Part 1 Responses to Referee's comments

We appreciate the comments from the reviewer and truly believe these comments can help us to improve our manuscript. We consider the corresponding changes can be included in the revised document to achieve publication status. We provide responses to the main and specific comments in sequential order as follow:

Responses to Referee #1

Main comment #1

"Probability distribution functions considered in the study. In this study, the authors propose a method to constrain parameter ranges for parameters that follow uniform, normal, and exponential probability distribution functions. These are the probability distribution functions that the case study model parameters reportedly follow. Some of the claims are debatable. For instance, parameters CI and Kc are reported to follow normal distributions (page 7, line 29) based on the following statement (page 7, line 25): "It is obvious that the box and whiskers are symmetrical and the length of whiskers is longer than that of the box [...].". Looking at Fig. 5, however, the whiskers are not symmetrical and, on the upper side, not longer than the box, suggesting that the ranges of these parameters do not follow a normal probability distribution. Therefore, the method used to constrain the ranges of these parameters might not be the optimal, potentially changing the results of the study."

Responses to main comment #1:

There are three types of distribution discussed in the investigation. In order to distinguish them, a simple method in section 3.2.2 was used based on shapes of the cumulative frequency curve and the histogram as well as the sizes of whiskers and box in the box-plot. Despite simplicity, it is subjective and unintelligible to readerships. For avoiding the confusion as described in this comment, a Kolmogorov-Smirnov (K-S) test will be employed to objectively identify each distribution type in the revised paper. Indeed, we carried out K-S tests to evaluate statistical distributions of all parameters in the hydrologic model. The results of K-S tests for parameters CI, Kc, and SM are listed in the following Table A. It is shown that both exponential and uniform distributions are rejected for the three parameters while normal distribution is not. It implies that the three parameters follow normal distributions. Therefore, the simple method used earlier does not change the results of the study, although it is subjective.

Table A. The results of K-S tests for parameters CI, Kc, and SM

	CI			Kc			SM		
	Normal	Exponential（2P）	Uniform	Normal	Exponential（2P）	Uniform	Normal	Exponential（2P）	Uniform
Statistic	0.0623	0.32805	0.1151	0.09199	0.37961	0.10694	0.05983	0.30392	0.10982
P-Value	0.80925	5.40E-10	0.1306	0.34466	3.08E-13	0.18882	0.84521	1.23E-08	0.16628
α	0.2	0.01	0.2	0.2	0.01	0.2	0.2	0.01	0.2
Reject?	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes

Main comment #2

"The authors report that parameter range selection has a direct impact on calibration efficiency and propose a new method to improve model calibration (page 1, line 12). The reported results, however, indicate that the improvement in the calibration efficiency by the proposed methodology is quite modest. For instance, in Fig. 9 different cases involving different combinations of parameters keeping the initial range and others having the "optimal" range are compared. The model efficiency different between case I (all the parameters set at the initial ranges) and any other of the considered cases is of the order of 0.002 at best. This suggests that the benefits of using the proposed technique are small."

Responses to main comment #2:

Notwithstanding a small increase in maximum E_{NS}, there is a significant improvement in minimum E_{NS} by using the proposed method. Comparing case 6 (using the optimal combination of ranges) with case 1 (using the initial ranges) in Fig. 9, we find that the maximum E_{NS} increases by 0.001 while the minimum E_{NS} (except outliers) increases by 0.01. The rising minimum E_{NS} with the fixed maximum contributes to the shrinkage of the range of the possible solutions. As a result, the uncertainty of the model performance can be effectively controlled. Moreover, the methodology can be used to analyze the parameter correlation and sensitivity by computing two indexes $R_{\mathrm{C\,Y,X}}$ and S_E. The paper presents the preliminary study of the proposed methodology. In the preliminary study, we adopt a Xinanjiang model with several parameters to evaluate the calibration efficiency of the methodology. Since the parameter Im having negative effect on other parameters is a little bit insensitive in a Xinanjiang model, a modest improvement in calibration efficiency is found after the application of the methodology. In future, we will consider using other complicated hydrologic models with more parameters to further study the application of the methodology.

Main comment #3

"The language should be improved to make the manuscript easier to understand and more compelling. More specifically, the following aspects should be revised: verb tenses (e.g. page 3, line 23-24: "single parameter is selected" - "correlation and sensitivity were estimated"; page 6, line 15: "The index *R*c was quantified" instead of "The index *R*c were quantified"), spelling errors (e.g. page 6, line 13: "contribute" instead of "contributes"; page 9, line 25: "of" instead of "pf"), and sentence structure (e.g. page 9, line 15 "[...] parameters [...] are of high sensitive to E_{ns}"). I would strongly recommend the article to be checked for language."

Responses to main comment #3:

We will revise the manuscript as the suggestion:

Page 3, line 23-24: "single parameter is selected" >> "single parameter was selected"

Page 6, line 15: "The index *R*c were quantified" >> "The index *R*c was quantified"

Page 6, line 13: "contributes" >> "contribute"

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Page 9, line25-26: "...when Case 4 compared with Case 1, Case 2 and Case 3 It can be explained..." >> "... when Case 4 is compared with Case 1, Case 2 and Case 3. It can be explained..."

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E_{NS}"

In addition, we will check the paper carefully and correct the other language errors. For example:
Page 1, line 3: "Qiaofeng." >> "Qiaofeng"
Page 1, line 14: "characteristics of single parameter value was analysed" >> "of single parameter value was analysed"
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Page 8, line 7: "different parameter range are selected" >> "different parameter ranges are selected"
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Page 10, line 13: "the extension range followed by" >> "the extended range followed by"
Page 10, line 17: "to adopted" >> "to be adopted"

Specific comment #1

"Page 4, line 28 and page 6, line 2: "plenty of tests". The text suggests that the authors defined their sampling size and cumulative frequency value through a process of trial and error. Since this might affect the subsequent results I think that evidence should be provided to support the authors' claims."

