Replies to Referee #2

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

Bin Xiong, Lihua Xiong, Jie Chen, Chong-Yu Xu, Lingqi Li

We are very grateful for the review's 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.

> ***General Comment*** *This work covered an interesting topic. It is qualified for HESS after a minor revision. Authors incorporated multiple variables into time-varying model by GLM, and called this a nonstationary mode considering TCCCs. They calculated and compared AIC of this mode with that of the stationary mode and the nonstationary mode with a single covariate in two stations in Weihe. Then they concluded this TCCCs nonstationary mode was the optimal one for nonstationary low flow frequency analysis in Weihe.*

AUTHORS' REPONSE: Thank you for your positive evaluation and a good summary of the paper.

> *It's a pity that they did a lot of work without clearly stating their motivation. Authors first raised an issue in review that the previous studies in low flow failed to provide a link between hydrological process and frequency analysis, and this made it difficult for tracing the origins of low flow change. While readers might think they intend to trace these origins (which was also hinted by the title), they defended that "the goal of this study is to develop a nonstationary low-flow frequency analysis framework". It is better for them to keep consistent in the whole introduction section.*

AUTHORS' REPONSE: Thank you for your comments and the good suggestion. This is also pointed out by reviewer 1.

Following the reviewer's advice, we have also better stated our study motivation as 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."

We have also explicitly defined and stated the study objectives in the 6th paragraph of the Introduction Section, as follows:

"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."

Besides, to better show the advantage of this framework, which was composed of the time-varying and GLM method, they should compare it with other models using only climatic indicators or a single indicator of human activity, just as they mentioned in the review, not just the mode with either AIK or BFI as the explanatory variable.

AUTHORS' REPONSE: Thank you for the comment. Our study had included the model with climate indicators. But, indeed, the model with a single indicator of human activity (e.g. irrigation, population, GDP as mentioned by the first reviewer) was not involved in the original submission. Thus to address this comment, the main and supplementary texts are revised to compare the nonstationary mode considering TCCCs with the nonstationary mode considering human activity (irrigation, population, GDP), as also stated in the reply to reviewer 1. These human activity indices are shown in Fig. 1. The supplement will cover the additional nonstationary models (M2b, M5 and M6, as shown in Table 1). 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)

In addition, there are some mistakes and improper statements in this paper; outlines of methods and results are unclear, and the discussion is weak. It is better for authors to put together contents of results and discussion, and further discuss their results and compared with other related works.

AUTHORS' REPONSE: Thank you for your comment. The mistakes and improper statements will be carefully examined and corrected in the modified draft carefully proofreading; to clarify methods, a flow chart of methodology and the table which summarizes the explanatory variables have been added to the text; and we will revise contents of results and discussion, following the reviewer's good suggestion. Thus, further discussion of results and comparison with other related works will be presented in the revised draft.

Specific Comment *The logic of review in the introduction is not smooth. Some references mentioned in the paragraph starting from Line 52, such as Lars Gottschalk's work, were badly concluded and they'd better be put in the next paragraph.*

AUTHORS' REPONSE: Thank you for pointing out this and for your good suggestion. To address your comment, we have revised the introduction as mentioned above.

A flow chart of methodology is needed.

AUTHORS' REPONSE: This is a good point. To address your comment, we have added it (Fig. 2).

<Figure 2> (newly-added)

Line 127 Meaning of this sentence is obscure.

AUTHORS' REPONSE: The sentence will be revised as following: "The distribution type used to build the nonstationary model is outlined"

Further explanation for the selection of 8 candidate variables is needed.

AUTHORS' REPONSE: Thank you for the comment. To address this comment, the 1st paragraph of Sect. 2.3 Candidate explanatory variables will be revised. And the reason of selection has been listed in Table 3.

<Table 3> (newly-added)

Indices more related to irrigation, like irrigation area, need to be considered, since (Line278) In the Weihe basin, the impacts of agricultural irrigation on runoff have been found to be significant.

AUTHORS' REPONSE: Thank you for the comment. We strongly agree that the incorporation of indices more related to irrigation (i.e. irrigation area) will better reflect the impacts of agricultural irrigation on low flows. Thus, following reviewer's suggestions, we have included this index (irrigation area) as mentioned above.

Both those 8 explanatory variables and data resources can be summarized in two tables.

AUTHORS' REPONSE: This is a good point. To address this comment, we have revised the text and added Table 3.

I don't see much use in Figure 2.

AUTHORS' REPONSE: Thank you for the comment. Following your suggestion, the Figure will not be included in the revised text.

