

## Rainfall spatial variability in the application of Catchment Morphing for ungauged catchments

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### ABSTRACT

Catchment Morphing (CM) is a newly proposed approach to apply fully distributed models for ungauged catchments and has been trialled in several catchments in the UK. As one of the most important input datasets for hydrological models, rainfall spatial variability is influential on the stream variabilities and simulation performance. A homogenous rainfall was utilized in the previous experiments with Catchment Morphing. This study applied a spatially distributed rainfall from CEH-GEAR rainfall dataset in the morphed catchment for ungauged catchments as the follow-on study. Three catchments in the UK were used for rainfall spatial analysis and CEH-GEAR rainfall data were adopted for additional spatial analysis. The results demonstrate the influence of rainfall spatial information to the model performance with CM and illustrate the ability of morphed catchment to deal with spatially varied information. More spatially distributed information is expected to be introduced for a wider application of CM.

**Key words:** Catchment Morphing, rainfall spatial variability, streamflow prediction, ungauged catchments

### HIGHLIGHTS

- Rainfall spatial variability is important for streamflow predictions.
- Catchment Morphing is a useful approach for ungauged catchments.
- Spatially variable rainfall inputs can benefit streamflow predictions using Catchment Morphing.

## 1. INTRODUCTION

Although the availability of various hydrological models with more complex structures is increasing, the application in ungauged catchments is still limited due to the obstacle of transferring knowledge from gauged to ungauged catchments (Sivapalan 2003). One reason is that some hydrological models (e.g. conceptual models) have specific assumptions and simplifications to keep the model efficient, which makes the models limited to represent the real catchments. These models always have several parameters to be calibrated and the parameters are site specific and not suitable to be applied in ungauged catchments. For ungauged catchments, there is not sufficient available data for model calibration and validation. It is not yet feasible to utilize model parameters from a gauged to an ungauged basin due to the limitation of our knowledge on hydrological processes (Sivapalan 2003). The heterogeneity of catchment geomorphology, e.g. its terrain, area, shape, land surface condition, soil types, etc., is the root cause of the difficulty in predicting catchment response (Hrachowitz *et al.* 2013).

The hydrological models, especially physically distributed models, can be treated as systematic hypotheses of a catchment (Beven 2001), therefore making it possible to be used as learning tools for the further understanding of hydrological processes and streamflow modelling (Beven 2007; Dunn *et al.* 2008). A novel approach, Catchment Morphing (CM), has been proposed to transfer a well-trained hydrological model from gauged to ungauged catchment (Zhang & Han 2017b). This approach uses a fully distributed model as a representation of a natural catchment and calibrated the model with a gauged catchment. This approach has been applied to several catchments in the UK and produced acceptable results (Zhang & Han 2017b). However, this application utilized a homogenous rainfall input for the ungauged catchments.

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Rainfall is among the most important inputs for hydrological modeling and has significant spatial variability in the synoptic regime and catchment morphology (McMillan *et al.* 2012). Runoff variability corresponds to the increase in the rainfall spatial variability (Wood *et al.* 1988). Runoff modeling skills are closely intertwined with rainfall variability and measurement accuracy. Large uncertainty existed in estimated model parameters without considering the rainfall spatial variability (Chaubey *et al.* 1999). Streamflow properties are influenced by spatially distributed rainfall (Arnaud *et al.* 2002). Previous studies have found out that the rainfall spatial distribution contributed significantly to runoff modeling when the antecedent soil water condition is dry (Shah *et al.* 1996) and when the rainfall spatial variability scale is larger than hillslope scale (Nicótina *et al.* 2008). In contrast, some studies argued that rainfall spatial variability could be smoothed out by the hydrologic processes because of the damping within catchments.

As a newly derived approach, a lumped rainfall input was applied in the initial experiment for CM in the ungauged catchment. We applied spatially distributed rainfall from both rainfall gauges and CEH-GEAR (the Centre for Ecology & Hydrology – Gridded Estimates of Areal Rainfall) 1 km gridded rainfall to the catchments to explore the influence of rainfall spatial variability on the approach.

## 2. DATASETS AND METHODOLOGY

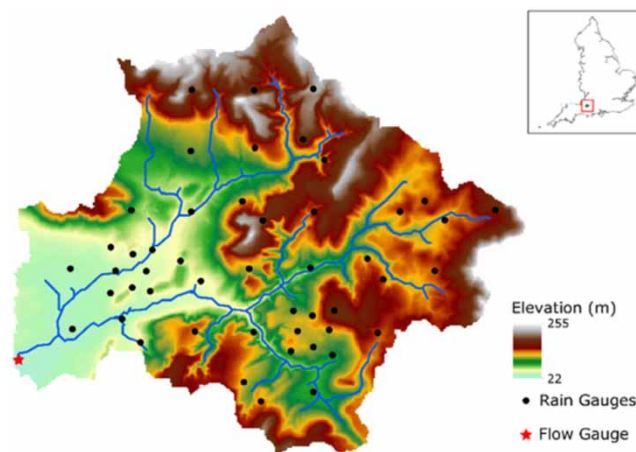
### 2.1. Brue catchment

The Brue catchment is located in the southwest of England as shown in Figure 1, draining an area of 132 km<sup>2</sup> to its river gauge at Lovington (Dai *et al.* 2015). The elevation of the catchment is higher in the north and east where the river rises ranging from 22 m to 255 m. The digital elevation model was downloaded from the Ordnance Survey of Digimap Resource Centre. There are three soil types, i.e. mud, clay and sand, according to the national soil type data downloaded from Digimap Service. The slope ranges from 10.85% to 0.07% and shares a similar spatial pattern with the elevation. Flow length mainly depends on the distance from the node to the outlet, ranging from 0 to 19.81 km.

