Replies to Referee #1

"Multiple Causes of Nonstationarity in the Weihe Annual Low Flow Series"

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We are very grateful for your comments and suggestions. We provide responses to each individual point below. For clarity, comments are given in italics, and our responses are given in plain text.

> *There are many researches focusing on reasons, causes and modelling of nonstationarity of hydrological extremes such as: Xihui Gu, Qiang Zhang, Vijay P. Singh, Peijun Shi, 2017. Nonstationarities in the occurrence rate of heavy precipitation across China and its relationship to climate teleconnection patterns. International Journal of Climatology, DOI: 10.1002/joc.5058. Xihui Gu, Qiang Zhang, Vijay P. Singh, Peijun Shi, 2017. Changes in magnitude, frequency and timing of heavy precipitation across China and its potential links to summer temperature. Journal of Hydrology, 547, 718-731. Xihui Gu, Qiang Zhang, Vijay P. Singh, Peijun Shi, 2017. Nonstationarity in timing of extreme precipitation across China and impact of tropical cyclones. Global and Planetary Change, 149, 153-165. Xihui Gu, Qiang Zhang, Vijay P. Singh, Lin Liu, 2016. Nonstationarity in the occurrence rate of floods in the Tarim River basin, China, and related impacts of climate indices. Global and Planetary Change, 142, 1-13. Qiang Zhang, Xihui Gu, Vijay P. Singh, Mingzhong Xiao, Xiaohong Chen, 2015. Evaluation of flood frequency under non-stationarity resulting from climate change and human activities in the East River basin, China. Journal of Hydrology, 527, 565-575. Qiang Zhang, Xihui Gu, Vijay P. Singh, Mingzhong Xiao, Chong-Yu Xu, 2014. Stationarity of annual flood peaks during 1951-2010 in the Pearl River basin, China. Journal of Hydrology, 519, 3263-3274. What are the motivations, research objectives and novel points of this current study when compared to standing researches? My strong suggestion is that thorough literature review is pretty necessary. New findings, new ideas, new methods, if any, should be pointed out with enough citations to justify authors' statements.*

AUTHORS' REPONSE: Thank you for pointing this out and the good suggestion. We realize that this is our negligence. After reviewing the literatures mentioned by the reviewer, we also strongly agree that in order to state our motivation and innovation more clearly, it is necessary to include the aforementioned references and the other relevant reverences. Thus, following the advice of the reviewer, we have revised the 3rd paragraph of Introduction Section to provide more comprehensive literature review by discussing important recent publications in the field, including those introduced by the reviewer.

The related paragraph is to be changed into the following: "In hydrological analysis and design, conventional frequency analysis estimates the statistics of a hydrological time series based on recorded data with the stationary hypothesis which means that this series is "free of trends, shifts, or periodicity (cyclicity)" (Salas, 1993). However, global warming and human forces have changed climate and catchment conditions in some regions. Time-varying climate and catchment conditions can affect all aspects of the flow regime, i.e. changing the frequency and magnitude of floods, altering flow seasonality, and modifying the characteristics of low flows, etc. The hypothesis of stationarity has been suspected (Milly et al., 2008). If this problematic method is still used, the frequency analysis may lead to high estimation error and costly design. Therefore, considerable literatures have introduced the concept of hydrologic nonstationarity into analysis of various hydrological variables, such as annual runoff (Arora, 2002; Jiang et al., 2017; Jiang et al., 2015; Liu et al., 2017; Xiong et al., 2014; Yang and Yang, 2013), flood (Chen et al., 2013; Gilroy and Mccuen, 2012; Gu et al., 2016; Kwon et al., 2008; López and Francés, 2013; Tang et al., 2015; Xiong et al., 2015; Yan et al., 2016; Zhang et al., 2014; Zhang et al., 2015), low flow (Du et al., 2015; Jiang et al., 2014; Liu et al., 2015), precipitation (Cheng and AghaKouchak, 2014; Gu et al., 2017a, b, c; Mondal and Mujumdar, 2015; Shahabul Alam et al., 2014; Villarini et al., 2010) and so on. Compared with the literatures on annual runoff, floods and precipitation, the literatures on the nonstationary analysis of low flow are very limited."

