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A new method of rainfall temporal downscaling: a case study on sanmenxia station in the Yellow River Basin

G. F. Chen, D. Y. Qin, R. Ye, Y. X. Guo, and H. Wang

Department of Water resources research, China institute of water resources and hydropower research, Beijing, China

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Correspondence to: G. F. Chen (chengf02@163.com)

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Abstract

Distributed hydrological models are effective tools for Predictions in Ungauged Basins (PUB). The rainfall input uncertainty is an important source of hydrological model uncertainty. With the improvement of hydrological model accuracy, the requirements of the accuracy of input data are correspondingly improved. Daily rainfall data is the most common data that the researchers can get, however this cannot satisfy the requirement of hydrological simulation. Therefore, researches of daily rainfall temporal downscaling method is focus in distributed hydrological models. In the Yellow River Basin, the random distribution method, the sinusoidal distribution method and the normal distribution method all underestimate the maximum rainfall intensity. This paper raises a new daily rainfall downscaling method called proportional method based on the rainfall hyetograph of 28 years. This method significantly improves the accuracy of the maximum rainfall intensity simulation and the rainfall process curves, so this method can improve the accuracy of modeling the hydrology process and reducing the input uncertainty of the rainfall data.

1 Introduction

The natural hydrological process is really complex; it is affected by a lot of factors, so it is hard to obtain accurate hydrological forecasting results (Yang et al., 2009). The International Association of Hydrological Sciences (IAHS) launched a short PUB program of ten-year to reduce uncertainty in hydrological forecasting and explore hydrological models of new methods to achieve a major breakthrough in hydrological theory, particularly in developing countries to meet the needs of society and economy (Liu et al., 2005). The following six tasks are included in the plan of the PUB program: (1) Develop new approaches for hydrological interpretation from existing data archives: data rescue and re-analysis, basin inter-comparisons and global hydrology; (2) Advance existing theories regarding process heterogeneity, and improve their descriptions through detailed process studies; (3) Advance the learning from the application of existing models, towards uncertainty analyses and model diagnostics; (4) Use of new data collection approaches for large-scale process understanding, model development and improved predictions; (5) Develop new hydrological theories based on scaling, multi-scaling and complex, systems approaches, nonlinear pattern dynamics and eco-hydrological relationships; (6) Develop new, multi-scale, spatially distributed modelling approaches with a focus on model falsification over a wide range of basin scales (Sivapalan et al., 2003).

Development of distributed hydrological models is included in the growing fast and the most effective tools of PUB. PUB research program focused on estimating and reducing uncertainty in forecasting, including model uncertainty, input uncertainty of spatial and temporal variables and the uncertainty caused by heterogeneity and the limited level of awareness by the people. Input uncertainty of rainfall data is an important aspect of uncertainty of distributed hydrological models. Rainfall is the most active factor in the global water cycle. The characteristics of rainfall such as amount and intensity can influence regional water resources and droughts and floods largely. In hydrological modeling, both spatial and temporal accuracy of rainfall data are crucial to modelling accuracy. Different spatial downscaling methods and technology, such as remote sensing and radar combines, significantly improved spatial accuracy of rainfall data in the last decades.

In the aspect of improving temporal accuracy, the self-recording rain gauges can record rainfall data continuously. However, daily rainfall data is the most common and reliable data for the researchers. In order to satisfy the requirement of hydrological modelling, many temporal rainfall downscaling methods are developed to downscale daily rainfall data into smaller time scales, in order to reducing input uncertainty of rainfall data.

In the famous hydrological model Soil and Water Assessment Tool (SWAT), a triangle method is used to describe the process of storm in a wet day. This model has been used in different areas, good results could got by this method (Neitsch et al., 2005).

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Wang et al. (2006) used random distribution method to downscale daily rainfall in the program of Digital Model of The Yellow River Basin. This method exaggerated the ratio of rainfall under lager rainfall intensity. The main target of the program was soil erosion and sediment transportation; the random distribution method would give a conservative result leading to safe design of hydraulic constructions.