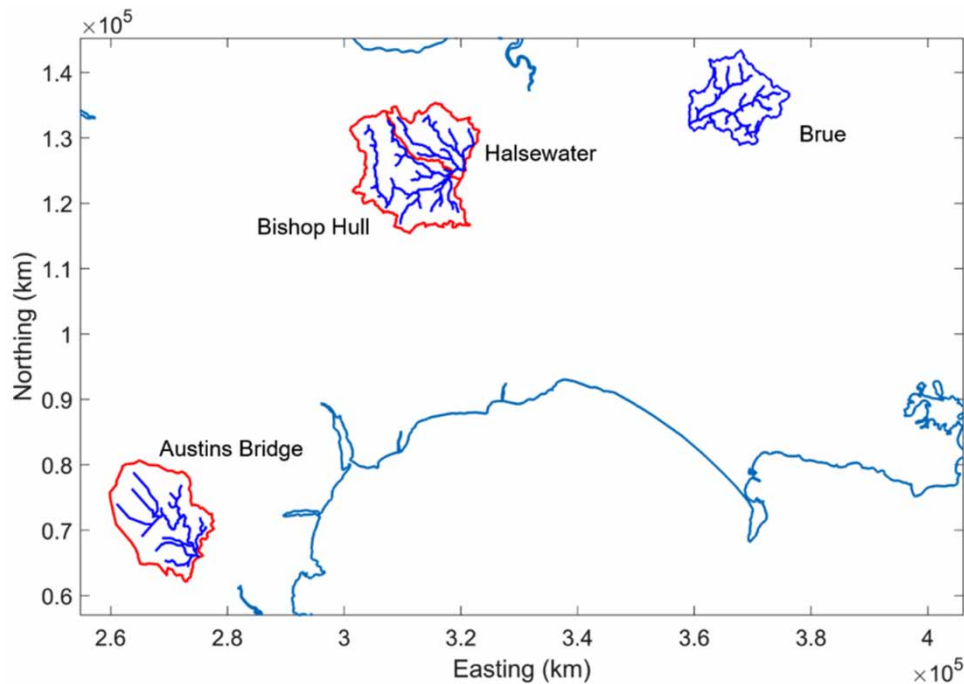
There is a specially designed HYdrological Radar Experiment (HYREX) dense rainfall network with 49 tipping bucket rain gauges distributed in the whole catchment, as displayed in Figure 1 (Moore *et al.* 2000). The data of dense rain gauges, the flow station and the atmospheric data are available at the British Atmospheric Data Centre (BADC), which covers the period from 1994 to 1999.

### 2.2. Ungauged catchments in the southwest UK

Three catchments in the southwest of the UK are chosen for rainfall spatial variability in this study, as their locations and inner river networks are shown in Figure 2 and basin information in Table 1. The details of all catchments were published on the Flood Estimation Handbook (FEH) online service. The catchment area ranges from 94 km<sup>2</sup> to 249 km<sup>2</sup> and slope varies from 77.6 m/km to 121.5 m/km. Although they are located in the spatial proximity, the annual average rainfall from 1961 to 1990 is significantly different, from 851 mm to 1,770 mm. The percentage runoff (PR) from the Flood Estimation



**Figure 1** | Map of the rain gauges and terrain elevation in the Brue catchment. The black points represent the rain gauge locations and the star is the flow gauge location.



**Figure 2** | The locations of tested catchments in the UK.

**Table 1** | Basic information of the catchments

Name	Area (km <sup>2</sup> )	Slope (m/km)	FEH PR (%)	Real PR (%)	Average annual rainfall (mm)
Bishop Hull	204	98.0	32.9	41.0	964
Halsewater	94	77.6	30.6	17.8	851
Austins Bridge	249	121.5	32.8	46.1	1,770

Handbook (FEH) (Robson & Reed 1999) in Table 1 was used for runoff adjustment, which was derived from the 29-class Hydrology Of Soil Types (HOST) classification. PR is an intuitive indicator to describe the runoff generation magnitude of a catchment and with values around 30% for three catchments.

### 2.3. Catchment Morphing

A fully distributed model describes a catchment with physically based processes, as close as possible to the real-world response. SHETRAN is a physically based distributed hydrological model for water flow and sediment and solute transport in catchments (Ewen *et al.* 2000), which originated from the Système Hydrologique Européen (SHE) (Abbott *et al.* 1986). Given SHETRAN is built as a baseline model with a gauged catchment that is validated with measured data, a morphed new model can be created by changing the catchment geomorphology characteristics of the baseline model. Since the morphed model is embedded with new characteristics from the ungauged catchment, it is presumed as a representation of the new catchment. This process is defined as Catchment Morphing (CM).

In CM, the objective is not to change the baseline model exactly to the target catchment, but to capture some major geomorphology characteristics of the target catchment. By capturing the characteristics that affect runoff generation the morphed model is expected to have the ability to simulate the streamflow. In this study, catchment slope and area are changed to morph the catchments as they are two major indicators that influence the runoff generation.

The baseline model was built from the Brue catchment with SHETRAN and three catchments in the southwest of England were used in this study for Catchment Morphing. The three models were created respectively by CM from the baseline model. The catchment area was changed by multiplying the cell size with a ratio of two catchment areas (area of the target

catchment/area of the Brue catchment) and the catchment average slope was changed in a similar way. As a result, the created catchments were treated as representations of the target catchments. The three catchments were treated as ungauged catchments (i.e., their flow observations were not used for calibration on CM) and predicted using the morphed model with the local rainfall data.

#### 2.4. Rainfall gauge data

The locations of rain gauges in three catchments are shown in Figure 3. In order to apply distributed rainfall in the morphed model, the rainfall input data for the baseline model were deduced for each catchment with the distribution of rain gauges and the proportions adopted by FEH, as shown in Figure 3. The proportions of rainfall gauges in three catchments are listed in Table 2. The proportions of the rainfall gauges in the morphed catchments (Figure 3(b), 3(d) and 3(f)) remained the same as those used in FEH, and the relative positions of the rainfall gauges were simulated as close as possible with the target catchments. For example, as shown in Figure 3(b), the lighter gray part of the catchment uses the rainfall from Fulwood gauge and the darker part uses the rainfall from Manudown gauge. It is worthwhile noting that the partitioning of the baseline model is not precise, but is supposed to bring a general idea of whether distributed rainfall data would bring improvements to runoff modelling with Catchment Morphing. Moreover, not all the rain gauges are located inside the catchment, which is possible to bring certain uncertainty in runoff modelling. The 15-min data from 01/Oct/1998 to 01/Jan/1999 were chosen in this study for all the catchments.

#### 2.5. CEH-GEAR gridded rainfall

The CEH-GEAR dataset provides 1 km gridded daily and monthly rainfall data for the UK from 1890 onwards. This dataset is derived from the historical rain gauge observations from the Met Office and interpolated including a normalization step based on average annual rainfall to generate the national gridded daily and monthly dataset (Keller *et al.* 2015). This dataset is among the most reliable spatial distributed rainfall in the UK and has been applied to a large number of studies. In this study, we use CEH-GEAR dataset to provide spatial distribution of rainfall in the catchment. Figure 4 shows the gridded accumulated rainfall from CEH-GEAR in 1998 in the Halsewater and Bishop catchment. Clearly, a spatial distributed pattern can be found in that rainfall in the northwest of the catchments is significantly larger than the southeast.

Due to the lack of dense rainfall gauge networks in these three catchments, it is difficult to obtain sufficient rainfall spatial information with the existing gauges. We apply the spatial information from CEH-GEAR to the Halsewater catchment in this study and the temporal information from gauge observation. We use the 15 min temporal distribution in each day from gauge observation to interpolate the daily values of CEH-GEAR. To be specific, we first sum the total rainfall amount in each day and calculate the ratio of rainfall in each 15 min time step; then multiply this ratio to the daily rainfall value in CEH-GEAR to obtain the rainfall data in the resolution of 15 min/1 km of the catchment.