Why do you need to study all the series from AM1, 7, 15 to 30?

AUTHORS' REPONSE: Thank you for the comment. The main reason for including four series is to investigate whether the time scale of the series will affect the nonstationary mode. As shown in Figure 6 (in the text), the effect of time scale is existed but limited.

In some subplans in Figure 8, AIC of either M2 or M3 is worse than M1. What is the *probable cause? The conclusion in Line 391 cannot be directly generated from Figure8.*

AUTHORS' REPONSE: This phenomenon mainly appears in the AM_1 and AM_7 series. AM_1 and AM_7 series are more vulnerable, which means that multiple causes can affect them. The nonstationary mode with one or two physical explanatory variables (M2 or M3) cannot work well for AM_1 and AM_7. However, the overall decreased trend caused by multiple factors is consistent with the nonstationary mode with time (M1). In the revised version we will provide with more explanations.

What is the impact of location difference on the different AIC results in two stations? Needs to add discussion.

AUTHORS' REPONSE: This is a good point. Following the reviewer's suggestion, we will add a supplemental paragraph to discussion section.

The standard of selecting M4 variables with stepwise selection method needs to be further clarified.

AUTHORS' REPONSE: Thank you for your comment. Following the reviewer's suggestion, we have clarified the standard of the models variables using Fig. 2.

Table5 and 6 can be merged into one table.

AUTHORS' REPONSE: Agree, will be done.

Formula 2, no need to put "i=" on the top

AUTHORS' REPONSE: Will be done.

Table2, add explanation for parameters down below the table

AUTHORS' REPONSE: Will be done.

The definition, reason of selection, and formula of 8 indices should be listed in a table.

AUTHORS' REPONSE: Will be done.

Line228, 234, 242 add blank space before the paragraph (need to check in the whole paper)

AUTHORS' REPONSE: Will be done.

Line298 slash tag between "n" and "day" is missing (check the whole paper)

AUTHORS' REPONSE: Will be done.

Line304 mistake in time tense

AUTHORS' REPONSE: Will be done.

Line388 incomplete sentence

AUTHORS' REPONSE: To address this comment, we have corrected this.

Figure1 mark the location of Weihe in the map of China with a rectangular frame

AUTHORS' REPONSE: Will be done.

Figure3 adding R

AUTHORS' REPONSE: Figure will be modified.

Figure 3 &4 lines are too thick

AUTHORS' REPONSE: Will be improved.

Figure5&6 differences among colors are too delicate to be seen

AUTHORS' REPONSE: Will be improved.

Table 3 &4 add division lines among rows of different stations

AUTHORS' REPONSE: Will be done.

Mistake in references, year of "Bivariate frequency analysis of nonstationary low-flow series based on the time-varying copula" was 2015

AUTHORS' REPONSE: Thank you for pointing out this. We have corrected this.

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

References

Smakhtin, V. U.: Low flow hydrology： a review, Journal of Hydrology, 2001.

Figures

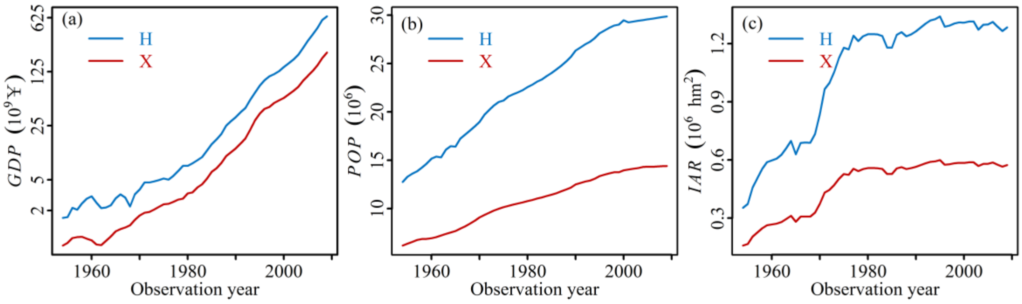

Figure1. Human activity indices in both Huaxian and Xianyang. (a), (b) and (c) are for population (*POP*), gross domestic production (*GDP*) and irrigated area (*IAR*), respectively.

