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# A robust and parsimonious regional disaggregation method for deriving hourly rainfall intensities for the UK

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## Abstract

A regional rainfall disaggregation method from daily to hourly intensities is presented for the entire UK, which was developed for use with regionalised hydrological and water quality models. The approach is based on the inter-dependence of the hourly rainfall intensities during a rainfall event. The analysis of 23 229 days with at least 15 mm of precipitation from 238 weather stations throughout the UK allowed regional parameters for climatically homogeneous regions of the UK to be derived for each season. The method reproduces well the main statistical characteristics of the data (mean, minimum and maximum intensity and standard deviation). The method is fully operational, computationally efficient and can be applied to any location throughout the UK.

## 1. Introduction

Water quality legislation is increasingly requiring standardized approaches to management and monitoring across regions and countries. Regionalised models (e.g. nitrates: Lord and Anthony, 2000; pesticides: Holman et al., 2004; erosion: Brazier et al., 2001; phosphorus: Hutchins et al., 2002) are an important tool for helping comply with legislation in a cost-effective manner, allowing *ex ante* evaluation of the effectiveness and consequences of environmental and agricultural policy measures. Many of these models tend to operate on a daily timestep, combining the mechanisms of infiltration-excess and saturation-excess runoff generation into a single process. Although infiltration excess surface runoff is generally accepted as being less important in humid and temperate regions, it is becoming increasingly apparent that it can be an important process in a wide range of soils (Evans 1996) due to land use changes or to farming practices which impact on the infiltration characteristics of the soil (Holman et al., 2003). However, in many countries there are insufficient numbers of rainfall stations recording the necessary sub-daily data to directly allow national-scale simulation. For example, the Meteorological Office in the UK runs a network of more than 5000 rainfall stations, but hourly rainfall data are only collected for a few hundred stations.

One solution to obtain fine temporal resolution rainfall data is to disaggregate the coarse (e.g. daily) data. Disaggregation is achieved by applying stochastic rainfall models to reproduce the main statistics of the data. The two main categories of such stochastic models are profile-based (e.g. Hershenhorn and Woolhiser, 1987; Koutsoyiannis and Xanthopoulos, 1990) and pulse-based (e.g. Onof and Wheater, 1993; Cowpertwait et al., 1996a) rainfall models, but all were developed for use with individual station data (Cameron et al., 2000) which are inappropriate for regional or national studies.

Only a few attempts have been made to derive regional parameters for stochastic rainfall models. Econopouly et al. (1990) found that it was possible to export the calibrated Hershenhorn and Woolhiser (1987) model over a long distance in the United States of America if the condition of climatic similarity was respected. Gyasi-Agyei (1999) tried to compute regional parameters in Australia for the Gyasi-Agyei – Willgoose model. Cowpertwait et al. (1996b) derived regional parameters for Great Britain but used only 27 sites with hourly records. Koutsoyiannis et al. (2003) presented a methodology for spatial-temporal disaggregation aimed at generating hourly rainfall series for several sites from daily rainfall series from all the sites and hourly rainfall series from at least one site.

These methods showed the promise of regional rainfall disaggregation but failed to propose robust operational methods because of the complexity of multi-site parameter estimation (Kottegoda et al., 2003; Favre et al., 2002). Nevertheless robust, computationally efficient regionalised disaggregation methodologies will be required for water quality modelling to support regional and national policy. The aim of this study is therefore to develop a robust and parsimonious rainfall disaggregation method from daily to hourly intensities that is applicable throughout the UK.

## 2. Data set

A total of 389 stations spread over England, Wales, Scotland and Northern Ireland corresponding to 5798 station/years with hourly rainfall data between 1983 and 1999 have been analysed. Only intense rainfall episodes have been selected, defined as days (from 09:00 a.m. to 09:00 a.m.) when the total daily rainfall was ≥15 mm. Table 1 summarises the distribution of the 23 229 intense events and 238 stations for the 9 homogeneous regions (Fig. 1) defined following Gregory et al. (1991).