Kondo et al. (1997) developed a method based on the following two rules in 1997: the intensity (per rainfall amount per hour) was close to sinusoidal distribution; the peak density values and the last time of the rainfall were proportional to the daily rainfall amounts. Kondo used this method to build a relationship between heat and water in no-vegetated surface and got really reasonable results.

Yang et al. (2003) invented another method based on the following rules: The rainfall intensity was close to normal distribution during the duration of rainfall; the last time of rainfall of a day was proportional to daily rainfall amounts. The method was used to build a distributed model in the Yellow River Basin; the runoff simulated by this model could meet the actual situation quite well.

But all above methods were calibrated by simulation results of models, which was not direct calibration. Errors and uncertainty of these methods could not be calculated directly.

The Yellow River basin is located in the north and west of China, the basin area is 1900 km from the east edge to the west edge, and 1100 km from the south to the north. The area of the basin is about 795 000 km^2. The flood and drought in the Yellow River Basin was serious historically, so hydrological simulation in this area is of great importance. There are three major sources of rainstorm and flood in the Yellow River Basin: the first from Hekouzhen to Longmen; the second from Longmen to Sanmenxia and the third from Sanmenxia to Huayuankou. In these areas, the distribution of hydrological stations is sparse. These areas are typically areas of ungauged basin; it is not good news to researchers on distributed hydrological models and hydraulic constructions.

Sanmenxia station selected as the case study in this work is located in these areas. The station has good rainfall observation data. The above temporal downscaling methods should be calibrated directly by using this data. A new method is developed base on the data and has been compared with the random distribution method, sinusoidal distribution method and the normal distribution method.

2 Material and methods

This paper uses rainfall data from 1970 to 1997 of the Sanmenxia hydrological station. The data includes start time, end time and rainfall amount of each single rainfall events. Encryption monitoring is added when the rainfall duration is too long. The data comes from the Hydrology Statistical Yearbooks of the People's Republic of China, subvolume of the Yellow River Basin. These books were published by Hydrology Bureau of the Water Resources Ministry. The Hydrology Bureau is authority of thousands and hundreds of hydrology stations all around the country, so the data would be reliable and accurate.

Using this data, the rainfall hyetographs of each single rainfall events could be drawn. The rainfall intensity between two Monitoring time points can be calculated by the ratio of rainfall amount and rainfall duration. We move the point of the maximum rainfall intensity to the origin point of the axis, and then we can easily compare different rainfall hyetographs. In this case, the left part of the graphics shows the process before the point of the maximum rainfall intensity, and the right part shows the process after the point. Then, we can draw the real outsourcing curve of the Sanmenxia Station from the rainfall hyetographs of each single rainfall events from 1970 to 1997, and then we can compare the rainfall hyetographs using different daily rainfall downscaling methods and the real outsourcing curve.

Random distribution method

The random method considered the rainfall events happened in random, so the rainfall amount is allocated into every smaller time scales in random. The method could be described as Eq. (1).

$$\gamma_j = \begin{cases} [P - \sum_{i=1}^{j-1}(\gamma_i t_i)] \cdot \mathrm{rand}(j)/t_j & j = 1,2,\cdots,\tau-1 \\ [P - \sum_{i=1}^{\tau-1}(\gamma_i t_i)]/t_j & j = \tau \end{cases} \tag{1}$$

Where P is the daily rainfall amount (mm); τ is the rainfall duration (h); t_i is the $\mathrm{i_{th}}$ period of the duration (h); γ_i is the rainfall intensity in the $\mathrm{i_{th}}$ period ($\mathrm{mm\,h^{-1}}$).

