most of Luton Hoo area is urban, followed by arable and horticulture. On the other hand the rest of Upper Lee subcatchment until the Water Hall gauge has a smaller proportion of urban areas. Chalk soil characterizes the 130 km² Minram subcatchment. Although, the catchment is homogeneous and mainly rural, there is a small urban segment due to the city of Welwyn Garden. The Beane subcatchment of 176 km² has two flow gauges located on Stevenage and Hertford. It consists of rural and urban area due to the build-area of Stevenage city. The soil type is chalk and clay. The most part of the 136 km² Rib subcatchment is rural, with a small proportion of urban. The soil type is chalk which is under laid by extensive deposits of boulder clay. There are two available flow gauges at Griggs Bridge and Wadesmill. The Ash subcatchment is the smallest one with an area of 79 km² and is classified as mainly rural. Only a very small proportion of the subcatchment is covered by urban areas. The soil type of Ash is clay. The Stort has the largest subcatchment area of 278 km². In the upper part of Stort the area is mainly rural, whereas the valley in the lower part is urban. Three cities of Bishop Stortford, Sawbridgeworth, and Harlow affect the runoff. The geology is chalk and clay. Overall, the 1040 km² Upper Lee at Feildes Weir is mainly rural, characterised by arable farming. The area has seen significant growth in housing, with urban areas covering 15 % of the total area.

A relatively fine subdivision of the subcatchments into subunits of about 15-25 km² is applied, so that the model spatial discretisation is not the major control on how well the spatial rainfall can be represented. As there is one raingauge per 60 km² on average, a smaller subdivision seems unjustified. The locations of the subdivisions are based on the soil and land cover type, and stream network.

4. RAINFALL RUNOFF MODELLING

4.1 Model description

The Probability Distributed Model, PDM [Moore, 2007] assumes that rainfall during each time step accumulates in the soil moisture store, where a specific function is used to describe the distribution of storage capacity over the catchment (Fig. 2).
The soil moisture storage is depleted by evaporation as a linear function of the potential rate and the volume in storage. The soil moisture storage capacity, $c$, is assumed to be described by a Pareto distribution (Eq. 1).

$$ F(c) = 1 - \left(\frac{c}{c_{\text{max}}}\right)^b $$

where $c$ is the storage capacity in the catchment, $c_{\text{max}}$ is the maximum capacity at any point in the catchment, and $b$ controls the spatial variability of storage capacity over the catchment.

The effective rainfall $ER$ is equal to positive values of Eq. 2 integrated over the catchment area.

$$ ER_k = r_k - ae_k - c_k + s_{k-1} $$

where $r$ is the rainfall (mm) in time step $k$, $s$ is the spatially variable soil moisture storage (mm), and $ae$ is the actual evapotranspiration which is assumed equal to the potential evapotranspiration multiplied by the relative saturation of the catchment.

The PDM was combined with a routing component consisting of two linear reservoirs in parallel, representing the quick and slow response of the system. The parameter $%q$ defines the proportion of total effective rainfall going to the fast response reservoir, while $k(\text{quick})$ and $k(\text{slow})$ are the time constants of the fast and slow reservoirs, respectively. The simulated streamflow at the outlet of the subunit is determined by the combination of the two pathways. The latter is routed to the catchment outlet through a channel routing module consisting of a conceptual linear reservoir with residence time $T$.