## 3. Statistical analysis

Meteorological processes may vary depending on the period of the year (Guntner et al., 2001), but the small number of intense rainfall events for the summer months in some regions necessitated the aggregation of several months to get significant samples of data. Consequently the analysis has been carried out for 4 seasons (winter: January–March; spring: April–June; Summer: July–September; Autumn: October–December) in the 9 regions.

### 3.1. Analysis strategy

Let $h_k$ be the dimensionless hourly rainfall intensity at hour $k$ in its discrete form:

$$h_k = \frac{q_k}{\sum\limits_{j=1}^{n} q_j} \quad (1)$$

where $q$ is the observed hourly intensity in mm/h and $n$ the length of the rainfall event. In this study, the adopted approach is equivalent to assume that there was only one rainfall event per day, Eq. (1) becomes:

$$h_k = \frac{q_k}{\sum_{j=1}^{24} q_j} \quad (2)$$

The dimensionless hyetograph expresses the dimensionless accumulated quantity of rainfall after $k$ hours.

$$H_k = \sum_{j=1}^{k} h_j = \frac{\sum_{j=1}^{k} q_j}{\sum_{j=1}^{24} q_j} \quad (3)$$

Kottegoda et al. (2003) and Garcia-Guzman and Aranda-Oliver (1993) suggested that the successive values of $H_k$ were not independent. We propose here to describe this dependence of the dimensionless hourly rainfall intensities by representing the dimensionless intensity during the most intense hour by a statistical distribution, and by defining explicit relationships between the dimensionless intensities during the most intense hour and the other hours (Boughton, 2000).

### 3.2. Hour of maximum rainfall

The 24 hourly rainfall intensities are classified from the most intense hour to the least intense hour and noted as $q_1$ to $q_{24}$. $h_1$ is derived from Eq. (2) and then represented by a statistical distribution covering all rainfall events in the climatically homogeneous region. It was hypothesised that $h_1$ was best described by the Log-Normal distribution (Fig. 2), which was assessed using a Kolmogorov-Smirnov two-sample test. In 81% of the 36 Kolmogorov-Smirnov tests (9 climate zones and 4 seasons) the hypothesis could not be rejected at $\alpha$=0.05, and in 95 % of the cases at the 0.01 level. The Log-Normal distribution was therefore adopted as the best description of the dimensionless intensity of the hour of maximal rainfall. Values of the mean and the standard deviation of the Log-Normal distributions for the climatic region-season combinations are given in Table 2.

The fitted mean and standard deviations of the Log-Normal distributions show regional variations due to the climatic variations over the UK, corroborating the climatic regions used. In the summer, the fitted mean values increase from west to east associated with a transition from rainfall associated with Atlantic depressions, which create frontal precipitation events with a moderate intensity over rather long periods, to convectional events generating heavy showers and thunderstorms. In winter periods the reverse is true with fitted mean values decreasing eastwards. The UK is the first land met by Atlantic fronts which get weaker as they move east. In all regions the mean values have their maximum for the summer period and their minimum for the winter. Consequently, these seasonal variations are more severe for the eastern regions than the western regions where the precipitation events are more stable in both amount and type.

### 3.3. Other 23 intensities

The other 23 dimensionless intensities $h_k$ are directly related to the rainfall amount during more intense hours:

$$h_k = \frac{q_k}{\sum_{j=1}^{24} q_j} = r_k * \left( \sum_{j=1}^{k-1} h_j \right) \quad (4)$$

with $k$ the hour number between 2 and 24 and $r_k$:

$$r_k = \frac{q_k}{\sum_{j=1}^{k-1} q_j} \quad (5)$$



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It was found that the best type of regression to express the relationship between rainfall depths $r_k$ and $h_1, h_2 \ldots, h_{k-1}$ is exponential (Fig. 3). $h_k$ is therefore expressed as:

$$h_k = -\left(\frac{\sum_{j=1}^{k-1} h_j}{p}\right) \ln\left(\frac{\sum_{j=1}^{k-1} h_j}{100}\right) \quad (6)$$

Values of $p$ for the 2nd to 5th hours are given in Table 2. The distributions of the coefficients of determination for the regressions are graphically presented in Fig. 4 for the 2nd, 3rd, 4th and 5th hours. These coefficients of determination tend to improve towards the less intense rain hours as the information on the shape of the hyetograph held by previous hours increases.