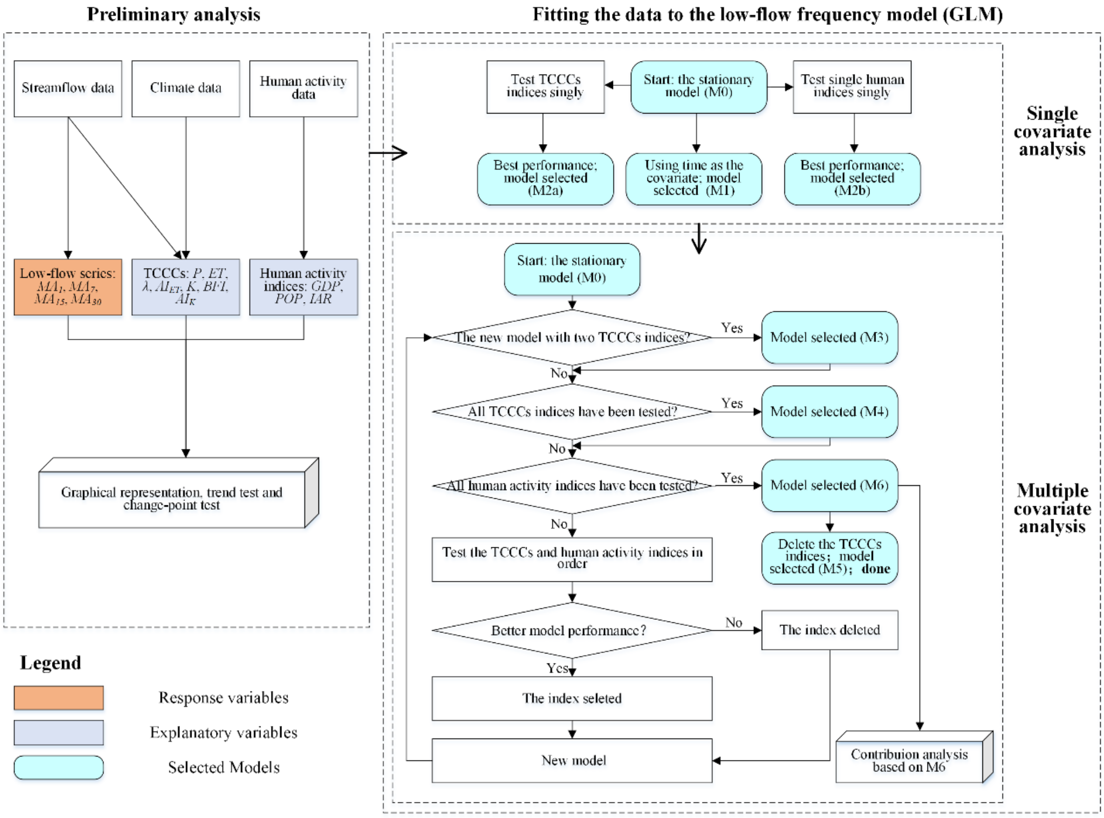

Figure 2. The framework of nonstationary low-flow frequency analysis.

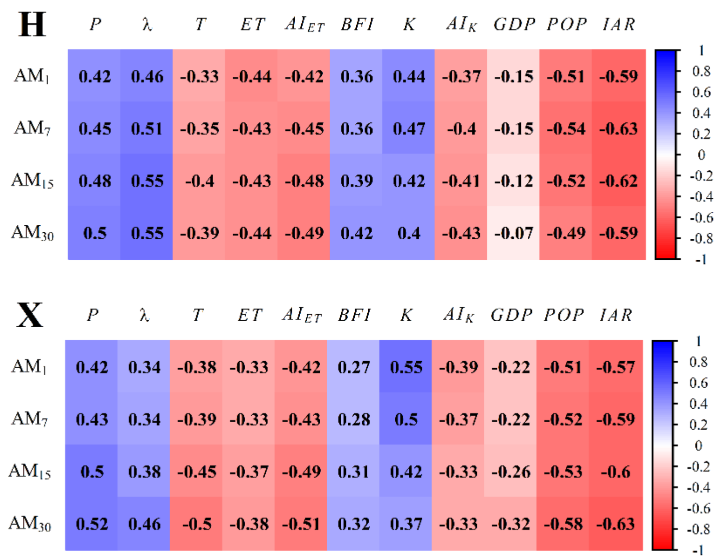

Figure 3. The Pearson correlation coefficients matrix between the annual minimum flow series and eight candidate explanatory variables in Huaxian (H) and Xianyang (X) stations; the darker color intensity represents a higher level of correlation (blue indicates positive correlation, and red indicates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