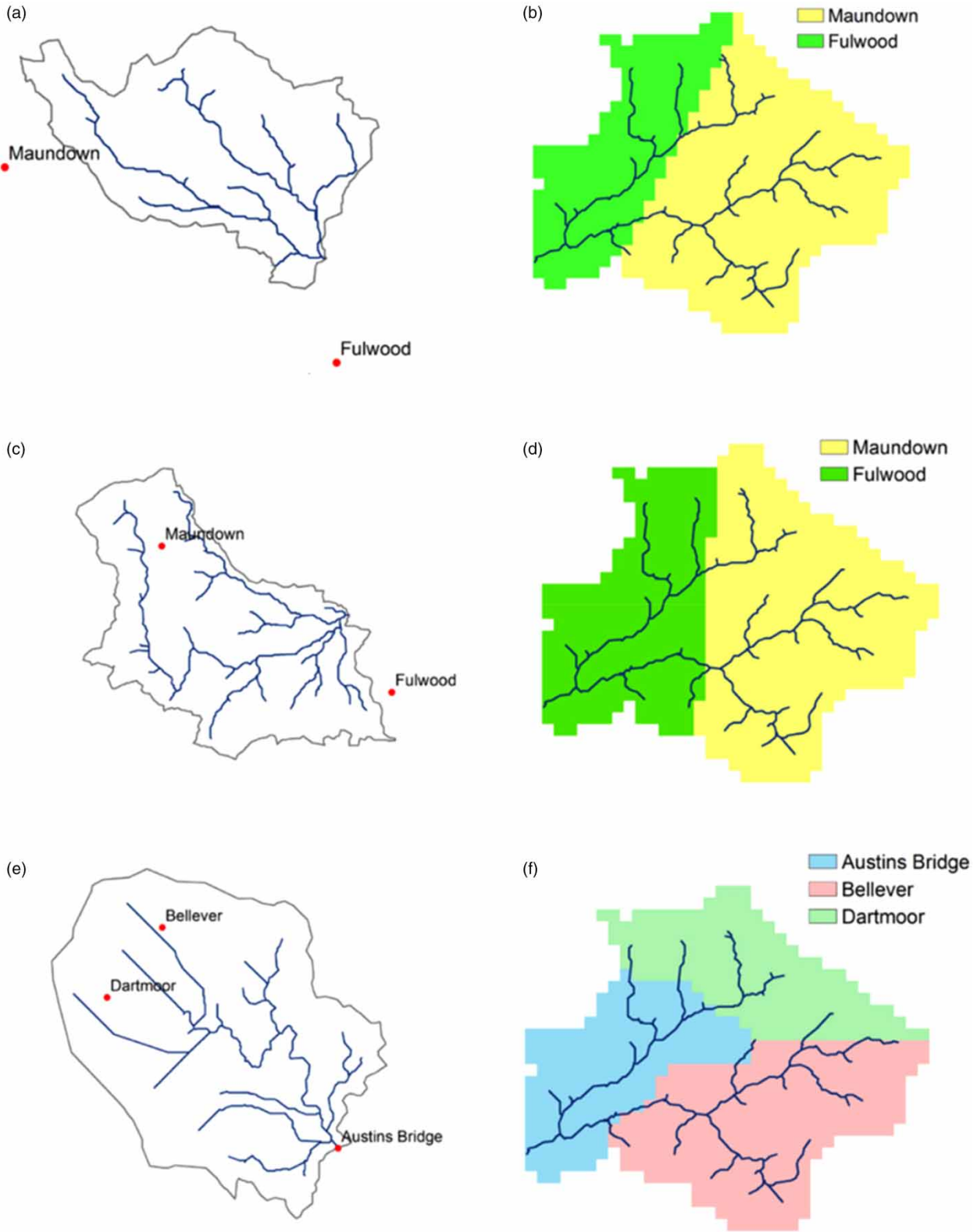
### 3. RESULTS AND DISCUSSION

#### 3.1. General model performance

The performance of morphed models in three catchments is listed in Table 3 and hydrographs are shown in Figure 5. According to the results, model performance varied when adopting distributed rainfall, in which Halsewater experienced a slight increase while it decreased in the Bishop and Austins Bridge catchment in the original modelling. However, increases could be found for Austins Bridge and Halsewater when considering adjusting the runoff with FEH PR, and all three catchments had improved performance when adjusting the runoff with real PR.

According to the hydrographs in Figure 5, the difference existed in both peak volumes and time to peak. Clear overestimation in Figure 5(c) of the Bishop Hull catchment was found in the runoff modelling from distributed rainfall, while for the other two catchments, the difference was not as significant between runoff modelling from distributed rainfall and average rainfall.

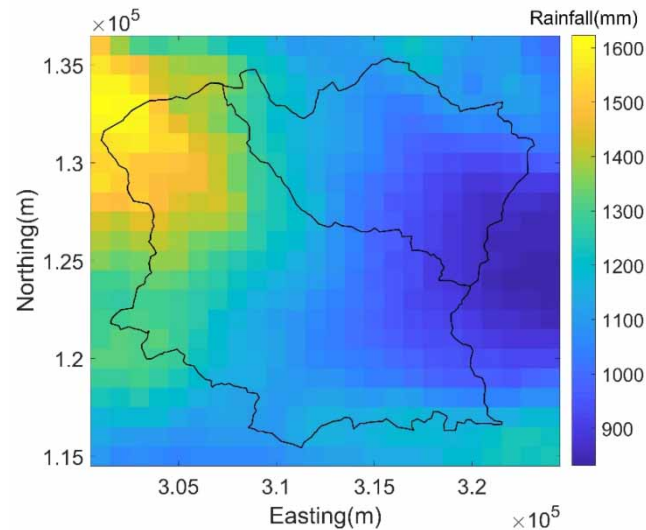
It is worth noticing that more obvious improvements could be seen in runoff modelling after adjustment, and the hydrographs of runoff modelling using distributed rainfall and runoff after adjustment are shown in Figure 5(b), 5(d) and 5(f). For the Bishop Hull (Figure 5(b)) and Austins Bridge (Figure 5(f)) catchment, although the original modelling performance of the distributed rainfall was worse than that of the average rainfall, better performance could be found in the adjusted runoff performance. Especially for the Bishop Hull catchment, the runoff after adjustment by the real PR was significantly better than the performance with the average rainfall.



**Figure 3** | The distribution of rainfall gauges in (a) Halsewater, (c) Bishop Hulls, (e) Austins Bridge, and the corresponding rainfall distribution in the morphed catchments for (b) Halsewater, (d) Bishop Hulls, (f) Austins Bridge.