Sinusoidal distribution method

The method could be described in Eq. (2).

$$\gamma = \gamma_{\max}\sin(\frac{\pi t}{\tau}), 0 \le t \le \tau, \tau = \frac{5}{3}\cdot\sqrt{P}, \gamma_{\max} = \frac{3\pi}{10}\cdot\sqrt{P} \tag{2}$$

Where, $\gamma(\mathrm{mm\,h^{-1}})$ is the real time intensity; $\gamma_{\max}(\mathrm{mm\,h^{-1}})$ is the peak value of γ during a day; τ(h) is the rainfall duration. P(mm) is the daily rainfall amount.

Normal distribution method

Normal distribution method is a method in which the argument can range from the negative infinity to the positive infinity. In this paper, we focus on the area 3σ each side of the original point, and the modelling results are close enough to the real daily rainfall amount (99.73%). Then the time period 6σ is the daily rainfall durationThe method could be described in Eq. (3).

$$\gamma = \frac{6P}{\tau\sqrt{2\pi}}\exp(-18(t/\tau - 1/2)^2) \tag{3}$$

Where P(mm) is the daily rainfall amount; $\gamma(\mathrm{mm\,h^{-1}})$ is the real time rainfall density; τ(h) is the rainfall duration.

Proportional method

Base on the data of the Sanmenxia Station, a new method is developed to fit the real situation.

We divided the duration of the real outsourcing curve into 24 parts, and then calculate the rainfall amount of the central I part, the central 3 parts, 11 parts and 24 parts. Then we get the ratio of this rainfall amount of each situation to the total daily rainfall. The statistics show that the ratio of these 4 periods is 1:2:3:3.6. We can simulate the rainfall process using the following method; we can call it proportional method:

1. Simulate the rainfall duration. Because the sinusoidal distribution method performs well in the Yellow River Basin in modelling the rainfall duration, so we can use the Eq. (4):

$$\tau = \frac{5}{3}\sqrt{P} \quad (4)$$

   Where P(mm) the daily rainfall amount,τ(h) is the daily rainfall duration.

2. Divide τ into 24 parts, each part is $\frac{\tau}{24}$; divide the rainfall into 3.6 parts, each part is $\frac{P}{3.6}$.

3. Allocate the rainfall amount according to the proportion. Distribute the rainfall amount $\frac{P}{3.6}$ into the central time period $\frac{\tau}{24}$; $\frac{P}{3.6}$ into the $\frac{2\tau}{12}$ time period next to the centre; $\frac{P}{3.6}$ into the $\frac{8\tau}{24}$ time period next to the above $\frac{2\tau}{12}$ time period; and divide the last rainfall amount$\frac{0.6}{3.6}P$into the rest $\frac{11\tau}{24}$ time period.

4. According to actual situation of different areas, the time rainfall occurs most frequently can be found. Assume the initial rainfall intensity and the ending rainfall intensity are both zero; calculate the real time rainfall intensity from the outside to the inside.

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3 Results and discussion

3.1 Comparison

According to hyetographs of all single rainfall evens between 1970 and 1997 of the Sanmenxia Hydrological station, we can get outsourcing curves of all the hyetographs. And rainfall amount corresponding to this curve can be calculated. According to this amount and using the selected three existing downscaling methods, we can get three simulation hyetographs.

3.1.1 Comparison between the simulation hyetographs of the random distribution method and the real outsourcing curve

Obviously the results of the random distribution method are different every time. Just one simulation result is showed in this paper. We put one half of the simulation rainfall hyetograph to both sides of the original point, and let the data fits the descending order from the inside to the outside from the original point, therefore the simulation hyetograph of the random distribution method can be symmetric. The Fig. 1 shows that the hyetograph of this method attenuates too fast, so the high value part of rainfall intensity of the graph is exaggerated, and the smaller rainfall intensity part of the graph is weakened. Furthermore, this method is too random to control; the part of rainfall with the maximum rainfall intensity could be 90% of the total daily rainfall amount as an extreme sample.

3.1.2 Comparison between the simulation hyetograph of the sinusoidal distribution method and the real outsourcing curve

The Fig. 2 shows the comparison between the simulation hyetograph by the sinusoidal method and the real outsourcing curve. The rainfall proportion with high value rainfall intensity is smaller than the real situation, while the low rainfall intensity part is bigger than the real situation.