## 4. Evaluation

The disaggregation method was evaluated for the 9 climate regions of the UK. The relative intensities of the first hours were selected randomly from the calibrated Log-Normal distributions and then the intensities in subsequent hours were derived using the correlation formulae. As an example, Fig. 5 compares the observed and predicted rainfall intensities for the Central England region in summer for the first 4 h. The evaluation tested whether the disaggregation method reproduces the standard and extreme statistics (Cameron et al., 2000) of the observations for each hour.

Because the disaggregation method outputs rainfall intensities and not time series, the analysis was limited to the mean intensity, standard deviation, maximum and minimum dimensionless intensities. The minimum dimensionless intensity is well reproduced. Figure 6 shows the results for the mean intensity, standard deviation and maximum dimensionless intensity for the first 4 h.

The two-sample t test was used to determine if the observed and predicted intensities were drawn from populations with the same mean. In 90% of the cases the hypothesis could not be rejected at the 5% level for the first 4 h. Although, this proportion deteriorated for the 5th hour, when the hypothesis could not be rejected in only 45% of the cases, the rainfall intensities are unlikely to be significant for generating infiltration-excess runoff.

The standard deviation is generally well predicted, it is only slightly underestimated for the highest intensities of the first and second hours. The prediction of the maximum hourly intensities was also generally good, although a greater dispersion of the predictions for the high events above 30 mm/h around the 1:1 line was observed (Fig. 8).

Globally, this disaggregation method proves to be robust and to give satisfactory results.

## 5. Conclusions

A robust and parsimonious disaggregation method from daily to hourly rainfall intensities applicable in homogeneous regions of the UK for water resources modelling is presented. The method assumes that the intensity during the most intense hour dictates the type of rainfall event and therefore the intensities during the other 23 h of the day. Consequently, these 23 fractions are directly related to the rainfall amount falling during more intense hours. 23 229 days with at least 15 mm of precipitation from 238 meteorological stations spread over the UK were analysed. In 81% of the cases the Log-Normal distribution represents well the relative rainfall intensities during the most intense hour, and that the relations between rainfall depths are well explained using an exponential regression.

An evaluation of its capability to reproduce the main statistics of the data concluded that it is successful for its purpose for water resources modelling, although it showed some discrepancies with the observations for the infrequent very intense events. Nevertheless the significant advantages of the proposed method are: 1) its national appli-



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cability, as all parameters have been determined for 9 regions dividing the UK, and 2) its extreme simplicity of use.

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**Table 1.** Distribution of the meteorological stations and rainfall events.

| Region | Number of Stations | Number of events |
|---|---|---|
| Northern Ireland(NI) | 15 | 942 |
| North of Scotland (NS) | 21 | 3284 |
| East of Scotland (ES) | 16 | 1241 |
| South of Scotland (SS) | 32 | 4443 |
| North West England (NWE) | 14 | 1689 |
| North East England (NEE) | 22 | 1107 |
| South West England (SWE) | 49 | 5260 |
| Central England (CE) | 28 | 2089 |
| South East of England (SEE) | 41 | 3216 |
| Total | 238 | 23 229 |