**Table 2** | The proportions of rainfall gauges in three catchments

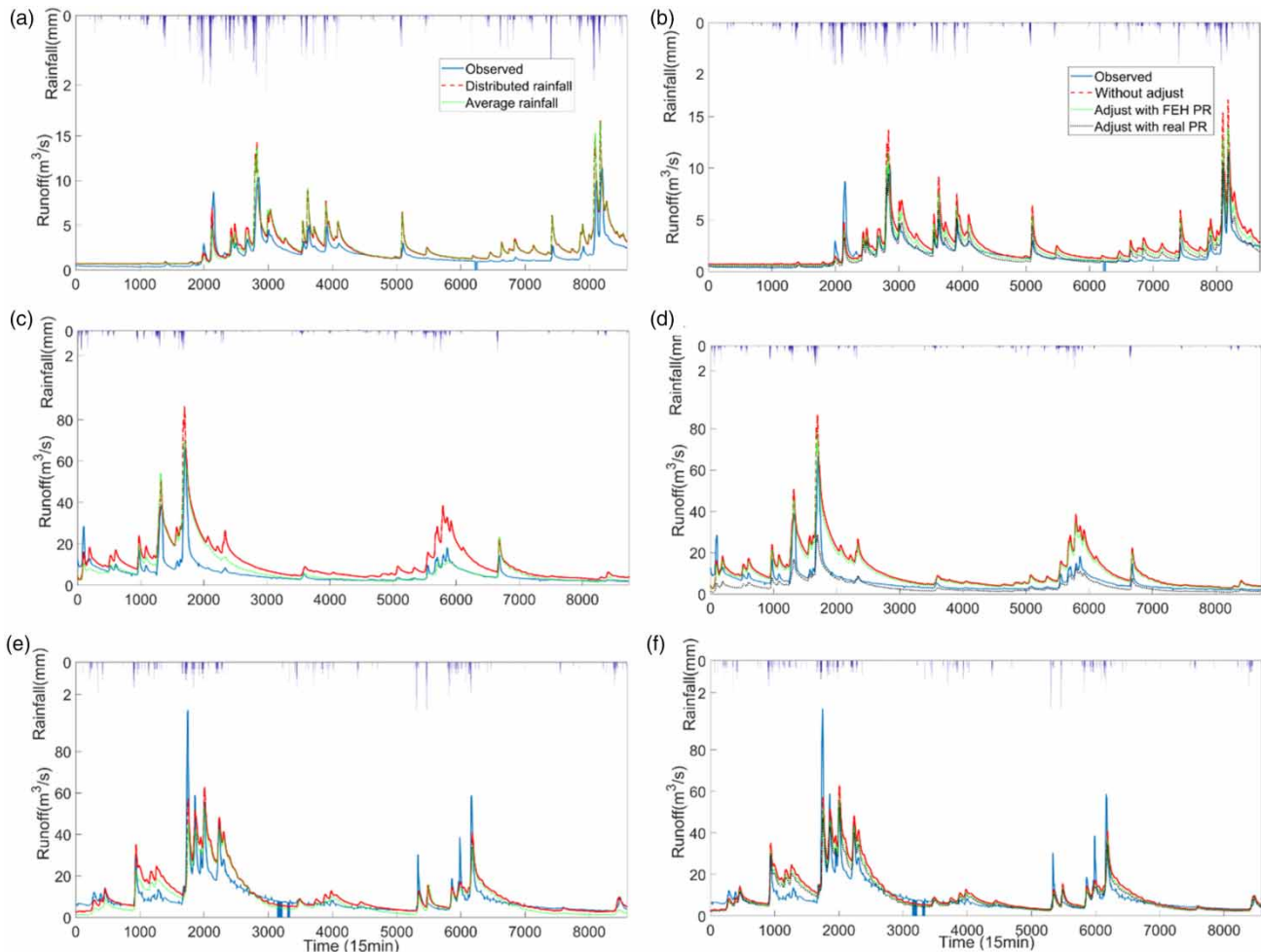
Catchments	Rainfall gauges	Proportions
Halsewater	Maundown	63%
	Fulwood	37%
Bishop Hulls	Maundown	60%
	Fulwood	40%
Austins Bridge	Austins Bridge	29%
	Bellever	43%
	Dartmoor	28%

**Figure 4** | The annual accumulated rainfall by CEH-GEAR in Halsewater catchment.**Table 3** | Model performance influenced by distributed rainfall in three catchments assessed by NSE

	Average rainfall			Distributed rainfall		
	Original	Adjusted with FEH PR	Adjusted with real PR	Original	Adjusted with FEH PR	Adjusted with real PR
Halsewater	0.39	0.71	0.81	0.42	0.74	0.84
Bishop Hull	0.03	0.25	0.58	-0.98	-0.48	0.77
Austins Bridge	0.62	0.55	0.70	0.61	0.70	0.72

In general, the original model performance of distributed runoff did not improve significantly compared with the average runoff. However, the adjusted runoff by PR demonstrated clearly better performance according to the result, which implied that the distributed runoff captured more characteristics of the real runoff and miscalculated the runoff magnitude.

To illustrate the runoff modelling influenced by distributed rainfall, one example in the Halsewater catchment is shown in Figure 6 and Table 4. The runoff was simulated with three different rainfall inputs, i.e. average rainfall, rainfall from the Maundown station and Fulwood station respectively, in which the model parameters and model setting are the same for all three rainfall inputs. In general, the runoff was overestimated with the average rainfall in the catchment shown in Figure 6. It can be found the runoff modelled with rainfall in the Maundown was clearly overestimated while Fulwood under-estimated the runoff. Moreover, the best original model performance was found when using the rainfall input in the Fulwood station, while the worst was the rainfall from the Maundown according to the results in Table 4. Conversely, the best model performance after adjustment by the real PR was from the rainfall in the Maundown station while the worst was rainfall in the Fulwood station. When adjusting the