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So the method is improved based on the following two principles: the total daily rainfall amount and the maximum value of the rainfall intensity should meet the real situation; so the duration of the rainfall would be shorter than the real situation. The simulation result by the new sinusoidal distribution method is showed in Fig. 3. The rainfall proportion with high rainfall intensity is higher than the real situation, while the low rainfall intensity part is lower than the real situation.

3.1.3 Comparison between the simulation hyetograph of the normal distribution method and the real outsourcing curve

The duration simulated by the sinusoidal distribution is close to the real value. So in the normal distribution method, the equation to simulate rainfall duration follows the method in the sinusoidal distribution. Then using Eq. (4) we can get the simulation hyetograph simulated by the normal distribution method. As showed in Fig. 6, the simulation result exaggerates the rainfall proportion with low rainfall intensity and weakens the rainfall proportion with high rainfall intensity.

So we improve the traditional normal distribution method by the following principles: the total daily rainfall and the maximum rainfall intensity meet the real situation. The simulation curve by the improved method is showed in Fig. 7. The simulation result exaggerates the rainfall proportion with high rainfall intensity and weakens the rainfall proportion with low rainfall intensity.

According to the preceding discussion, the existing three methods for daily rainfall temporal downscaling can not simulate the real situation of the Yellow River Basin. They can not fit the high intensity part and the low one at the same time. So a new method should be developed in this area.

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3.2 A new daily rainfall downscaling method

Following this proportional method described in part 2 of this article, we can draw the comparison figure between the simulation hyetograph and the real outsourcing curve in the Sanmenxia Station, Fig. 6.

The proportional distribution method performs better than the other three existing methods in simulation the rainfall process of the Sanmenxia Station in the Yellow River Basin, and the simulation hyetograph fits the real outsourcing hyetograph quite well both in high intensity part and the low intensity one.

In order to exam the adaptability of the method in other parts of the Yellow River Basin, we draw the comparison chart of the simulation hyetograph and the real outsourcing curve of the Anningdu Station and the Tangnaihai Station (Fig. 7). The result shows that the proportional method performs very well in modelling the rainfall process in these two stations too.

3.3 Direct calibration of the proportional method

Two rainfall series of daily rainfall process of the Sanmenxia station are selected to calibrate the new method. One of them contains two records of large amount daily rainfall; the other contains more large rainstorms. The new method, proportional method, and one of the existing methods, normal distribution method, simulate both the series and comparisons are taken between the two simulation process and the process of real situation.

In simulation of the first series, showed as Fig. 8, both two methods show their shortages. The series contain two large rainfall evens. The proportional method exaggerates the maximum rainfall intensity of the first rainfall event, but can simulate the second one quite well. The normal distribution method also exaggerates the maximum rainfall intensity of the first rainfall event. At the same time the method weakens the maximum rainfall intensity of the second one, the simulation value is just 1/3 of the actual value.

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The second series contain some rainstorms. This meets the real situation of the wet period of the Yellow River Basin. The proportional method can simulate the process of most of the rainfall events quite well excepting one of the largest maximum rainfall intensity, which is showed in Fig. 9. While the maximum rainfall intensities simulated by the normal distribution method are all lower than the actual values, just 1/2 ∼ 1/4 of the real values, which is not conducive to simulate the whole rainfall process or even floods in this area. Both of the two methods can not accurately simulate the start and end time of the rainfall events.

4 Conclusions

The Yellow River Basin is located in the northeast part of China. Just when the rainfall intensity exceeds the infiltration rate of this area, the rainfall which exceeds the infiltration amount generates surface runoff. So the rainfall intensity plays an important roll in the water resources and floods and droughts of this area. In distributed hydrological models developing of this area, the input data should be accuracy, especially the rainfall intensity values. But the rainfall data which is reliable and long enough and researchers can get easily is usually the daily rainfall data. Valid methods of daily rainfall temporal downscaling should be used in the development of the distributed hydrological models. But the four methods used widely are not reasonable in the Yellow River Basin; all of them can not meet the actual situation at the rainfall proportion with low rainfall intensity and the ratio of rainfall with high rainfall intensity at the same time. A new method, proportional method is developed to meet the real situation of this area.