Following the reviewer's advice, we have also explicitly defined and stated the study objectives in the 6th paragraph of the Introduction Section.

The related paragraph is to be changed into the following: "The goal of this study is to trace origins of nonstationarity in low flows through developing a nonstationary low-flow frequency analysis framework with the consideration of the time-varying climate and catchment conditions (TCCCs). In this framework, the climate and catchment conditions are quantified using the eight indices, i.e., meteorological variables (total precipitation P, mean frequency of precipitation events λ, temperature T, potential evapotranspiration ET, climate aridity index AI_{ET}, base-flow index BFI, recession constant K and the recession-related aridity index AI_K). The specific objectives of this study are: (1) to find the most important index to explain the nonstationarity of low-flow series; (2) to determine the best subset of TCCCs indices and human activity indices for final model through stepwise selection method to identify nonstationary mode of low-flow series; and (3) to quantify the contribution of selected explanatory variables to the nonstationarity."

Following the reviewer's advice, we have also better stated our study motivation. The related paragraph is to be changed into the following: "Low flows are more vulnerable to influences of climate change and human activities than high flows. However, compared with the nonstationary flood frequency analysis, the studies on the nonstationary frequency analysis of low-flow series are not very extensive because of incomplete knowledge of low flow generation (Smakhtin, 2001). Most of previous studies explain nonstationarity of low-flow series only by using climatic indicators or a single indicator of human activity. However, the indicators of catchment conditions (e.g. recession rate) related to physical hydrological process have seldom been attached in nonstationary modelling of low flow series. This lack of linking with hydrological process makes it impossible to accurately quantify the contributions of influencing factors for the nonstationarity of low flow series, and such a scientific demand for tracing the sources of nonstationarity of low-flow series and qualifying their contributions motivated the present study."

There are no exact and/or results included in the Abstract section. Or only limited words describing results. More details and particularly in a quantitative way should be provided for description of results and conclusions

AUTHORS' REPONSE: The reviewer is correct. In the modified abstract, we will provide more quantitative results and conclusions. In the revision of the second part of the Abstract, the description of results and findings is to be modified as following: "The results show that the inter-annual variability in the variables of those selected best subsets plays an important role in modeling annual low flow series. Specifically, analysis of annual minimum 30-day flow in

Huaxian shows that in explaining nonstationarity, AI_K is of the highest relative importance among the best subset of eight candidates, followed by *IAR (note to reviewer: Irrigated area – a newly added index in the revised version), BFI* and *P*; and the final model (M6) with a minimum AIC value of 207.0 is nonstationary GA distribution model with best subsets (i.e. AI_K, *IAR*, *BFI* and *P*) as explanatory variable, while the AIC values of other models just with AI_K or time as explanatory variables or without any explanatory variable are 217.4, 225.5, 232.3, respectively. The incorporation of multiple indices related to low-flow generation permits tracing various driving forces. The established link in nonstationary analysis will be beneficial to analyze future occurrences of low-flow extremes in similar areas."

> *In Introduction section, it was noticed that there are numerous researches focused on nonstationary low flow frequency analysis. However, no novel points were listed and hence research motivations were not well justified. Besides, as a tributary of the Yellow River, evaporation or evapotranspiration, irrigation, population, GDP and so on should be included as factors influcing low flow changes. Related works have been done using Budyko framework by Prof. Dawen Yang from Tsinghua University and Prof. Qiang Zhang from Beijing Normal University and other colleagues from China. Besides, I still have no idea about how the authors developed the framework to evaluate low flow frequency from a nonstationary perspective.*

AUTHORS' REPONSE: Thanks to the reviewer for pointing out this. Firstly, in the introduction section, the part of the content has been reorganized and modified in order to clarify our research motivations more clearly. Related part for study motivation, refer to the response of the first comment above.

Secondly, we did not include indices more related to irrigation, population, GDP and so on for the following reasons: (1) the indices (*K*, AI_K and *BFI*) in this study are related to human activities; (2) the indices (*K*, AI_K and *BFI*) are linked to physical hydrological process; (3) too many variables greatly increase the computational complexity and the complexity of the analysis.