### 4.2 Model identification method

The PDM model parameters for every subunit were first estimated using a regionalisation method. This method is summarised by:

- Calibration and validation (8 and 4 years respectively) of each of the gauged subcatchments in the Upper Lee using a lumped PDM model. The Nash Sutcliffe Efficiency, NSE, was used for the calibration.
- Regression analysis to relate the calibrated model parameters and known catchment characteristics. The catchment characteristics (land cover, soil type, climate and topography) are taken from the Flood Estimation Handbook [details in NERC, 1999].
- Using the regression equations (Table 1), estimate the parameter values for all the subunits within the subcatchments. Hence the equations, developed at the subcatchment scale, are assumed to apply to the smaller subunit scale [details in Pechlivanidis et al., 2007].
- Spatial multipliers are used to optimise the regionalised estimates to gauged streamflow at the case study subcatchments. Whereas the parameter estimates vary spatially, the multipliers do not, hence the values of each parameter are adjusted consistently across the subcatchment. This limits the calibration burden to 6 multipliers per subcatchment, despite the much larger number of parameters. This calibration of the multipliers was done using a uniform random search (URS),
whereby 30,000 sets of the multipliers were randomly sampled from pre-defined ranges and the one which led to the best performance using the NSE for each subcatchment individually was adopted. The initial soil moisture condition was not calibrated. However, the first 20% of the time-series was used as a warm-up period (during which the discrepancies were neglected in calculation of NSE) in order to remove sensitivity to initial conditions.

Table 1. Relationships of PDM model parameters with catchment characteristics

<table>
<thead>
<tr>
<th>Equation</th>
<th>Partial R</th>
<th>Total R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{\text{max}} = 25,093 - 1,240.6,10^x \times \text{URBCONC} - 6,780.56 \times \ln(\text{RMED}_2D) )</td>
<td>-0.79</td>
<td>0.88</td>
</tr>
<tr>
<td>( b = 0.022 - 202.14,10^x \times \text{AREA} + 3,593 \times \text{URBEXT1990} )</td>
<td>-0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>( k(\text{quick}) = -843.7 + 24.414 \times \text{RMED}_2D + 17.753 \times \ln(\text{URBEXT1990}) )</td>
<td>0.76</td>
<td>0.83</td>
</tr>
<tr>
<td>( k(\text{slow}) = 8755 + 3741.904 \times \ln(\text{BFIHOST}) - 18151.5 \times \text{URBEXT1990} )</td>
<td>0.62</td>
<td>0.64</td>
</tr>
<tr>
<td>( % q = 1.923 - 0.003 \times \text{DPLBAR} - 0.418 \times \ln(\text{ALTBAR}) + 0.013 \times \text{SPRHOST} )</td>
<td>-0.83</td>
<td>0.98</td>
</tr>
<tr>
<td>( T = 30.7 + 0.074 \times \text{SAAR} - 43.811 \times \text{URBEXT1990} + 66.538 \times \ln(\text{PROPWET}) + 4.1 \times \ln(\text{DPLBAR}) )</td>
<td>0.97</td>
<td>0.99</td>
</tr>
</tbody>
</table>

4.3 Experiments with spatial rainfall

The investigation of the impact of spatial variability of rainfall on runoff was approached considering three spatial representations of rainfall: 1) No spatial variation in rainfall: rainfall is assumed uniform over the entire Upper Lee catchment; 2) No spatial variation in rainfall at subcatchment scale: rainfall is assumed uniform over each of the 9 subcatchments; and 3) Full spatial variation in rainfall: rainfall is variable within the subcatchments and estimated for each subunit. The arithmetic average of the subcatchment subunits provides the subcatchment and catchment mean areal rainfall. The Inverse Distance Weighting method was used to spatially interpolate rainfall from the 17 raingauges over the entire Upper Lee catchment. A prior statistical analysis did not show strong relationship (R² = 0.26) between rainfall distribution and catchment properties (elevation, exposition etc.); therefore the interpolation approach did not considered any topographical aspects.

The PDM model was initially calibrated for each subcatchment and rainfall scenario to assess the effect of spatial rainfall resolution on achievable model performance in terms of NSE over the 8-year calibration period. Then, the model parameter sets were kept constant at the values optimised using rainfall Scenario 3, and the three scenarios of rainfall were applied in turn, to investigate the effect of spatial rainfall on runoff. This was evaluated by measuring the change in NSE, and the percentage change from the observed data in the peak runoff, time to peak, and runoff volume for a rainfall event. Overall, five rainfall events were selected from the simulated period, which represent different types of rainfall event as described in Table 2.