The new method can simulate the rainfall process quite well, especially rainstorm events which happened frequently in the wet period of the Yellow River Basin. But it is hard to simulate the start time and end time of the rainfall. It is really hard work, in articles of Zhou et al. (2005, 2006) and Ye et al. (2007) it was found that it is unreasonable to simulate the start and end time of the rainfall. The most important work is calculating the process and the rainfall ratio with different rainfall intensities; the proportional method can do that quite well in the Yellow River Basin.

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The rainfall temporal downscaling is a focus in the development of distributed hydrological models and PUB. It is important to reduce the uncertainty of the input data. The simulation accuracy of the downscaling methods always influences the accuracy of the distributed hydrological models. The new downscaling method developed in this study can fit the real situation of the Yellow River Basin quite well; it would be a valid tool in improving the accuracy of distributed hydrological models of the Yellow River Basin.

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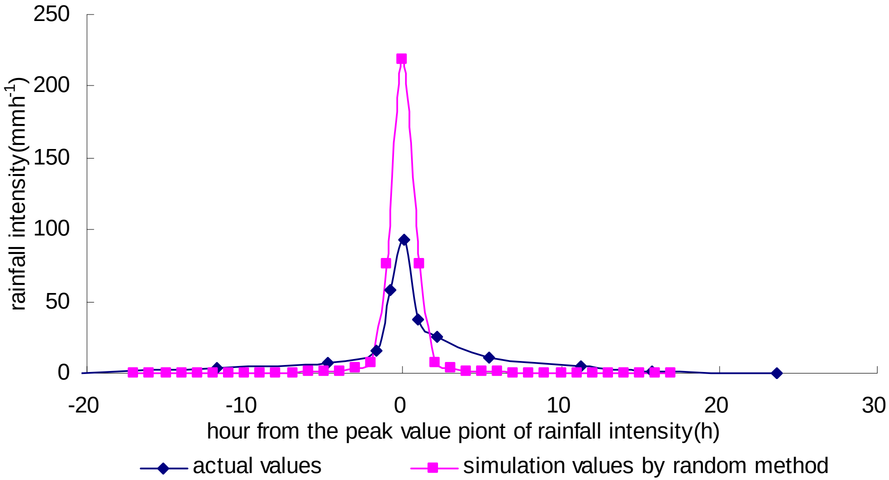

Fig. 1. Comparison between the simulation hyetograph of the random distribution method and the real outsourcing curve.

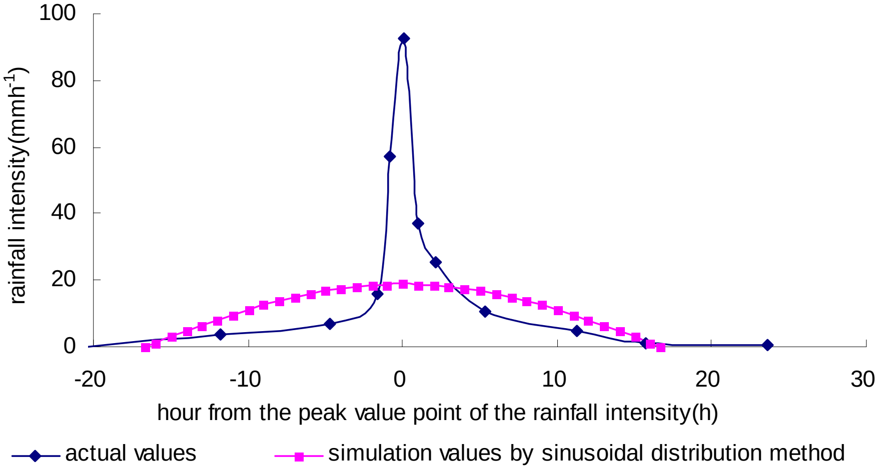

Fig. 2. Comparison between the simulation hyetograph of the sinusoidal distribution method and the real outsourcing curve.