But we strongly agree with the reviewer's professional comment that further work should be done. In the revised version, we have included the irrigation area (*IAR*), the Gross Domestic Product (*GDP*), and population (*POP*) indices in the modified text to compare the nonstationary mode considering TCCCs indices with the nonstationary mode considering human activity indices (GDP, population and irrigation). The process of their change with time has been presented in Fig. 1. The Pearson correlation coefficients between low-flow series and these indices have been presented in Fig. 2. The models (M2b, M5, and M6, as explained in Table 1) are developed. The summary of their results have been presented in Table 2. Analysis of all new results (Figs. 3, 4, 5, and 6) will be included in the revised text.

< Figure 1> (newly-added)

< Figure 3> (revised)

< Figure 4> (revised)

< Figure 5> (newly-added)

< Figure 6> (revised)

< Table 1> (revised)

< Table 2> (revised)

Thirdly, the framework is composed of the time varying and GLM method, and the method of stepwise selection for TCCCs indices and human activity indices. And to address this comment, we have added a flow chat of methodology (Fig. 2) to explain how the framework is organized.

In Method section, a working framework should be formulated besides some descriptions.

AUTHORS' REPONSE: Thank you for your good suggestion. Following the reviewer's suggestion we have added a flow chart of methodology to the text, as show in Fig. 2.

<Figure 2> (newly-added)

Why the authors choose Weihe River basin as a case study? Are there any unique features of the study region when compared to other alternative rivers?

AUTHORS' REPONSE: The nonstationarity of annual runoff in Weihe River basin has been shown to be very significant (Lin et al., 2012; Xiong et al., 2014). The previous studies have demonstrated that the climate change and human activities play an important role in annual runoff changes. When compared to other alternative rivers, the nonstationarity mode of low flows in the study region is so complex that it is difficult to be identified due to the influence of various factors. This feature aroused our interest in choosing the study area. We try to demonstrate that the nonstationarity of low flows in this basin is caused by multiple factors and more effective analysis model should incorporate not only a single climate index or human activity indices but also the other climate indices and catchment condition indices.

Thanks again to the reviewer for providing professional and insightful comments and advices which will significantly improve the revised version of the manuscript.

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Figures

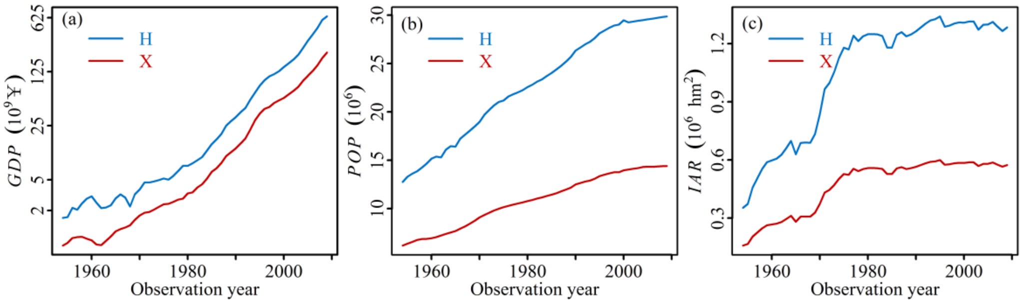

Figure1. Human activity indices in both Huaxian and Xianyang. (a), (b) and (c) are for population (*POP*), gross domestic production (*GDP*) and irrigated area (*IAR*), respectively.

