Hydrological response to future precipitation extremes under climate change

G H Li¹, Z N Chen¹, J Li¹ and X Wen³,⁴
¹CHN ENERGY DaDu River Hydropower Development Co., Ltd, No.7 Tianyun Road, Gaoxin District, Chengdu City, China
²Hohai University, No.1 Xikang Road, Nanjing 210098, China
³China Institute of Water Resources and Hydropower Research, No.1 Fuxing Road, Beijing 100038, China
⁴Email: njwenxin@163.com

Abstract. Adaptive management of future flood disasters is necessary under climate change. In this study, a Generalized Extreme Value (GEV) distribution based statistical model was established to simulate historical and future precipitation extremes in the Xin'an River basin, and the vertical mixed runoff model was driven by future precipitation extremes to simulate the hydrological response to extreme flood events. Compared to precipitation events for the period 1951-2017, the intensity of monthly extreme precipitation for the period 2020-2099 would be increased by 10.4%, 11.0% and 11.4% at a 10-, 20- and 50-year return period, respectively. Future precipitation extremes with a 10-, 20- and 50-year return period were used to drive the calibrated vertical mixed flow model and to simulate the hydrological response of the Xin'an River basin. The runoff peak is increased from 4930 m³/s for p=10% to 6528 m³/s for p=2%, while the flood volume is increased from 4.26 billion m³ for p=10% to 5.68 billion m³ for p=2%, respectively. The hydrological response to precipitation extremes identified herein can serve as a foundation for adaptive flood control operation in the future.

1. Introduction
The IPCC5 indicates that obvious variation of extreme climates is expected all around the world. As the consequence of global climate change, extreme rainfall will induce dangerous flood disasters at the local and worldwide levels. [1] Variation in extreme rainfall will show an obvious effect on flood characteristics and pose additional problems to the flood protection systems. In view of the rising tendency of extreme rainfall and its temporal-spatial uncertainty, it is necessary to quantify the changing characteristics and influences of extreme rainfall.

The variation characteristics of rainfall extreme occurrence was usually explored using the generalized linear models [2]. Some non-stationary distributions were also employed to analyse the extreme rainfall events, especially for those monsoon seasons or wet periods with large thresholds [3]. With the deviation average coefficient table, the application of generalized extreme value distribution can obtain better fitting effect, and it is also very convenient for hydrological frequency analysis and various statistical calculation [4],[5].
Climate changes and hydrological responses are often simulated and evaluated using coupled GCM-hydrological models. The GCMs became vital techniques for future climate variation projection [6], and for driving the hydrological model to forecast the corresponding streamflow change[7]. In particular, diverse hydrological simulation techniques were proposed and explored, such as MIKE SHE [8], VIC [9], SWAT [10] and et al. There are many studies focusing on the long-term effects of climate variation, extreme conditions are not deeply discussed.

Here, the statistical characteristics of extreme rainfall events was analyzed by generalized extreme value distributions, then the hydrological processes and flood events were simulated using mixed runoff model at diverse return levels.

2. Research area and data

Xin'an River is the largest tributary of Qiantang River Basin in coastal eastern area of China. The length of the mainstream is 373 kilometers, and the basin area is more than 11000 square kilometers. Xin'an river basin is rich in water resources, and it often suffers from extreme rainfall events in history. The average annual runoff is 7.23 billion cubic meters, and the maximum annual net flow is 10.652 billion cubic meters.

Climate observations extracted from China Grid Daily Climate Data 2.0 is applied in this research. Gridded temperature and rainfall at a spatial of 0.5°×0.5° from January 1951 to December 2018 is used. Six representative floods are selected, namely Jun. 7 1990-Jun. 23 1990, May 24 1995-Jun. 14 1995, Mar. 16 2002-Apr. 15 2002, Jun. 29 2013-Jul. 13 2013, Jun. 13 2014-Jul. 1 2014, Jun 8 2018-Jun 30 2018. The inflow data of the reservoir during these flood events is collected.

We analysed the daily precipitation, temperature, and evaporation over the period 2020-2100 based on CCSM4. The future predictions of temperature, precipitation and evaporation are temporally reduced on a daily basis (BCSDd). Representative Centralized Path (RCP) scenario 4.5 is used to represent medium emission conditions.

3. Methods
3.1. Generalized extreme value (GEV) distribution model

The GEV distribution is a family of continuous probability distributions developed within extreme value theory [11]. Extreme value theory provides the statistical framework to make inferences about the probability of very rare or extreme events [12]. The GEV distribution unites the Gumbel, Fréchet and Weibull distributions into a single family to allow a continuous range of possible shapes [13]. Here, the maximum likelihood method is employed to quantify the main variables of generalized extreme value distribution [14]. The historical and future extreme rainfall change characteristics is assessed using the GEV model.