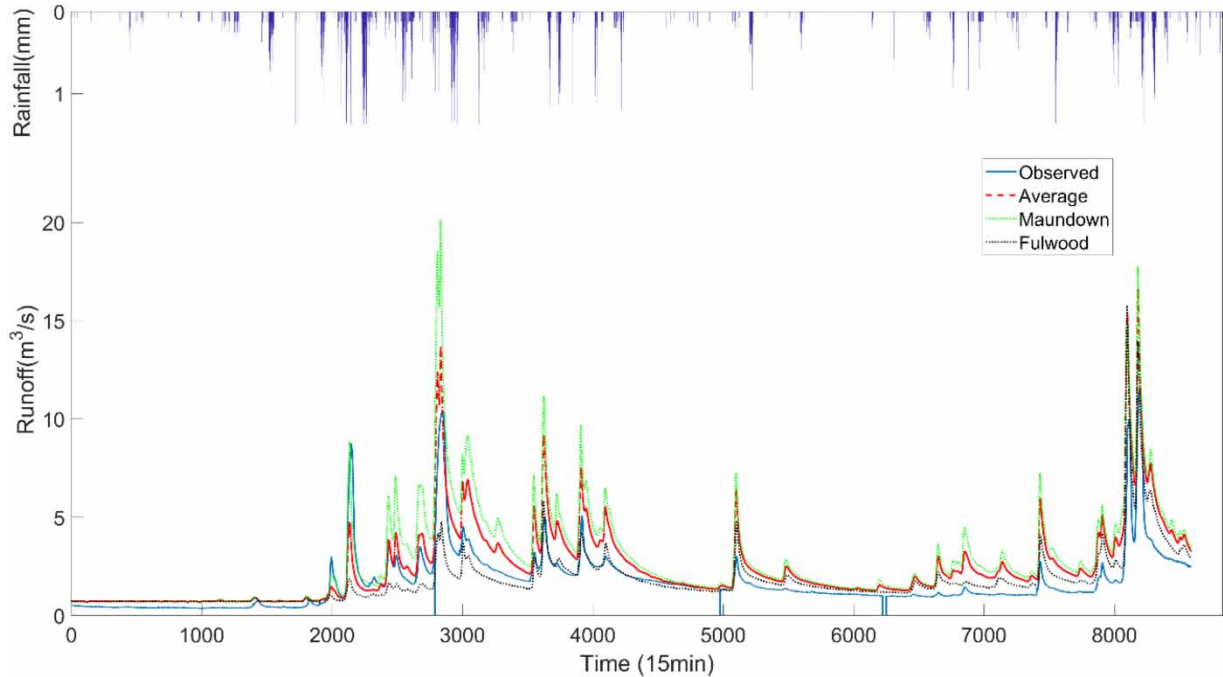


**Figure 5** | The hydrographs of modelled runoff by distributed and average rainfall, i.e. (a), (c), (e), and hydrographs of modelled and adjusted runoff by distributed rainfall, i.e. (b), (d), (f), in which, (a) and (b) are the Halsewater catchment, (c) and (d) are the Bishop Hull, (e) and (f) are the Austins Bridge catchment.

modelled runoff with FEH PR, the best performance appeared in the modelled runoff with average rainfall. Runoff from both average rainfall and Maundown improved notably with the adjustment of PR, while runoff from rainfall in the Fulwood station had a slight improvement. It is difficult to discover the true rainfall spatial distribution in the catchment; however, useful information can be achieved from the results. The average rainfall performed best in the overall consideration. The rainfall in the Fulwood station is closer to the true rainfall volume as a slight difference existed between the original performance and the adjusted performance indicating that the modelled PR was close to the real PR. The timing is better captured by the Maundown station as the adjusted performance was as high as 0.83 (NSE). NSE over 0.8 indicates a good agreement in the simulation. The results implied that the rainfall spatial variability is highly correlated to runoff simulation with CM.

A more specific example to describe the rainfall difference between two gauges and how the rainfall is propagated to the runoff is demonstrated in Figure 7 from the time step 2,800 to 3,200 in the Halsewater catchment, which is one of the largest peaks in the modelling period. Due to the antecedent modelling difference, the initial conditions of two modelled runoffs in the chosen period were distinct that the initial runoff by Fulwood was notably lower than that of Manudown. The total rainfall discrepancy between the two stations in the chosen time was that rainfall in Manudown was 24 mm larger than that in Fulwood, while the discrepancy of modelled runoff was 21 mm.

In Figure 7(a), it was noticed that the rainfall in the Fulwood station happened 1 to 2 time steps (15–30 mins) later than the rainfall in the Maundown station, which resulted in later peaks in the runoff generation shown in Figure 7(b). The peak volumes appeared at time 2,970 and 2,978 for the runoff based on the rainfall in the Maundown and Fulwood stations,



**Figure 6** | The hydrographs of modelled runoff with different rainfall input in the Halsewater catchment, i.e. average rainfall, rainfall in the Maundown station and the Fulwood station, respectively.

**Table 4** | The model performance by NSE in the Halsewater catchment with different rainfall inputs

Rainfall input	Original	Adjusted with FEH PR	Adjusted with real PR
Average rainfall	0.39	0.71	0.81
Maundown	-0.32	0.37	0.83
Fulwood	0.58	0.59	0.59

respectively. Moreover, the time to peak in the runoff generated by the average and distributed rainfall was both at time 2,972, which was between using a single station in either Manudown or Fulwood station.

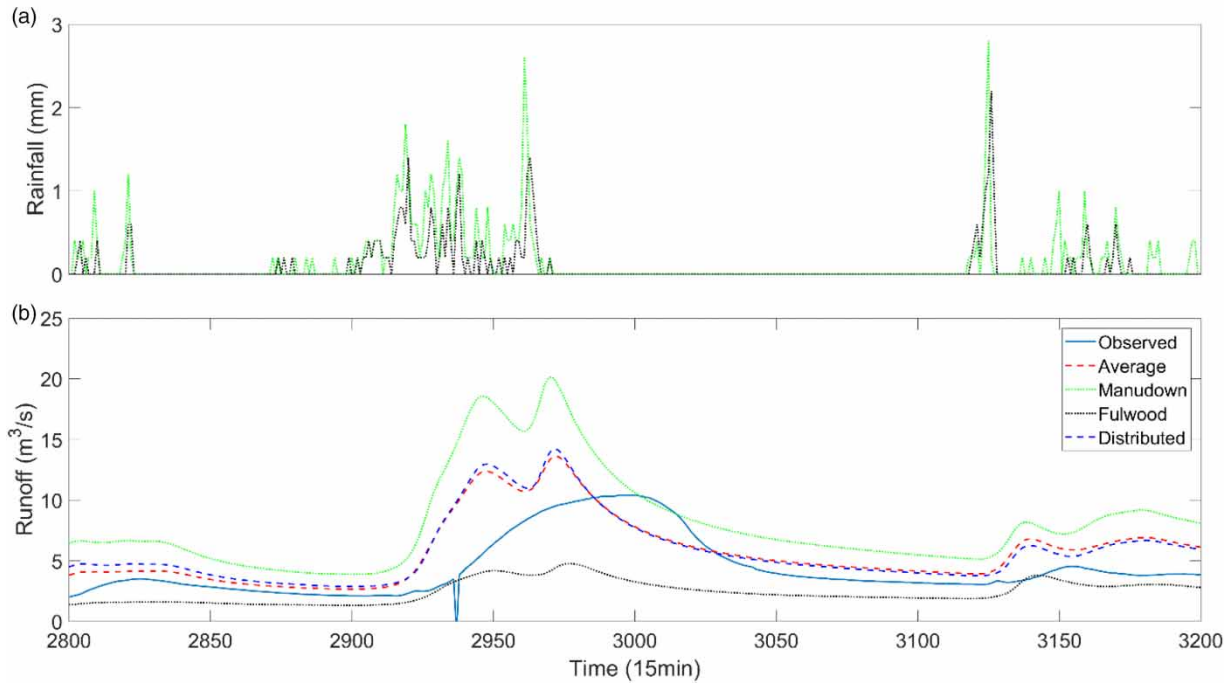
### 3.2. Model performance with CEH-GEAR rainfall