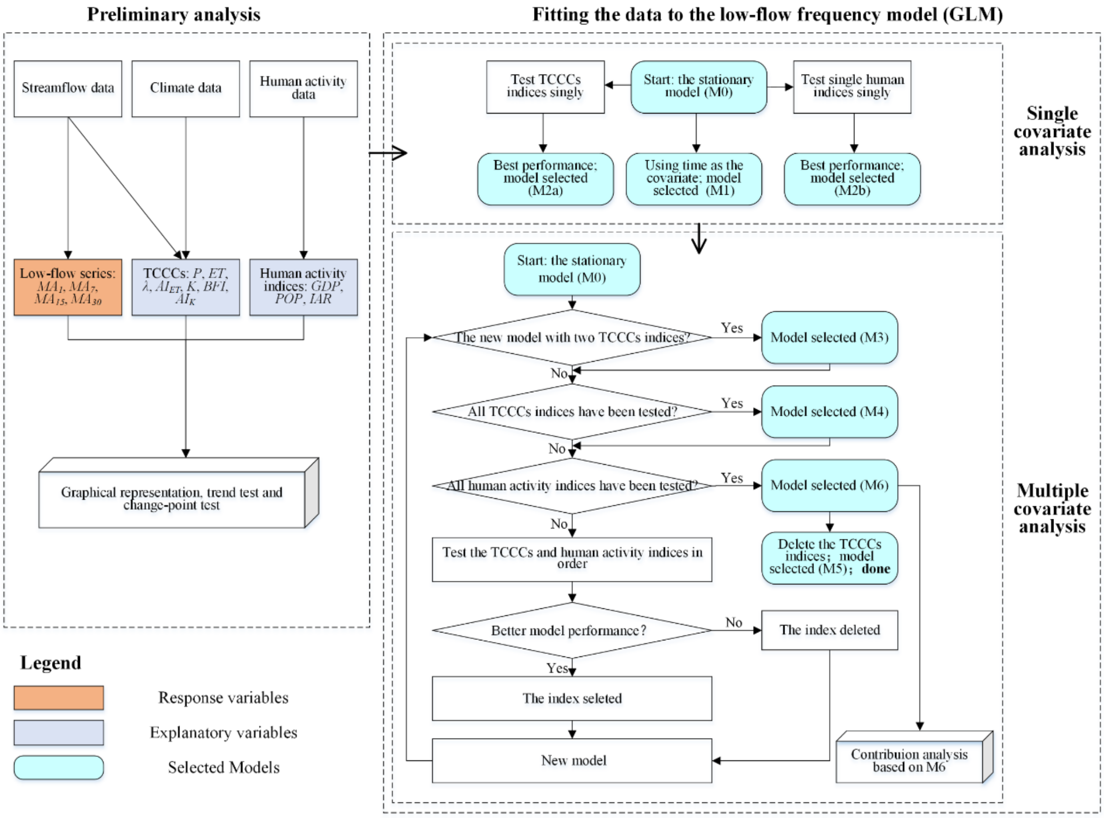

Figure 2. The framework of nonstationary low-flow frequency analysis.

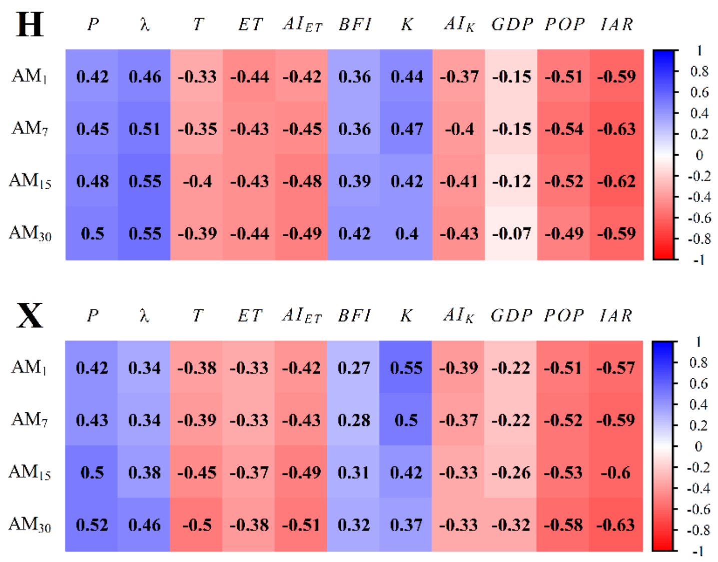

Figure 3. The Pearson correlation coefficients matrix between the annual minimum flow series and eight candidate explanatory variables in Huaxian (H) and Xianyang (X) stations; the darker color intensity represents a higher level of correlation (blue indicates positive correlation, and red indicates negative correlations).