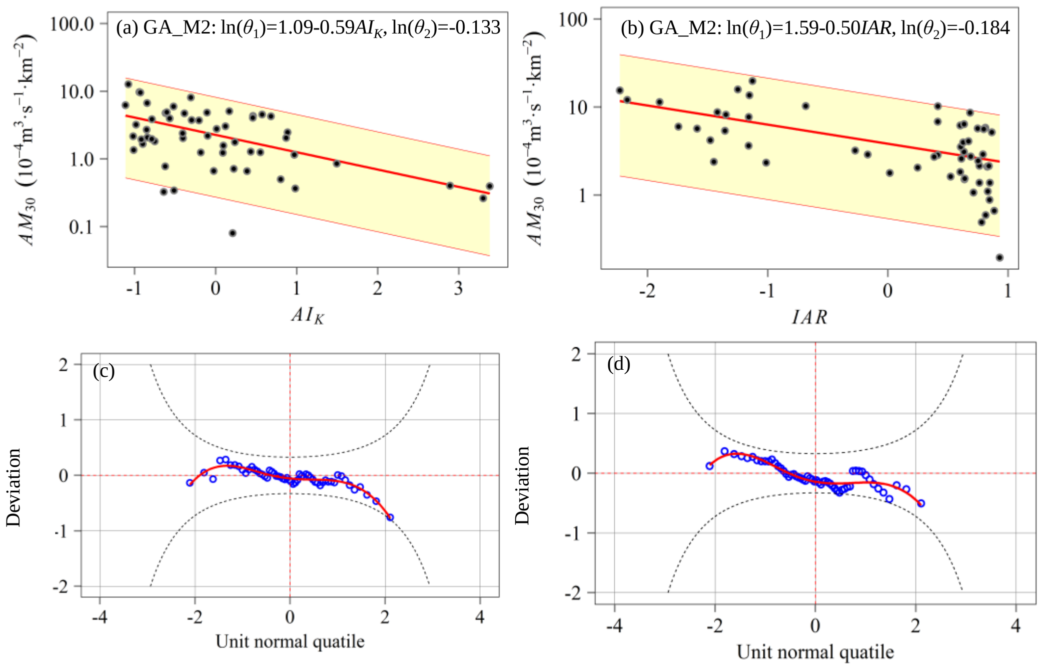

Figure 4. Performance assessments of the best M2 model (GA_M2) for AM_{30} in Huaxian (H) at left panel and Xianyang (X) at right panel. (a) and (b) are the centile curves plots of GA_M2 (red lines represent the centile curves estimated by GA_M2; the 50th centile curves are indicated by thick red; the 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).

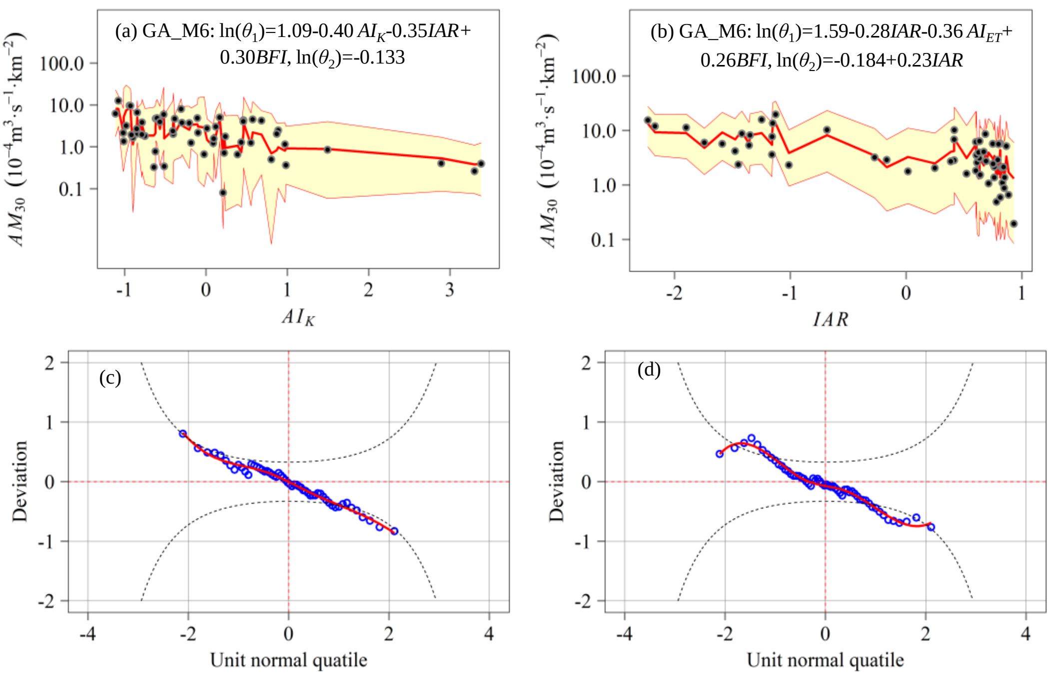

Figure 5. Performance assessments of the best M4 model (GA_M6) for AM_{30} in Huaxian (H) at left panel and Xianyang (X) at right panel. (a) and (b) are the centile curves plots of GA_M6 (red lines represent the centile curves estimated by GA_M6; the 50th centile curves are indicated by thick red; the 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).