Figure 8 presents the hydrograph comparisons between average rainfall and CEH-GEAR rainfall in 1998 in Halsewater catchment. The simulation with average rainfall clearly overestimated for most of the peaks after hour 3,000, which is significantly improved by the CEH-GEAR spatial rainfall. More detailed analysis of how spatial rainfall affects the runoff simulations is displayed event by event in the next section. The baseflow of the simulation in the second half is overestimated for both average and spatially distributed rainfall. The simulation of baseflow is mainly affected by the soil parameters. As this model is morphed from the baseline model in another catchment, it is possible that some discrepancy in the soil parameters exists.

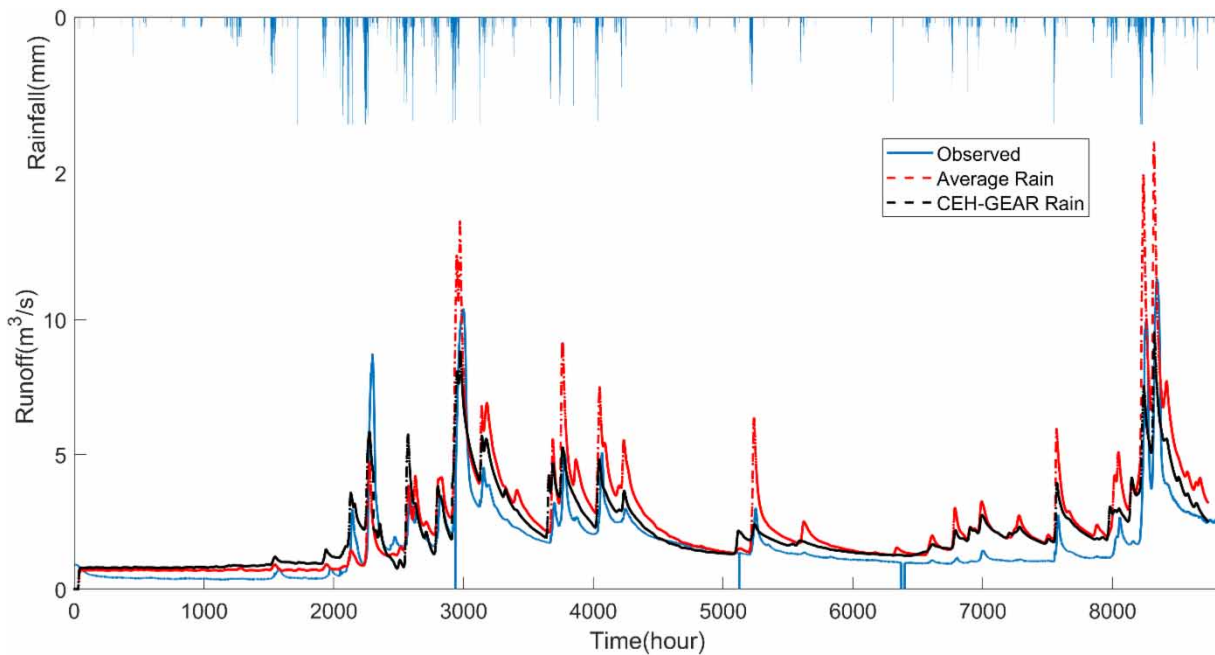
### 3.3. Event-based model performance analysis

As shown in the last section, the simulation results from distributed rainfall are improved compared with the average rainfall. In this section, four events were chosen for detailed analysis with events information listed in Table 5. The rainfall duration varies from 218 hours to 501 hours, and the total rainfall volume varies from 13.21 mm to 62.17 mm. The four events cover the largest peaks in the simulation period as shown in Figure 9 with the magnified hydrographs for all events displayed inside the figure.





**Figure 7** | An example of modelled runoff with rainfall in two stations in the Halsewater catchment, (a) is the rainfall volumes, (b) is the modelled runoff.

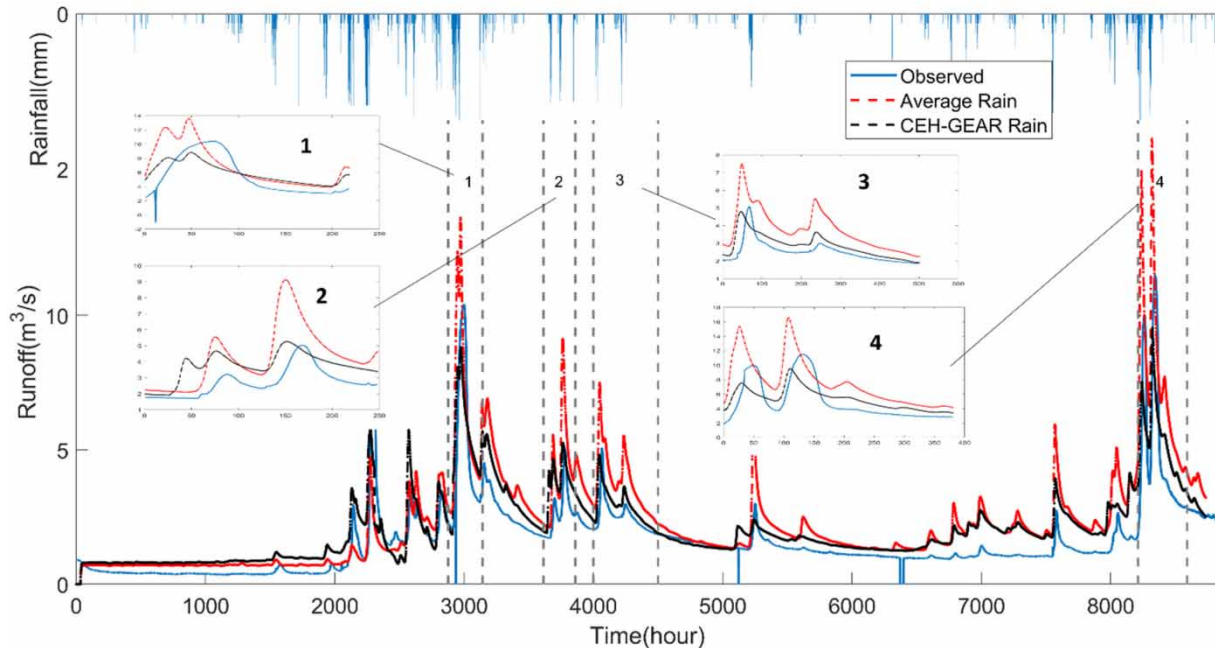


**Figure 8** | Comparison of simulated streamflow from averaged rainfall and CEH-GEAR rainfall.

The spatial distribution of accumulated rainfall in the four events is plotted in Figure 9. It is noted that the rainfall was unevenly distributed. Events 1, 2 and 4 show a similar spatial pattern that rainfall generally decreased from the northwest (upstream) to the southeast (downstream), while Event 3 presents a different spatial pattern that rainfall in the west and east is larger than that in the central region. The two rain gauges in Halsewater catchment are located in the upstream