**Table 2.** Regionalised seasonal parameter values for the UK.

| Region | | 1st hour Mean | Std Dev | 2nd hour *p* | 3rd *p* | 4th *p* | 5th *p* |
|---|---|---|---|---|---|---|---|
| NI | Winter | 3.048 | 0.44 | 2.03 | 2.86 | 3.38 | 3.75 |
| | Spring | 3.160 | 0.56 | 2.01 | 2.90 | 3.46 | 3.87 |
| | Summer | 3.225 | 0.40 | 1.91 | 2.71 | 3.21 | 3.45 |
| | Autumn | 3.015 | 0.39 | 1.96 | 2.76 | 3.27 | 3.55 |
| NS | Winter | 2.897 | 0.38 | 2.05 | 3.02 | 3.58 | 3.92 |
| | Spring | 2.932 | 0.43 | 2.03 | 2.93 | 3.49 | 3.78 |
| | Summer | 3.103 | 0.42 | 1.94 | 2.78 | 3.33 | 3.74 |
| | Autumn | 2.984 | 0.36 | 1.97 | 2.74 | 3.19 | 3.51 |
| SS | Winter | 2.974 | 0.43 | 2.06 | 2.90 | 3.37 | 3.62 |
| | Spring | 3.046 | 0.44 | 2.02 | 2.91 | 3.42 | 3.79 |
| | Summer | 3.146 | 0.43 | 1.88 | 2.73 | 3.25 | 3.47 |
| | Autumn | 3.018 | 0.37 | 1.98 | 2.81 | 3.22 | 3.44 |
| ES | Winter | 2.754 | 0.42 | 2.22 | 3.24 | 3.83 | 4.17 |
| | Spring | 2.991 | 0.48 | 2.08 | 2.96 | 3.51 | 3.84 |
| | Summer | 3.110 | 0.49 | 2.00 | 2.90 | 3.44 | 3.78 |
| | Autumn | 2.985 | 0.42 | 2.06 | 2.92 | 3.48 | 3.93 |
| NEE | Winter | 2.876 | 0.45 | 2.14 | 3.10 | 3.59 | 4.02 |
| | Spring | 3.045 | 0.47 | 2.09 | 3.04 | 3.63 | 4.14 |
| | Summer | 3.324 | 0.46 | 1.82 | 2.65 | 3.17 | 3.55 |
| | Autumn | 2.991 | 0.45 | 2.00 | 2.84 | 3.44 | 3.79 |
| NWE | Winter | 3.056 | 0.49 | 2.05 | 2.91 | 3.44 | 3.79 |
| | Spring | 3.102 | 0.48 | 1.96 | 2.80 | 3.36 | 3.75 |
| | Summer | 3.341 | 0.44 | 1.81 | 2.53 | 2.99 | 3.26 |
| | Autumn | 3.158 | 0.39 | 2.01 | 2.81 | 3.29 | 3.53 |

**Table 2.** Continued.

| Region | | 1st hour Mean | Std Dev | 2nd hour $p$ | 3rd $p$ | 4th $p$ | 5th $p$ |
|---|---|---|---|---|---|---|---|
| SWE | Winter | 3.059 | 0.39 | 2.00 | 2.87 | 3.25 | 3.52 |
| | Spring | 3.123 | 0.48 | 1.95 | 2.77 | 3.24 | 3.57 |
| | Summer | 3.339 | 0.42 | 1.72 | 2.46 | 2.80 | 3.08 |
| | Autumn | 3.101 | 0.37 | 1.94 | 2.80 | 3.29 | 3.54 |
| CE | Winter | 3.050 | 0.52 | 2.05 | 2.98 | 3.50 | 3.81 |
| | Spring | 3.075 | 0.49 | 1.95 | 2.82 | 3.34 | 3.74 |
| | Summer | 3.444 | 0.53 | 1.80 | 2.61 | 2.96 | 3.22 |
| | Autumn | 3.127 | 0.47 | 1.97 | 2.78 | 3.31 | 3.66 |
| SEE | Winter | 3.143 | 0.47 | 1.98 | 2.82 | 3.26 | 3.39 |
| | Spring | 3.297 | 0.49 | 1.82 | 2.58 | 2.99 | 3.33 |
| | Summer | 3.514 | 0.52 | 1.71 | 2.38 | 2.76 | 2.99 |
| | Autumn | 3.182 | 0.39 | 1.96 | 2.74 | 3.18 | 3.44 |