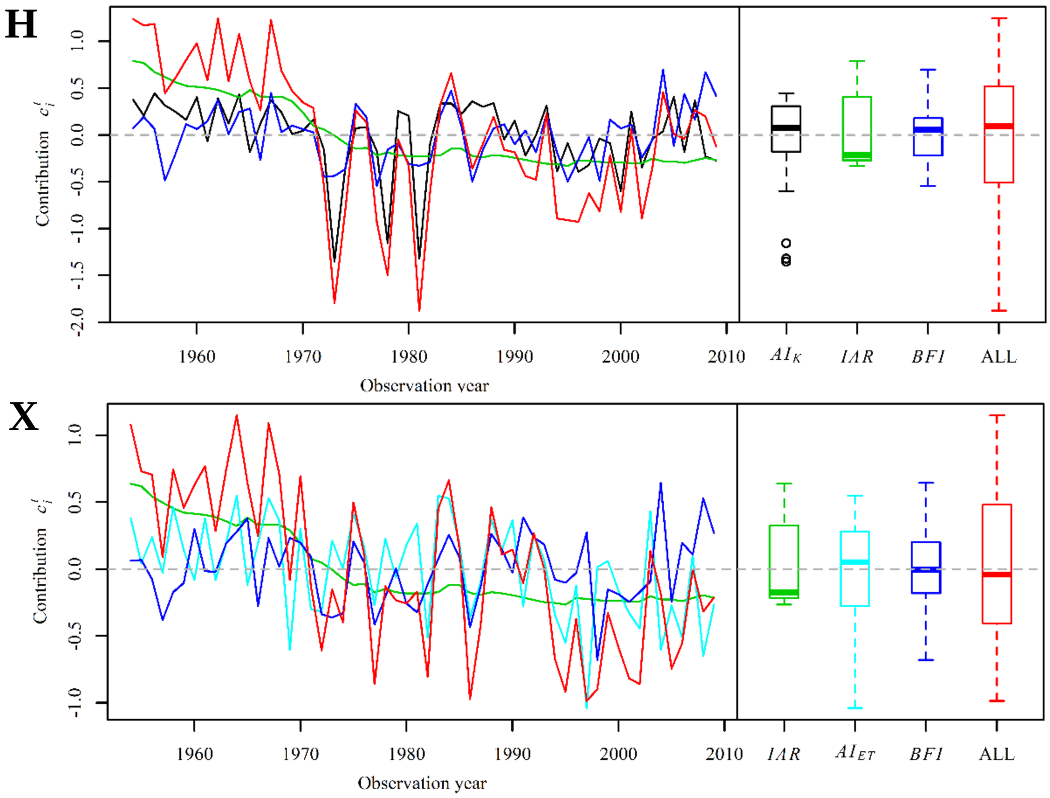

Figure 6. Contribution of selected explanatory variables to $c_i^t = \ln\left(\theta_1^t\right) - \ln\left(\bar{\theta}_1\right)$ in different periods based on GA_M6.

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	-

Table 3. Candidate explanatory variables and reason of selection.

Category	Name	Indices	Reason of selection (related to)	Unit
TCCCs				
	P	Precipitation	Main supply source	mm
	λ	Mean frequency of precipitation events	Water supply intensity	per day
	T	Temperature	Evaporation loss	℃
	ET	Potential evapotranspiration	Evaporation loss	mm
	AI_{ET}	Climate aridity index	Degree of meteorological drought	-
	BFI	Base-flow index	Water storage capability	-
	K	Recession constant	Water storage capability	day
	AI_K	Recession-related aridity index	Both the water storage and supply capability	-
Human activity				
	IAR	Irrigation area	Both irrigation diversion and evaporation loss	10^6 hm^2
	POP	Population	Water withdrawal loss for agricultural, domestic and industrial purposes	10^6
	GDP	Gross domestic product	Water withdrawal loss for agricultural, domestic and industrial purposes	10^9 ￥