3.2. Hydrological processes simulation

The vertical mixed model is widely used in hydrological process simulation, especially for those flood event simulation cases. The hydrological model has two core components, including excess saturation module and excess infiltration module. These two mechanisms coexist and are often used in short-term flood simulation. It consists of reservoir-area curve and infiltration curve. Falling rainfall can be divided into streamflow and underground runoff. The generation of runoff also requires certain conditions, which are related to the level of soil moisture. In areas with large soil moisture content, infiltration can convert into runoff, while the opposite is true in areas with low soil moisture content. Surface streamflow and underground streamflow are calculated in different ways. The former is calculated according to the infiltration drainage mechanism, while the latter is calculated according to the saturated drainage mechanism. The flowchart of the hydrological simulation is presented in Figure 2.

![Flowchart of the hydrological simulation model](image)

**Figure 2.** The flowchart of the hydrological simulation model.

4. Results and discussion

4.1. Temporal-spatial variations of extreme rainfall events

The past (1951-2017) and future (2020-2100) extreme rainfall events were fitted by generalized extreme value distribution, and compared to reveal the temporal-spatial variation characteristics of rainfall extremes in the research area. Figure 3 indicates the geographical pattern of the largest monthly precipitation from 1951 to 2017 with recurrence level of 2%, 5%, and 10%. The intensity of the extreme rainfall indicates a downward trend from south-western area to north-eastern area, and the average monthly rainfall amount rises from 413 mm with recurrence level of 10% to 536 mm with 2%. The largest monthly rainfall amount (441, 495, and 567 mm for recurrence level of 10%, 5% and 2%) and smallest amount (376, 425, and 493 mm for recurrence level of 10%, 5% and 2%) also indicates a similar change tendency.
Figure 3. The geographical pattern of monthly rainfall extremes in history of Xin’an River Basin

Figure 4 indicates the relative average variations of future monthly extreme rainfalls to the historical extreme rainfalls for recurrence level of 10%, 5% and 2%, respectively. The rainfall intensity will possibly rise by 10.8 to 11.8 percent for the future period. A downward tendency is observed in monthly extreme rainfall from north-eastern to south-western area, showing that the variation of humid area was comparatively greater than that of arid area. There is no remarkable influence of diverse recurrence level on the geographical pattern of extreme rainfall. The rainfall extreme variation becomes more significant as the recurrence level varies from 10% to 2%.

Figure 4. The geographical pattern of monthly rainfall extremes in future of Xin’an River Basin

4.2. Hydrological process simulation in extreme rainfall events
Six representative extreme rainfall events of the Xin’an River basin were chosen, namely Jun. 7 1990-Jun. 23 1990, May 24 1995-Jun. 14 1995, Mar. 16 2002-Apr. 15 2002, Jun. 29 2013-Jul. 13 2013, Jun. 13 2014-Jul. 1 2014, Jun 8 2018- Jun 30 2018. In consideration of the first five floods involve diverse types of flood process, containing large and small floods events, so they were used for calibrating the hydrological model and the last flood event was used for validating the model. The minimum discharge error is employed as the calibration objective. Figure 5 presents the simulated versus observed streamflow of the Xin’an River, a sound agreement confirms the adaptability and simulation ability of the model.
Figure 5. Simulated versus actual streamflow processes during six selected rainfall extremes.

The future flood responses to rainfall extremes with recurrence level of 2%, 5%, and 10% were simulated for the research area. As presented in Table 1, the maximum flow rose from 4930 m$^3$/s at 10-year period to 6525 m$^3$/s at 50-year period, and flood amount rose from $4.3 \times 10^9$ m$^3$ at 10-year period to $5.7 \times 10^9$ m$^3$ at 50-year period. The maximum streamflow will rise by 334 m$^3$/s in the future, and the flood amount will increase by $4.1 \times 10^8$m$^3$ at 50-year return period.

Table 1 Comparison between historical and future flood characteristics.

| Parameter                  | in future (2010-2100) | in history (1951-2017) |
|----------------------------|------------------------|------------------------|
| Recurrence level           | 10%    5%    2%   10%  5%   2% |
| Peak flow (m$^3$/s)        | 4929.65 5604.31 6524.93 4638.01 5396.07 6190.81 |
| Total flood volume (billion m$^3$) | 4.26    4.86   5.68  3.98  4.52   5.27 |
| 3-day largest flood volume (billion m$^3$) | 1.11    1.27    1.48  0.95  1.04   1.31 |
| 7-day largest flood volume (billion m$^3$) | 1.96    2.23    2.6   1.73  1.98   2.36 |