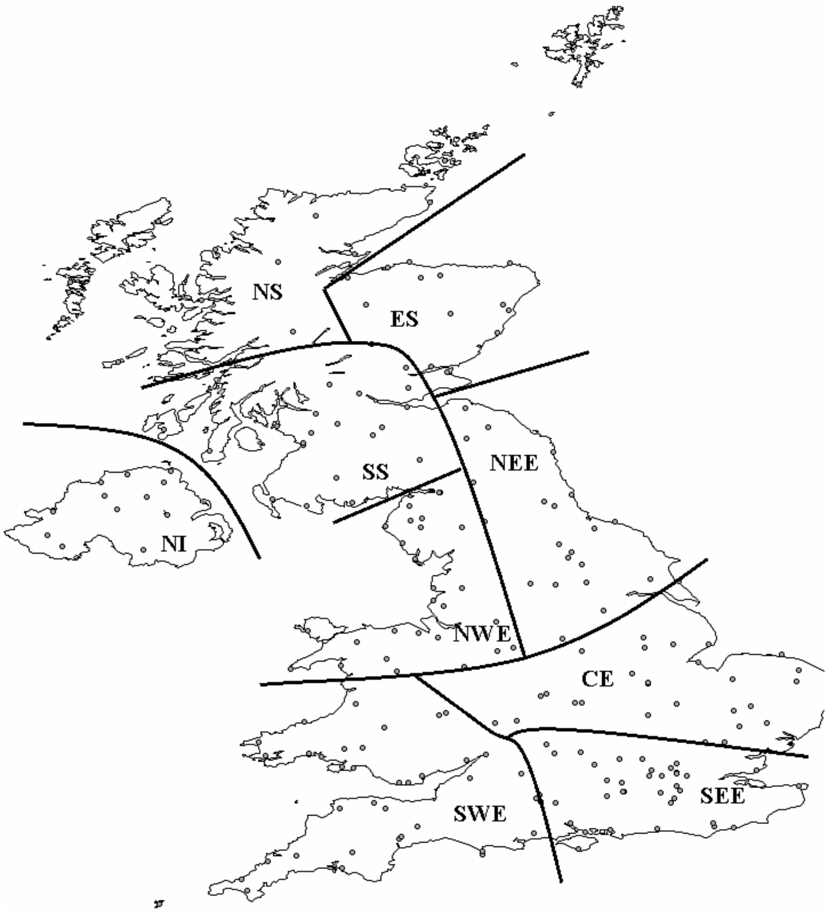


**Fig. 1.** The homogenous climate regions (adapted from Gregory et al., 1991) and the location of the meteorological stations providing hourly data.



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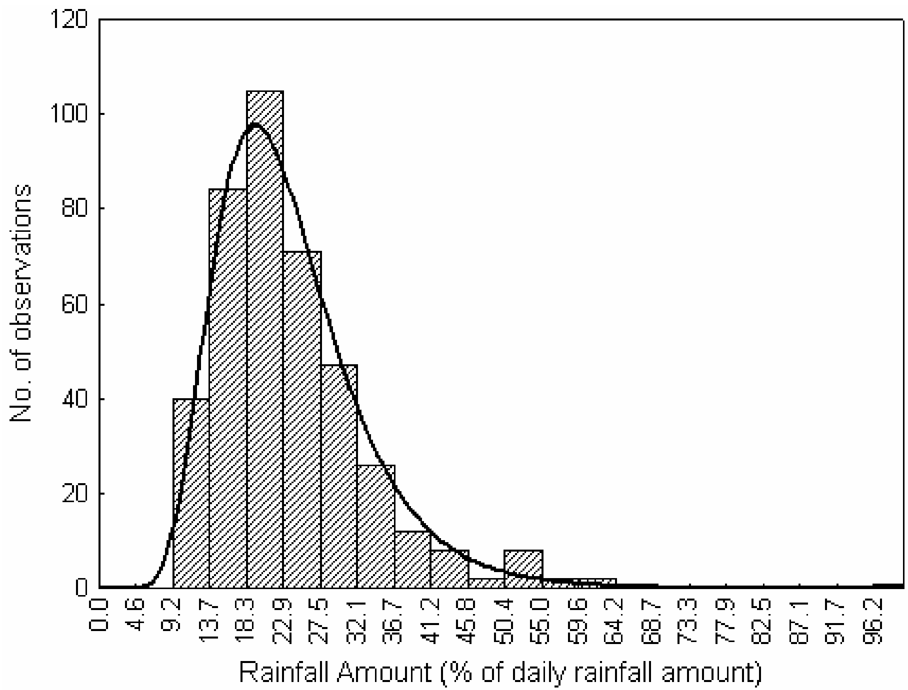