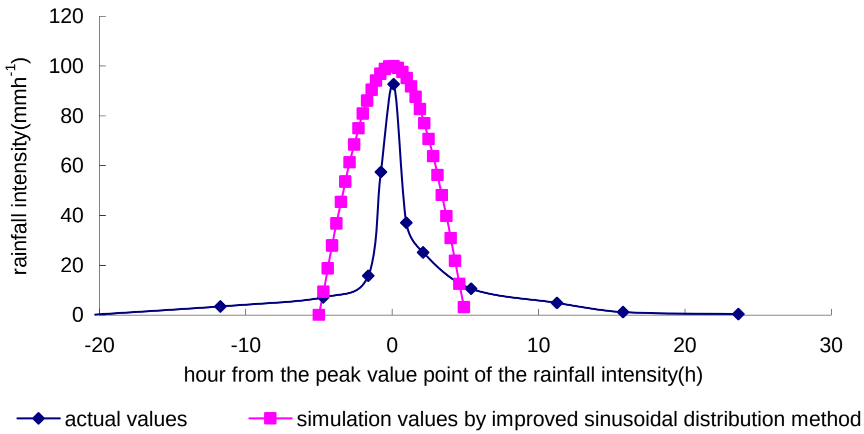

Fig. 3. Comparison between the simulation hyetograph of the improved sinusoidal distribution method and the real outsourcing curve.

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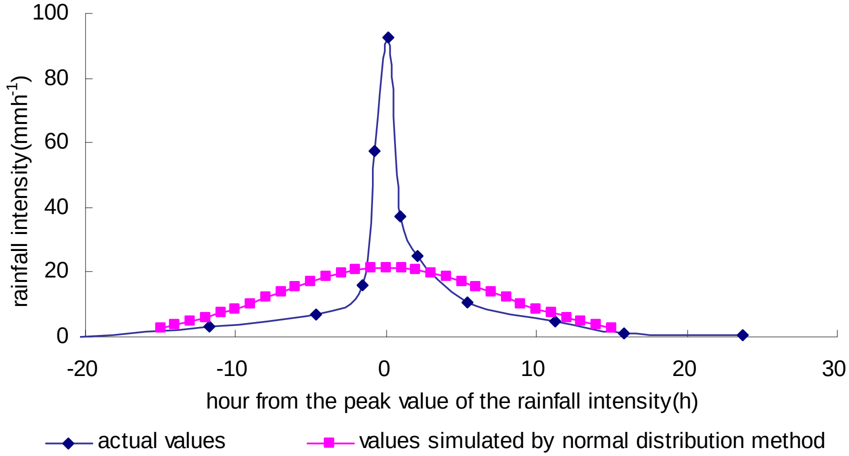

Fig. 4. Comparison between the simulation hyetograph of the normal distribution method and the real outsourcing curve.

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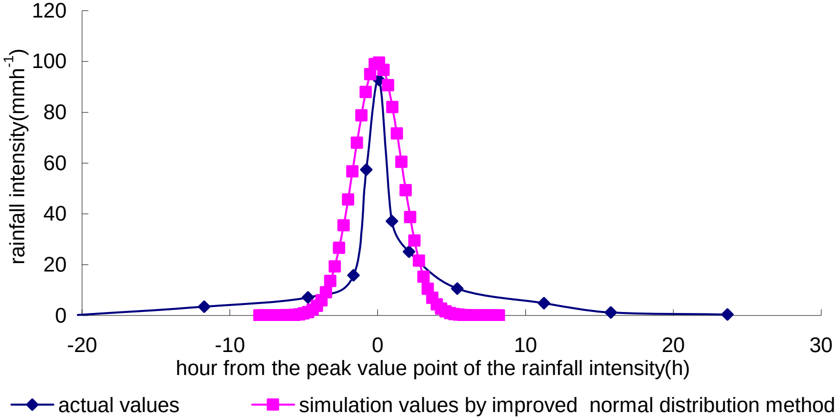

Fig. 5. Comparison between the simulation values by improved normal distribution method and the real outsourcing curve.