**Table 5** | The basic information of chosen events in Figure 9 in the Halsewater catchment

	Start time	End time	Duration (h)	Total rainfall (mm)
Event 1	2/5/1998 22:00	11/5/1998 23:00	218	13.21
Event 2	31/5/1998 13:00	10/6/1998 20:00	248	62.17
Event 3	16/6/1998 16:00	7/7/1998 12:00	501	
Event 4	9/12/1998 5:00	25/12/1998 00:00	379	56.93

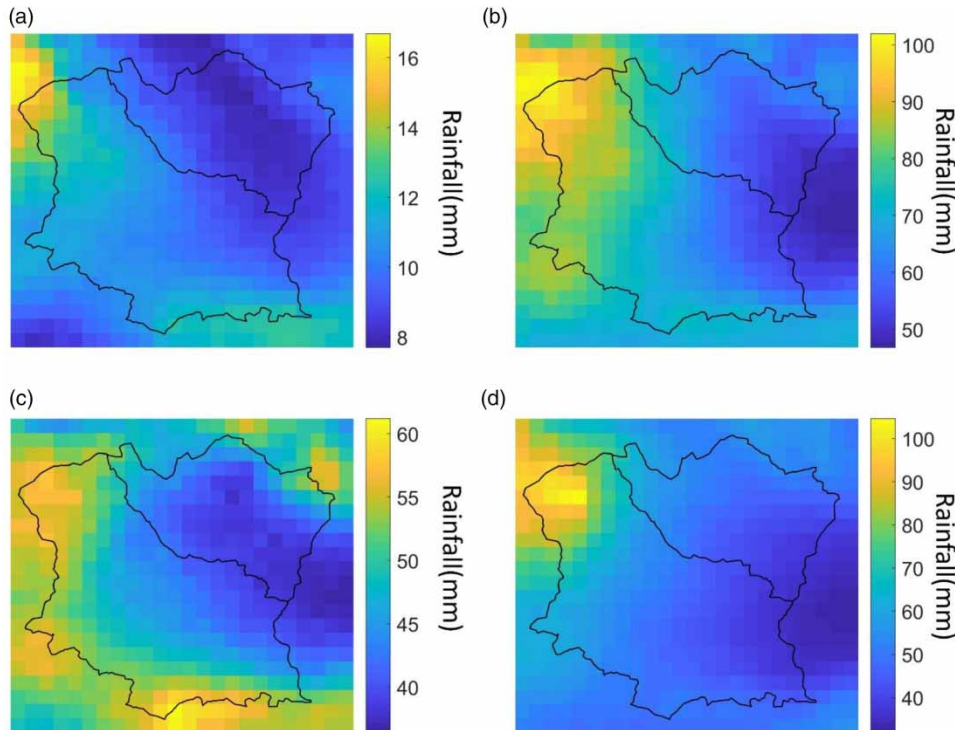
**Figure 9** | Events chose for further analysis.

and downstream respectively (shown in Figure 3(c)), but it is still far from capturing the spatial distribution correctly in the events. Moreover, the spatial pattern of rainfall differs from event to event, therefore, only two gauges in the network is not sufficient to describe the spatial variability properly.

The hydrographs of the observed and simulated flow of the four events are shown in Figure 11. The red dash lines are streamflow simulated with average rainfall from two gauges and the black lines are results with CEH-GEAR spatial rainfall. In general, streamflow from averaged rainfall over-estimated most of the peaks, which has been improved significantly with spatially distributed rainfall.

The limited rain gauges cannot capture the spatial variability that happened in the catchment according to the spatial maps from CEH-GEAR rainfall. As demonstrated before, the rainfall in the upstream of the basin is generally larger than that in the downstream, therefore, measuring rainfall from these two gauges is not precise enough to describe the rainfall. In event 1, the northwest corner has the largest rainfall, where the Maundown is located, and the rainfall in the southeast is also larger than the downstream of the basin, where the other gauge Fulwood is located. Therefore, rainfall in these two gauges is generally higher than the real rainfall at the catchment. Similar patterns can be found in other events. Especially in Event 3, rainfall in the northwest and southeast (where the rain gauges are located) is significantly higher than other parts of the catchment.

Another factor that affects the streamflow simulation is the routing of the flow. After runoff production from the hillslope, it travels further from the upstream to the downstream. Therefore, with the same rainfall, the runoff would be different whether the rainfall happens in the upstream or downstream. This can be observed from the simulation as well. For example in Event 1, a equally large rainfall happens both in upstream and downstream when applying average rain. As mentioned before, the rainfall measured by gauges is larger than that actually happening in the domain. Therefore, the streamflow from average rainfall