**Fig. 2.** Distribution of the relative rainfall intensity of the 1st hour $h_1$ – Central England region in spring.




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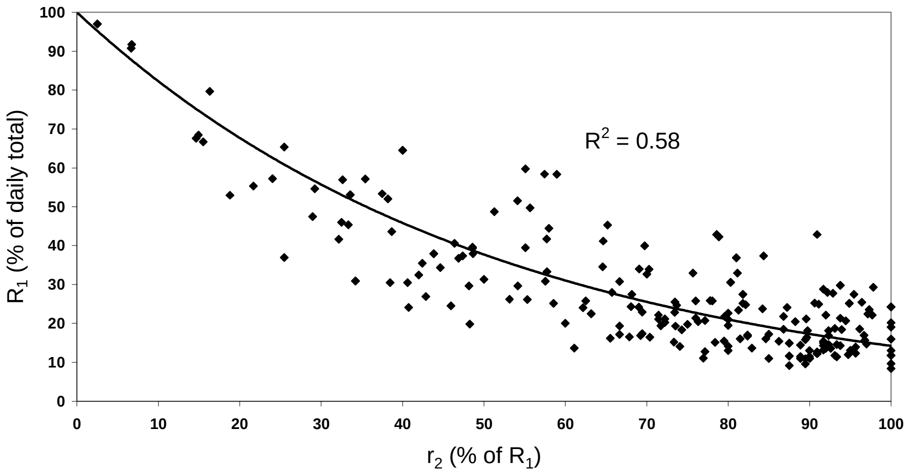


**Fig. 3.** Regression analysis of the relative rainfall intensity of the 2nd hour $r_2$ – spring CE region.

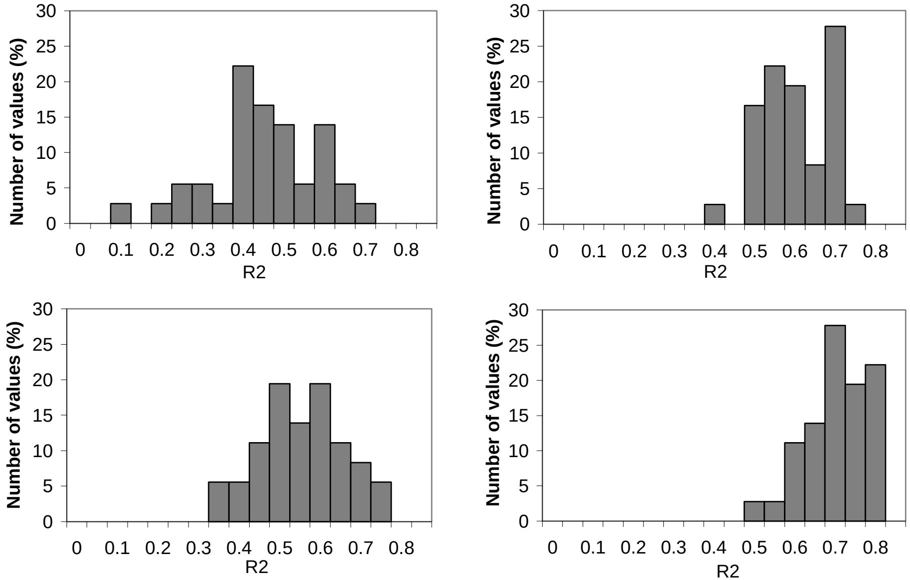


**Fig. 4.** Distribution of the coefficients of determination for top left: 2nd hour, top right: 3rd hour, lower left: 4th hour and lower right: 5th hour for all climatic regions and seasons.