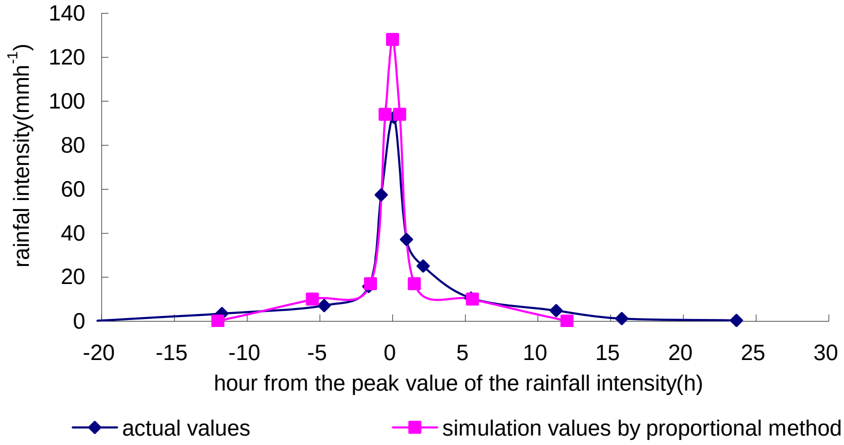

Fig. 6. Comparison between the simulation hyetograph and the real outsourcing curve.

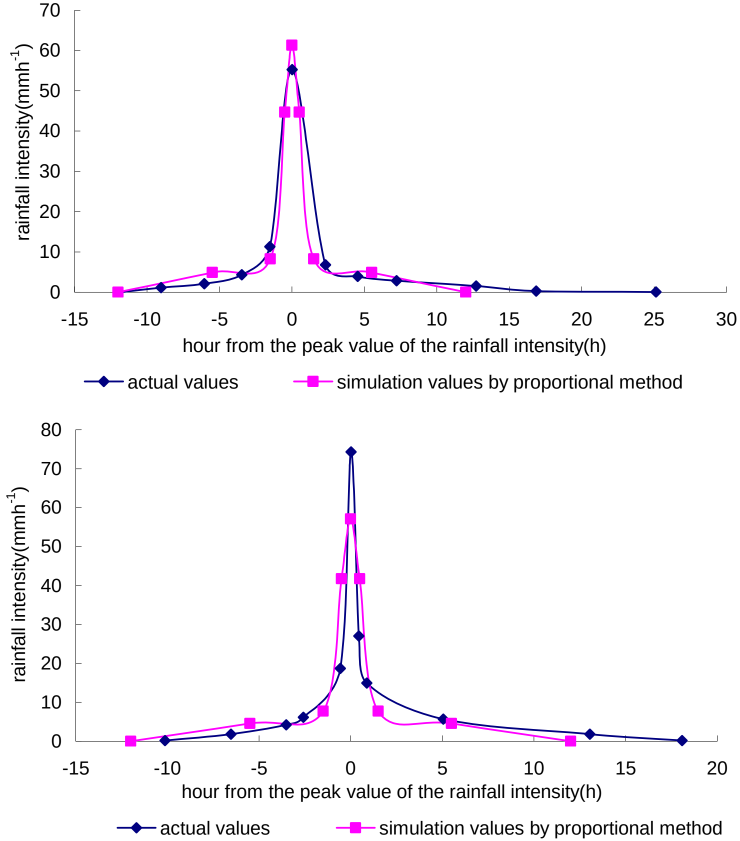

Fig. 7. Comparison between the simulation hyetograph and the real outsourcing curves of the Anningdu Station (above) and the Tangnaihai Station (below).