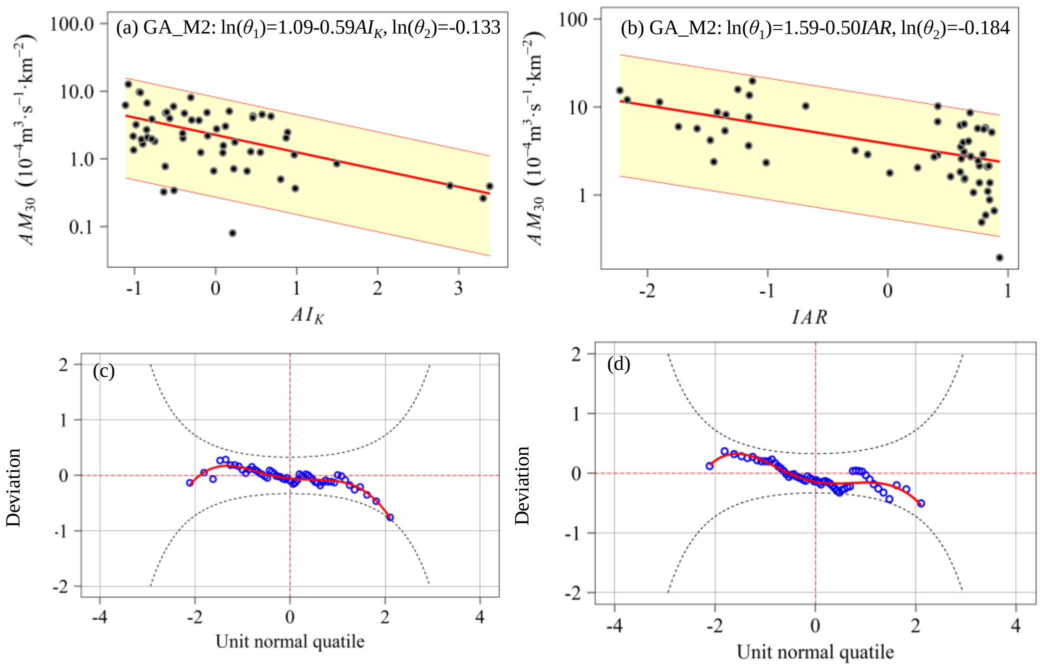

Figure 4. Performance assessments of the best M2 model (GA_M2) for AM_{30} in Huaxian (H) at left panel and Xianyang (X) at right panel. (a) and (b) are the centile curves plots of GA_M2 (red lines represent the centile curves estimated by GA_M2; the 50th centile curves are indicated by thick red; the yellow-filled areas are between the 5th and 95th centile curves; the black points indicate the observed series); (c) and (d) are the worm plots of GA_M2 for the goodness-of-fit test; a reasonable model fit should have the data points fall within the 95% confidence intervals (between the two red dashed curves).