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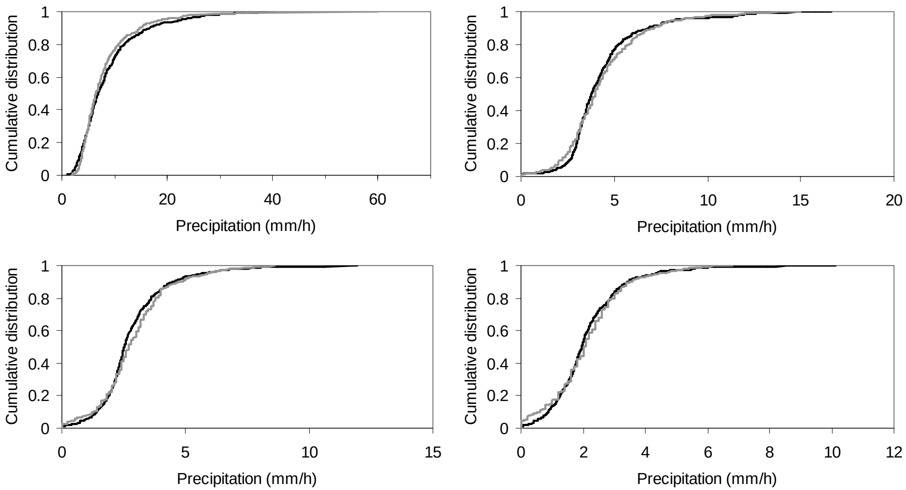


**Fig. 5.** Comparison of observed (grey line) and predicted (black line) rainfall intensities for top left: the 1st hour, top right: the 2nd hour, lower left: the 3rd hour and lower right: the 4th hour – Central England region in summer.

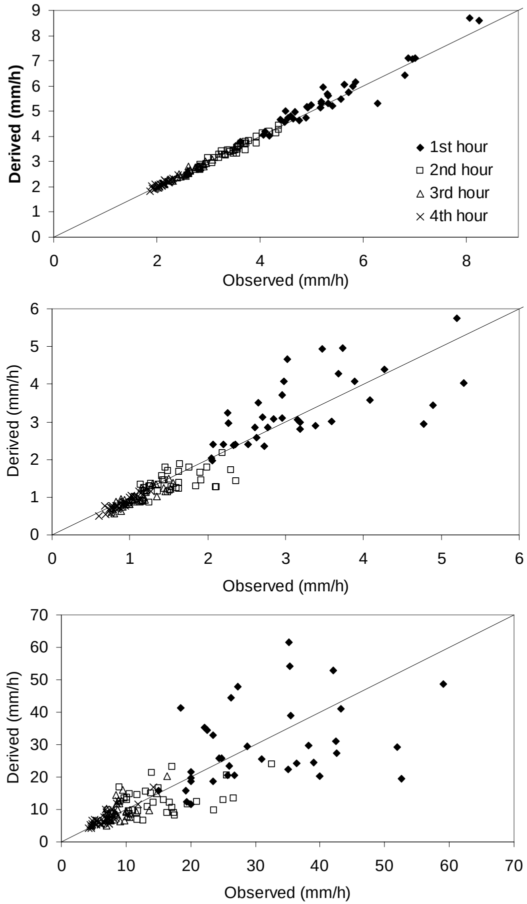


**Fig. 6.** Comparison of predicted vs observed (top) hourly mean intensities, (middle) standard deviation of hourly mean intensities and (lower) maximum hourly intensities for all climatic regions.



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