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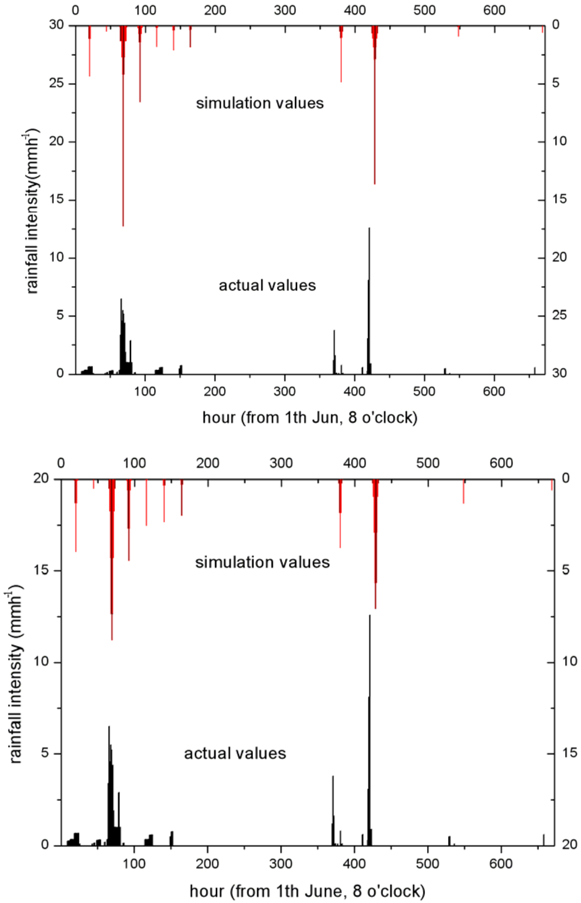

Fig. 8. Comparison between the simulation hyetograph of proportional distribution method (above) and the real hyetograph of normal distribution method (below).

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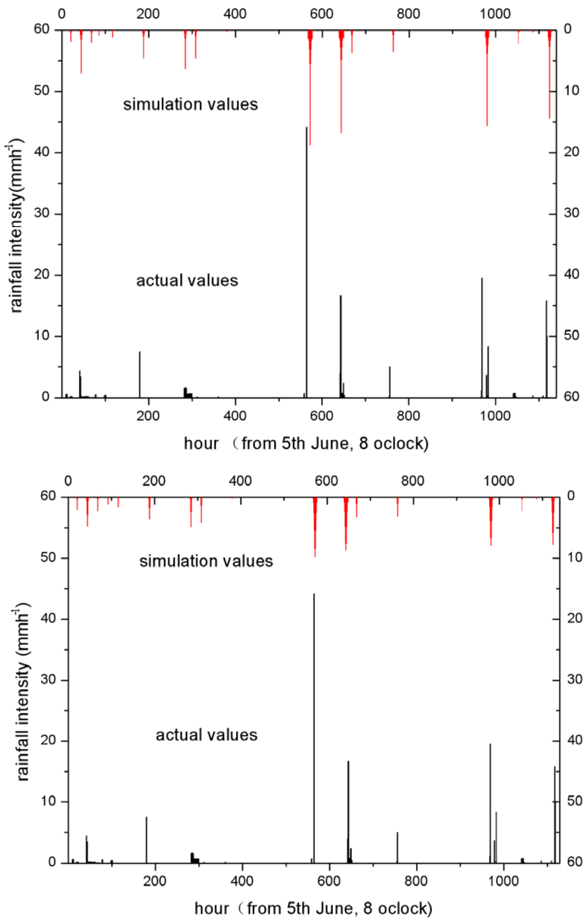

Fig. 9. Comparison between the simulation hyetograph of proportional distribution method (above) and the real hyetograph of normal distribution method(below).

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