**Figure 10** | The rainfall distribution map of the total rainfall based on radar rainfall data in four events.

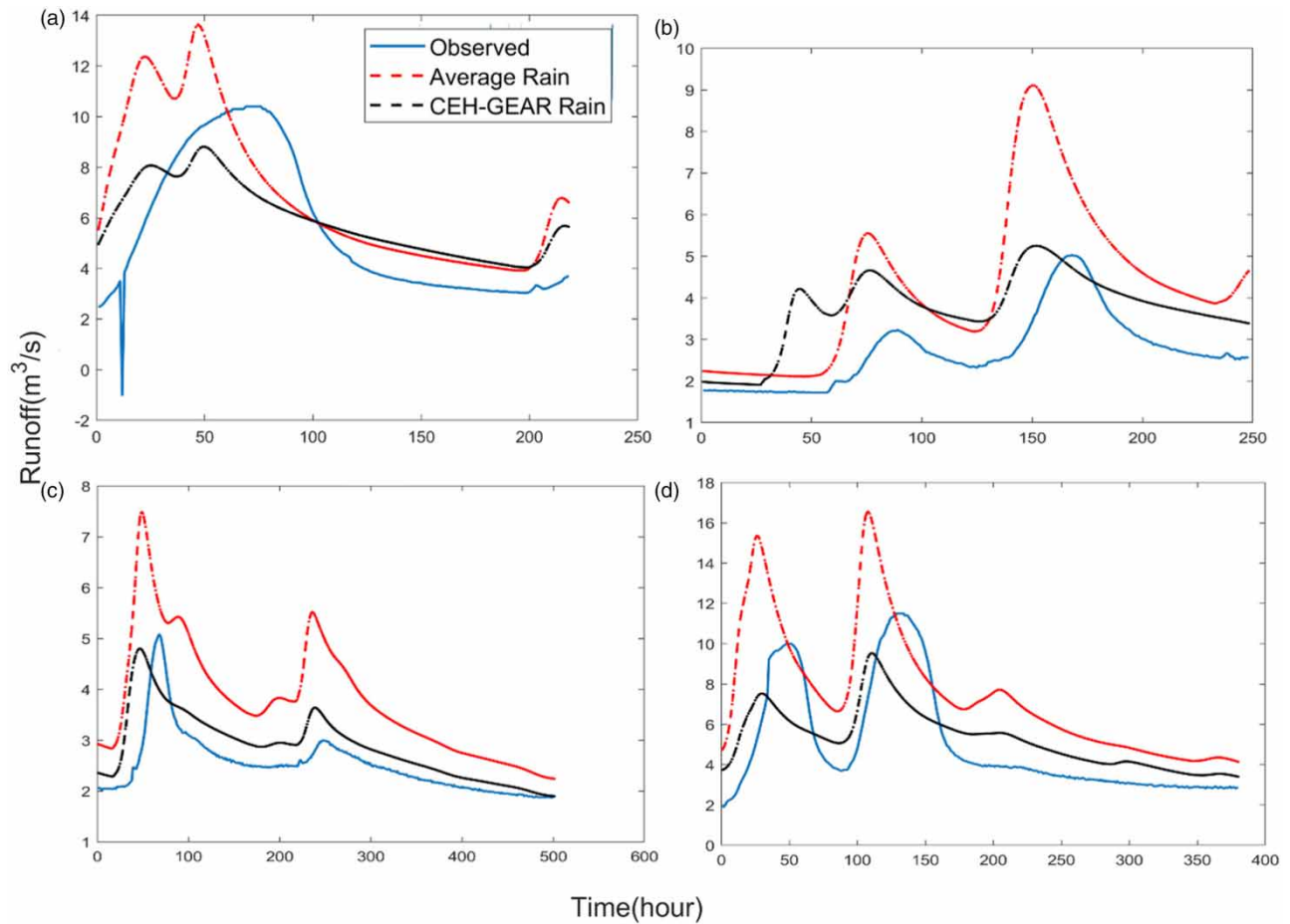
increased immediately with a larger peak than the spatially distributed rainfall as expected. Similar patterns can be discovered from other events as well.

### 3.4. Discussion

The distributed rainfall input was carried out in the experiment to investigate the influence on runoff modelling in ungauged catchments with CM. However, due to the limitation of available rainfall data, only three catchments were explored in this study but they provided useful results nevertheless. We compared the streamflow simulation between average rainfall from limited rain gauges and spatially distributed rainfall from CEH-GEAR rainfall dataset. The spatial rainfall is influential on runoff magnitude as well as the peak time. It was found out that the additional spatial rainfall information is helpful to improve the model performance, which demonstrates the ability to deal with spatial information in CM.

Catchment Morphing, as a newly proposed approach, is far from sophisticated for a wide application. Utilizing average rainfall is to maintain the simplicity of the approach for its initial experiment. Apart from rainfall data, the soil parameters were homogenous for all the catchments and the land cover data were from the baseline catchment. Ungauged catchments in the current study refer to the catchments without measured runoff data for hydrological model calibration, which is generally used for hydrological modelling in gauged catchments. Different from the requirement of long-term runoff data for calibration, most of the catchment geomorphology information is not difficult to measure, and the information can be translated to the model parameters, especially for a physical-based hydrological model. The advantage of CM is the possibility to mimic the catchment performance with little available information. The additional geomorphology information of the target catchment is supposed to benefit the runoff performance (Sangati *et al.* 2009). To enhance the proposed approach, heterogeneous inputs and parameter sets are expected for varied catchments to explore the potential improvement of CM.

It has been explored that rainfall spatial variability is significant to runoff modelling. The average rainfall is not sufficient for rainfall events with complex spatial variability and considering rainfall spatial variability is possible to improve the runoff modelling to some extent (Zhang & Han 2017a). As the catchment for modelling was morphed from the baseline model, it is almost impossible to maintain the same rainfall distribution with the target catchment. The catchment proportion in this study for



**Figure 11** | The hydrograph from four events.

distributed rainfall was set up manually, which is arbitrary and accompanied with bias. The more precise algorithm is to be developed to divide the catchment automatically, which is useful for heterogeneous soil parameters, land cover properties as well.

It is found that the rainfall data recorded by two gauges in the Halsewater catchment were significantly different in magnitude and recording time. By applying a 1 km spatial rainfall input dataset, the model has presented a significant improvement with CM, indicating the ability of CM to represent a spatially distributed input.

The objective of this study is to obtain overall information about the rainfall spatial variability. The usage of high-resolution rainfall data has demonstrated the importance of the spatial information to the runoff simulations. However, the spatial rainfall distribution analysed in this study only considers the rainfall distribution of the total event, ignoring the inner-event temporal variation. One shortcoming of CEH-GEAR dataset is that it only provides daily rainfall data and our model is simulating in 15 min temporal resolution. Therefore, we still use the inner-daily distribution from gauges to interpolate the CEH-GEAR dataset, which is possible to bring some uncertainty. A more comprehensive study of rainfall spatial variability is expected for the future.

We used NSE to evaluate the overall performance of the simulation and further detailed analysis is carried out in event-based resolution. The missing observed runoff data are part of the reasons for low NSEs.

#### 4. CONCLUSION

In this study, we have applied spatially homogenous data from rain gauges and distributed rainfall (1 km CEH-GEAR dataset) respectively to the morphed model to explore the potential for a wider application of Catchment Morphing. Using 1 km gridded rainfall input instead of the average rainfall has improved the streamflow simulations significantly. The results demonstrated the increasing spatial rainfall input is beneficial in streamflow simulation and the spatial input information can be used in the morphed model for further studies.

As a newly proposed and promising runoff modelling approach especially for ungauged catchment, it is worthwhile exploring CM more comprehensively to look for the potential to deal with more spatially heterogeneous information. As the study of CM is in its early stages, more research is expected to improve the approach to promote it for a wider application.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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