Various spatial properties of rainfall (e.g. variability location, mean, volume, maximum, duration, antecedent conditions, and evaporation) have been estimated for each event. However, the current analysis only focuses on the spatial variability of rainfall. The Spatial Deviation Index (ISDI) [Segond et al., 2007] was defined for each storm event and catchment as a measure of spatial variability of rainfall, with high values of ISDI indicating high spatial variability.

Table 2. Rainfall events and spatial characteristics for the Fieldes Weir catchment

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (hrs)</th>
<th>ISDI</th>
<th>Volume (10⁶ m³)</th>
<th>Mean (mm/hr)</th>
<th>Maximum (mm/hr)</th>
<th>Peak runoff (cumecs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/10/1992</td>
<td>18</td>
<td>0.47</td>
<td>2.94</td>
<td>1.68</td>
<td>4.57</td>
<td>27.48</td>
</tr>
<tr>
<td>03/02/1994</td>
<td>7</td>
<td>0.209</td>
<td>1.22</td>
<td>1.68</td>
<td>3.5</td>
<td>36.63</td>
</tr>
<tr>
<td>22/01/1995</td>
<td>32</td>
<td>0.231</td>
<td>2.46</td>
<td>1.49</td>
<td>4.9</td>
<td>49.38</td>
</tr>
<tr>
<td>08/01/1996</td>
<td>26</td>
<td>0.213</td>
<td>2.25</td>
<td>1.28</td>
<td>3.02</td>
<td>35.44</td>
</tr>
<tr>
<td>09/11/1998</td>
<td>12</td>
<td>0.273</td>
<td>0.67</td>
<td>0.59</td>
<td>1.36</td>
<td>14.47</td>
</tr>
</tbody>
</table>
5. RESULTS

The effect of spatial rainfall resolution on achievable NSE performance can be found in Table 3. On average for all subcatchments NSE values of 0.72, 0.75 and 0.76 are observed for Scenario 1, 2 and 3 respectively. Although, a finer resolution rainfall (Scenario 3) performs better on average, the difference in model performance between Scenarios 2 and 3 is not considered significant, while in some cases Scenario 2 outperforms Scenario 3. The available raingauge network structure could be a factor influencing the results as it might not support a finer spatial resolution than Scenario 2 (subcatchment scale).

Table 3. Model performance for the 8 years period based on NSE objective function

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>Stevenage</th>
<th>Griggs Bridge</th>
<th>Sheering</th>
<th>Mardock</th>
<th>Wadesmill</th>
<th>Water Hall</th>
<th>Hertford</th>
<th>Glen Faba</th>
<th>Feildes Weir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0.660</td>
<td>0.663</td>
<td>0.657</td>
<td>0.738</td>
<td>0.738</td>
<td>0.727</td>
<td>0.667</td>
<td>0.824</td>
<td>0.842</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0.690</td>
<td>0.686</td>
<td>0.765</td>
<td>0.761</td>
<td>0.740</td>
<td>0.801</td>
<td>0.681</td>
<td>0.868</td>
<td>0.858</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>0.689</td>
<td>0.677</td>
<td>0.763</td>
<td>0.776</td>
<td>0.745</td>
<td>0.798</td>
<td>0.684</td>
<td>0.869</td>
<td>0.859</td>
</tr>
</tbody>
</table>

Fig. 3(a) plots the NSE performance against the I SDI for all five events and all subcatchments using the fixed parameter set, illustrating the impact of the three rainfall representations on the NSE. The PDM model performs equally under all the three rainfall scenarios for less spatially varied events (Feb 1994, Jan 1995, Jan 1996 in Table 2). The importance of considering finer rainfall information is enhanced for the other two events. In the latter case, NSE values improved by up to 15 % when Scenario 3 rainfall was considered rather than Scenario 1. The conclusions from Fig. 3(a) are similar to those from previous case studies [Bell and Moore, 2000, Segond et al., 2007].