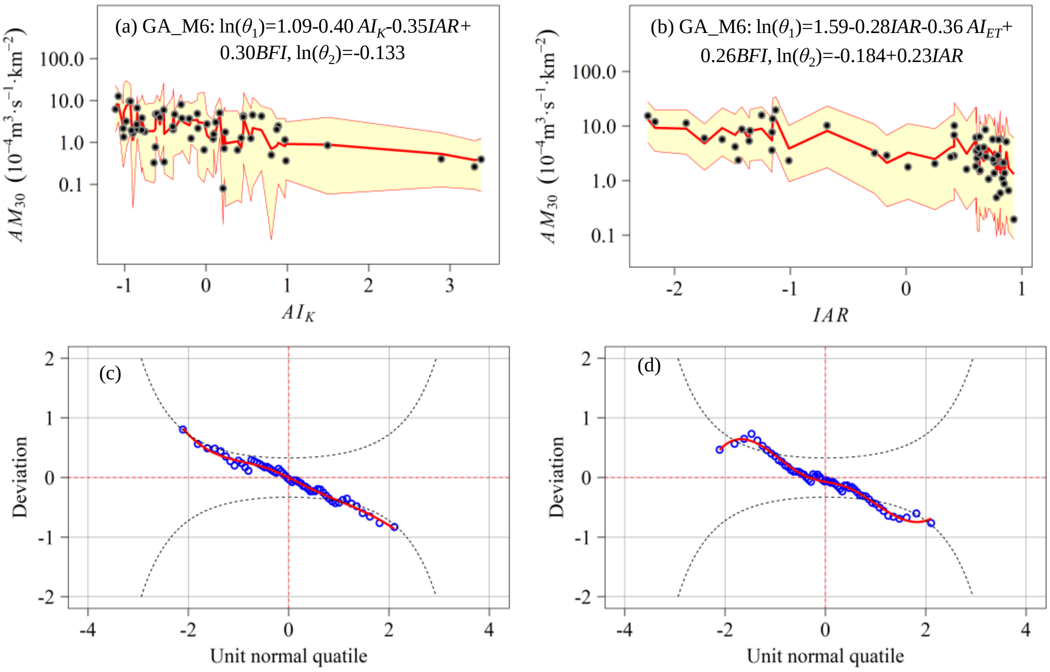

Figure 5. Performance assessments of the best M4 model (GA_M6) for AM_{30} in Huaxian (H) at left panel and Xianyang (X) at right panel. (a) and (b) are the centile curves plots of GA_M6 (red lines represent the centile curves estimated by GA_M6; the 50th centile curves are indicated by thick red; the yellow-filled areas are between the 5th and 95th centile curves; the filled black points indicate the observed series); (c) and (d) are the worm plots of GA_M6 for the goodness-of-fit test; A reasonable model fit should have the data points fall within the 95% confidence intervals (between the two red dashed curves).

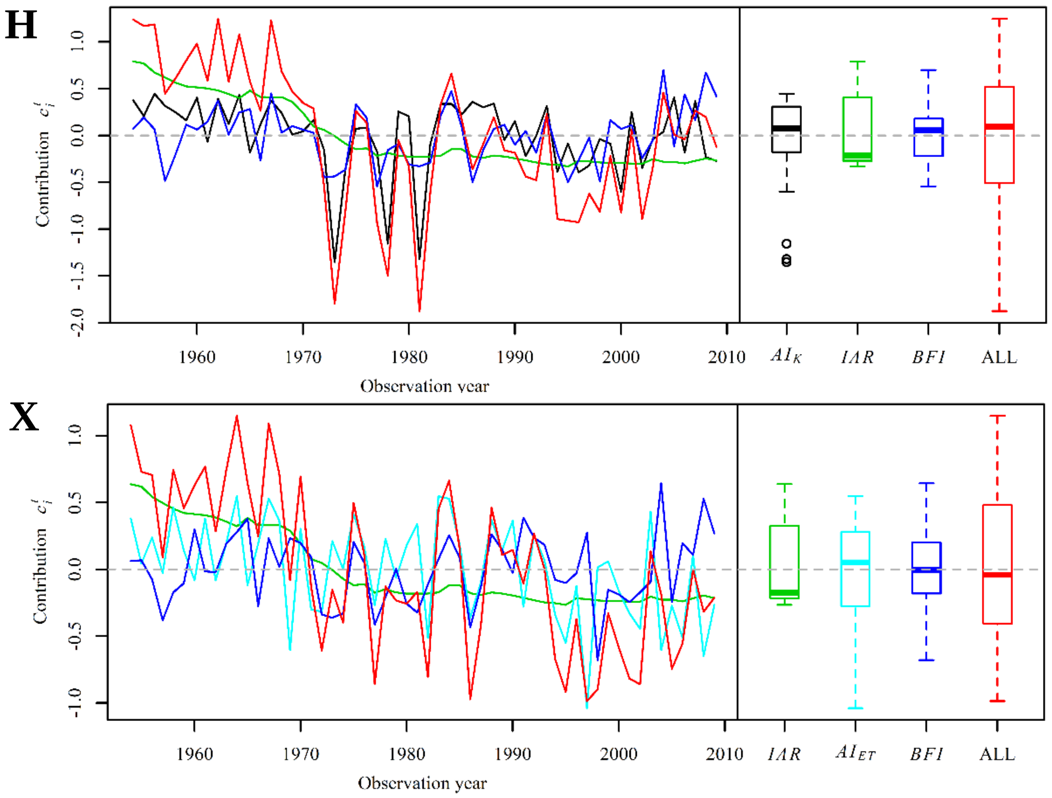

Figure 6. Contribution of selected explanatory variables to $c_i^t = \ln\left(\theta_1^t\right) - \ln\left(\bar{\theta}_1\right)$ in different periods based on GA_M6.

Tables

Table 1. Description of the developed nonstationary models using time, the indices of TCCCs or the indices of human activity (HA) as explanatory variables.