5. Conclusions

In this paper, the statistical characteristics of extreme rainfall events was analyzed by generalized extreme value distributions, then the hydrological processes and flood events were simulated using mixed runoff model at diverse return levels. As the result, the intensity of the extreme rainfall indicates a downward trend from south-western to north-eastern area. Compared to the extreme rainfall in 1951-2017, the rainfall intensity will possibly rise by 10.8 to 11.8 percent for the future period in 2020-2099. The maximum streamflow will possibly rise from 4930 m$^3$/s at 10-year return
period to 6525 m³/s at 50-year return period, and flood amount is expected to rise from 4.26×10⁶ m³ at 10-year return period to 5.68×10⁶ m³ at 50-year return period. The hydrological response determined in this paper can not only be used as the basis of flood prevention in the future, but also be used for risk assessment and prevention before disaster.

Acknowledgements
This research was funded by National Key R&D Program of China (2018YFC0407902), National Natural Science Foundation of China (U1765201, 52079040), Jiangsu Water Science and Technology Project (2019027, 2020065).

References
[1] Tye M R, Blenkinsop S, Fowler H J, Stephenson D B and Kilsby C G 2016 Simulating multimodal seasonality in extreme daily precipitation occurrence J. Hydrol. 537 117-29
[2] Gregersen I B, Madsen H, Rosbjerg D and Arnbjer-Nielsen K 2013 A spatial and nonstationary model for the frequency of extreme rainfall events Water Resour. Res. 49 127-36
[3] Mondal A and Mujumdar P P 2015 Modeling non-stationarity in intensity, duration and frequency of extreme rainfall over India J. Hydrol. 521 217-31
[4] Gao T and Xie L 2016 Spatiotemporal changes in precipitation extremes over Yangtze River basin, China, considering the rainfall shift in the late 1970s Global Planet Change 147 106-24
[5] Wen X, Fang G H, Qi H S, Zhou L and Gao Y Q 2016 Changes of temperature and precipitation extremes in China: past and future Theor. Appl. Climatol. 126 369-83
[6] Karl T R and Trenberth K E 2003 Modern global climate change Science 302 1719-23
[7] Neartzaki S D, Giannakis G V, Efstatoliou D, Nikolaidis N P, Sibetheros I A, Karatzas G P and Zacharias I 2015 Modeling suspended sediment transport and assessing the impacts of climate change in a karstic Mediterranean watershed Sci. Total Environ. 538 288-97
[8] Neupane R P and Kumar S 2015 Estimating the effects of potential climate and land use changes on hydrologic processes of a large agriculture dominated watershed J. Hydrol. 529 418-29
[9] Moussoulis E, Mallinis G, Koutsias N and Zacharias I 2015 Modelling surface runoff to evaluate the effects of wildfires in multiple semi-arid, shrubland-dominated catchments Hydrol. Process. 29 4427-41
[10] Du E H, Link T E, Wei L and Marshall J D 2016 Evaluating hydrologic effects of spatial and temporal patterns of forest canopy change using numerical modelling Hydrol. Process. 30 217-31
[11] Serpa D, et al 2015 Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting Mediterranean catchments Sci. Total Environ. 538 64-77
[12] Githui F, Gitau W, Mutua F and Bawwens W 2009 Climate change impact on SWAT simulated streamflow in western Kenya Int. J. Climatol. 29 1823-34
[13] Pierri L, Rondini D and Ventura F 2017 Changes in the rainfall–streamflow regimes related to climate change in a small catchment in Northern Italy Theor. Appl. Climatol. 129 1075-87
[14] Kharin V V, Zwiers F W, Zhang X and Wehner M 2013 Changes in temperature and precipitation extremes in the CMIP5 ensemble Climatic Change 119 345-57
[15] Liu F, Du Z M and Chen X F 2013 Combining water flooding type-curves and Weibull prediction model for reservoir production performance analysis J. Petrol. Sci. Eng. 112 220-6
[16] Dupuis D J 1998 Parameter and quantile estimation for a fatigue model Comput. Stat. Data. An. 29 55-68
[17] Kharin Y S and Voloshko V A 2011 Robust estimation of AR coefficients under simultaneously influencing outliers and missing values *J. Stat. Plan. Infer.* **141** 3276-88

[18] Cohn T A and Stedinger J R 1987 Use of historical information in a maximum-likelihood framework *J. Hydrol.* **96** 215-23

[19] El Adlouni S, Bobee B and Ouarda T B M J 2008 On the tails of extreme event distributions in hydrology *J. Hydrol.* **355** 16-33

[20] Kharin A Y and Shlyk P A 2009 Robust multivariate Bayesian forecasting under functional distortions in the chi (2)-metric *J. Stat. Plan. Infer.* **139** 3842-6