On Figs. 3(b-d), the catchments are ordered along the x-axis from smallest to largest scale. For each catchment there are five sets of three points plotted, corresponding to three rainfall scenarios for each of the five events. Each set of three points shows how the peak, volume and timing of each hydrograph change using the different representations of spatial rainfall. The Upper Lee is a relatively heterogeneous catchment; hence conclusions should be derived considering land cover and type properties, as well as catchment scale.

The impermeable clay/urban subcatchment of Sheering is most sensitive to the spatial distribution of rainfall with respect to runoff peak and volume (Figs. 3b,c,e). Results indicate the importance of a fine rainfall resolution when more spatially varied rainfall events occur (the first and last of the five events). An underestimation in the peak and runoff volume of 30 and 40 % respectively could occur in small impermeable catchments if spatial rainfall variability is not considered. However, there is significantly less improvement to hydrograph shape in the less spatially variable events. This was acknowledged in previous case studies [Tetzlaff and Unlenbrook, 2005]. Results from the larger impermeable Glen Faba subcatchment show that there might be a decrease in the significance of spatial information as the scale increases. This conclusion was justified by Segond et al. [2007]. It is interesting to see that the small urban subcatchment of Stevenage shows no significant sensitivity to spatial rainfall. The spatial model discretisation and the lack of raingauge stations near the city of Stevenage could explain this result. No clear relationship could be identified for the time to peak (Fig. 3d).

Some of the more permeable subcatchments (Mardock and Hertford) seem to damp the spatial variability of the rainfall input, based on peak and volume results (Fig. 3b,c,f). However, this is not such a significant effect for other permeable catchments (e.g. Wadesmill and Water Hall). Fine rainfall resolution does not significantly improve performance for the three less spatially variable events, while it slightly does so for the other two.

Although the hydrographs were quite insensitive to the spatial representation of rainfall at the largest two catchments (Glen Faba and Feildes Weir), there was no clear evidence that sensitivity decreases at larger scales, as previously reported by Segond et al. [2007].
Further work is underway to include more catchments and more events, and to consider more of the spatial properties of the rainfall, in order to improve the evaluation.

Figure 3. (a) Impact of spatial rainfall representation on NSE model performance;
Percentage change from the observed data for each rainfall event in: (b) peak flow, (c) volume, (d) time to peak for each subcatchment ranked according to catchment scale, and (e-f) streamflow simulation for all scenarios for Sheering and Mardock for 20th Oct

6. CONCLUSIONS

The importance of spatial variability of rainfall on runoff as a function of catchment scale and type and rainfall properties was demonstrated in the present study through a semi-distributed rainfall-runoff model. The model was calibrated using calibration multipliers based on a priori parameter values derived from regional relationships between known catchment characteristics and model parameters. Three rainfall scenarios were used corresponding to different degrees of spatial rainfall aggregation over the catchment, while a statistical analysis of five rainfall events indicated the importance of spatial rainfall on model performance and hydrograph properties.

Results show that spatial rainfall can influence the achievable model performance in terms of NSE by up to 15% when high spatially variable events are investigated. Although it is acknowledged in previous studies, there was no clear evidence that the sensitivity of runoff generation to spatial rainfall is related to catchment scale. Impermeable subcatchments are more sensitive than permeable subcatchments to the spatial variability of rainfall, particularly when spatially varied rainfall events occur. This sensitivity is significantly decreased in the case of less spatially variable events. Two permeable catchments seem to
damp the effect of the spatial variability of rainfall. However, this is not evident for the other permeable catchments. More events should be considered in the future studies to provide more coherent conclusions. Further research should also include use radar data to consider spatial variability of rainfall within the subunits, and also more detailed investigation of the significance of catchment type.

REFERENCES