Model codes	Distribution					Description	
	GA	WEI	LOGNO	PIII	GEV	Variable category	The numbers of variables
M0	GA_M0	WEI_M0	LOGNO_M0	PIII_M0	GEV_M0	-	Zero
M1	GA_M1	WEI_M1	LOGNO_M1	PIII_M1	GEV_M1	Time	One
M2a	GA_M2a	WEI_M2a	LOGNO_M2a	PIII_M2a	GEV_M2a	TCCCs	One
M2b	GA_M2b	WEI_M2b	LOGNO_M2b	PIII_M2b	GEV_M2b	HA	One
M3	GA_M3	WEI_M3	LOGNO_M3	PIII_M3	GEV_M3	TCCCs	Two
M4	GA_M4	WEI_M4	LOGNO_M4	PIII_M4	GEV_M4	TCCCs	Identified by the stepwise selection
M5	GA_M5	WEI_M5	LOGNO_M5	PIII_M5	GEV_M5	HA	Identified by the stepwise selection
M6	GA_M6	WEI_M6	LOGNO_M6	PIII_M6	GEV_M6	TCCCs+HA	Identified by the stepwise selection

Table 2. The summary of frequency analysis for four annual low flow series of Huaxian and Xianyang.

Series	Model codes	Optimal variable	AIC	Distribution parameters $\ln(\theta_1)$	$\ln(\theta_2)$	θ_3
Huaxian station						
AM_1	WEI_M0	-	104.6	-0.19	-0.418	-
	WEI_M1	t	91.1	-0.19-0.84t	-0.418-0.30t	-
	WEI_M2a	AI_K	95.0	-0.19-0.72AI_K	-0.418	-
	WEI_M2b	IAR	88.1	-0.19-0.87IAR	-0.418	
	WEI_M3	AI_K, BFI	91.3	-0.19-0.58AI_K +0.55BFI	-0.418	-
	WEI_M4	AI_K, BFI, ET, λ	87.9	-0.19-0.39AI_K +0.61BFI-0.54ET	-0.418+0.27λ	-
	WEI_M5	IAR, POP	85.2	-0.19-0.82IAR	-0.418-0.31POP	
	WEI_M6	IAR, BFI, POP	80.0	-0.19-0.78IAR+0.57BFI	-0.418-0.29POP	
AM_7	PIII_M0	-	155.0	0.43	0.219	0.007
	PIII_M1	t	136.8	0.43-0.59t	0.219+0.19t	0.007
	PIII_M2a	AI_K	135.7	0.43-0.76AI_K	0.219	0.007
	PIII_M2b	IAR	132.3	0.43-0.74IAR	0.219	0.007
	PIII_M3	AI_K, BFI	132.4	0.43-0.65AI_K +0.48BFI	0.219	0.007
	PIII_M4	AI_K, BFI, AI_{ET}, λ, P	127.5	0.43-0.62AI_K +0.57BFI-0.60AI_{ET}	0.219-0.32λ -0.30AI_K +0.21P	0.007
	PIII_M5	IAR, POP	130.3	0.43-0.63IAR	0.219+0.21POP	0.007
	PIII_M6	IAR, AI_K, BFI, POP	123.7	0.43-0.43AI_K-0.42IAR	0.219+0.23POP	0.007
AM_{15}	PIII_M0	-	203.5	0.83	0.105	0.069
	PIII_M1	t	188.0	0.83-0.46t	0.105+0.21t	0.069
	PIII_M2a	AI_K	184.2	0.83-0.75AI_K	0.105	0.069
	PIII_M2b	IAR	184.2	0.83-0.60IAR	0.105	0.069
	PIII_M3	AI_K, BFI	180.6	0.83-0.65AI_K +0.43BFI	0.105	0.069
	PIII_M4	AI_K, BFI, λ, K	170.4	0.83-0.70AI_K +0.42BFI	0.105-0.36λ -0.71AI_K -0.43K	0.069
	PIII_M5	IAR, POP	180.7	0.83-0.51IAR	0.105+0.23POP	0.069
	PIII_M6	AI_K, IAR, BFI, λ	168.8	0.83-0.44AI_K-0.36IAR+0.45BFI	0.105-0.36λ	0.069
AM_{30}	GA_M0	-	232.3	1.09	-0.133	-
	GA_M1	t	225.5	1.09-0.32t	-0.133	-
	GA_M2	AI_K	217.4	1.09-0.59AI_K	-0.133	-
	GA_M2b	IAR	218.3	1.09-0.47IAR	-0.133	-
	GA_M3	AI_K, BFI	213.7	1.09-0.50AI_K +0.32BFI	-0.133	-
	GA_M4	AI_K, BFI, AI_T	211.1	1.09-0.40AI_K+0.32BFI -0.34AI_T	-0.133	-
	GA_M5	IAR	218.3	1.09-0.47IAR	-0.133	-
	GA_M6	AI_K, IAR, BFI, P	207.0	1.09-0.40 AI_K-0.35IAR+0.30BFI	-0.133	-
Xianyang station						
AM_1	GA_M0	-	222.3	1.00	-0.118	-
	GA_M1	t	209.9	1.00-0.44t	-0.118	-
	GA_M2a	K	210.7	1.00+0.40K	-0.118	-
	GA_M2b	IAR	206.3	1.00-0.49IAR	-0.118	-
	GA_M3	K, T	204.3	1.00+0.37K-0.38T	-0.118	-
	GA_M4	K, T, BFI, λ	203.2	1.00+0.33K-0.32T+0.27BFI	-0.118-0.17λ	-
	GA_M5	IAR	206.3	1.00-0.49IAR	-0.118	-
	GA_M6	IAR, K, BFI, AI_{ET}	197.6	1.00-0.37IAR+0.24K+0.39BFI	-0.139+0.22AI_{ET}	-
AM_7	GA_M0	-	240.1	1.17	-0.139	-
	GA_M1	t	227.9	1.17-0.42t	-0.139	-
	GA_M2a	AI_{ET}	228.4	1.17-0.45AI_{ET}	-0.139	-
	GA_M2b	IAR	223.6	1.17-0.49IAR	-0.139	-
	GA_M3	AI_{ET}, K	223.7	1.17-0.38AI_{ET} +0.31K	-0.139	-
	GA_M4	AI_{ET}, K, BFI, λ	221.7	1.17-0.31AI_{ET} +0.3K+0.28BFI	-0.139-0.20λ	-
	GA_M5	IAR	223.6	1.17-0.49IAR	-0.139	-
	GA_M6	IAR, AI_{ET}, K, BFI	217.8	1.17-0.38IAR+0.38BFI+0.19K	-0.139+0.19AI_{ET}	-
AM_{15}	GA_M0	-	265.3	1.39	-0.139	-
	GA_M1	t	253.4	1.39-0.43t	-0.139	-
	GA_M2a	AI_{ET}	251.0	1.39-0.49AI_{ET}	-0.139	-
	GA_M2b	IAR	249.9	1.39-0.48IAR	-0.139	-
	GA_M3	AI_{ET}, K	249.2	1.39-0.45AI_{ET} +0.24K	-0.139	-
	GA_M4	AI_{ET}, K, BFI, λ	246.6	1.39-0.36AI_{ET} +0.23K+0.32BFI	-0.139-0.21λ	-
	GA_M5	IAR	249.9	1.39-0.48IAR	-0.139	-
	GA_M6	IAR, AI_{ET}, BFI	242.5	1.39-0.31IAR-0.44AI_{ET}+0.19BFI	-0.184-0.22BFI	-
AM_{30}	GA_M0	-	285.8	1.59	-0.184	-
	GA_M1	t	270.1	1.59-0.48t	-0.184	-
	GA_M2a	T	270.1	1.59-0.50T	-0.184	-
	GA_M2b	IAR	267.8	1.59-0.50IAR	-0.184	-
	GA_M3	T, P	267.1	1.59-0.34T+0.32P	-0.184	-
	GA_M4	T, P, BFI, K	265.4	1.59-0.33T+0.27P+0.22BFI+0.18K	-0.184	-
	GA_M5	IAR	267.8	1.59-0.50IAR	-0.184	-
	GA_M6	IAR, AI_{ET}, BFI	259.7	1.59-0.28IAR-0.36 AI_{ET}+0.26BFI	-0.184+0.23IAR	-