Responses to specific comment #1:

Before defining sampling size and cumulative frequency value, we performed a lot of trial tests. Figure A shows the variation curves of maximum and minimum E_{NS} with sample size. It is indicated that both maximum and minimum E_{NS} keep stable when sampling size is greater than 100. Avoiding the time-consuming computation, we assigned sampling size for the study as 100. Figure B gives the variation curves of maximum and minimum E_{NS} with cumulative frequency value. It is found that the maximum E_{NS} keeps constant despite a cumulative frequency value varying, while the minimum E_{NS} approaches the peak value of 0.881 when the cumulative frequency value is equal to 50%. Considering that higher minimum E_{NS} contributes to more efficient calibration, we selected the fixed cumulative frequency value of 50% to determine the ranges of maximum and minimum probability density (i.e. MINR and MAXR) for each parameter.

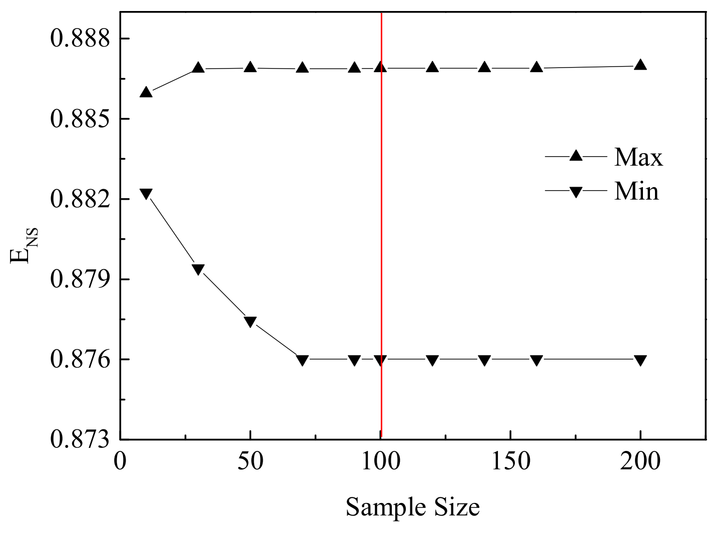

Figure A. Variation curves of maximum and minimum E_{NS} with sample size

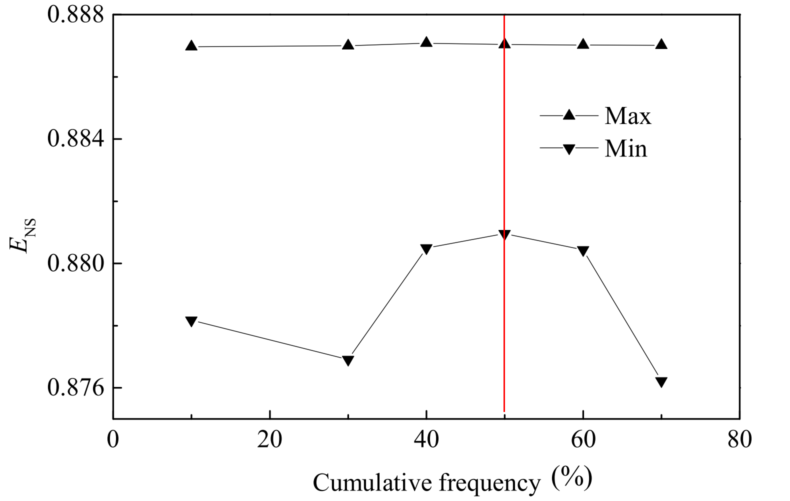

Figure B. Variation curves of maximum and minimum E_{NS} with cumulative frequency value

Specific comment #2

"Page 8, line 34: "[...] there is considerable improvement [...]". "Considerable" is a vague word, please provide a quantitative measure of the improvement. Similar problem in page 8, line 12. Please revise the results section to ensure that no vague words are used."

Responses to specific comment #2:

According to the review comments, we will revise the corresponding parts as follows:

Page 8, line 34: "It is indicated that there is a considerable improvement of both maximum and minimum E_{NS} when extension-MINR is used for calibration." >> "It is shown from Fig. 8e that there is little improvement in maximum E_{NS} when MINR is used for calibration instead of the initial range. There is an increase of 0.0003 in maximum E_{NS} if the initial range is replaced with the extension range or extension-MINR. As for minimum E_{NS} (except outliers), an increase of 0.001 in the case of MINR, a decrease of 0.003 in case of the extension range and an increase of 0.003 in the case of extension-MINR are found when the initial range is substituted with the three ranges respectively."

Page 8, line 12: "It is found that the minimum E_{NS} except extreme outliers rises convincingly and E_{NS} concentrates at larger value zone when MINR is used instead of the initial range." >> "It is found that the minimum E_{NS} except extreme outliers rises from 0.8805 to 0.8842 and E_{NS} concentrates at larger value zone when MINR is used instead of the initial range."

Page 9, line 29-30: "As for the cases of multi-parameter range selection (i.e. Case 5, Case 6 and Case 7), the results are much better than of Case 1-4." >> "As for the cases with multi-parameter range selection (i.e. Cases 5-7), the results are much better than those of cases with initial range or single-parameter range selections (i.e. Cases 1-4). There is approximately an increase of 0.001 in maximum E_{NS} and an increase of 0.01 in minimum E_{NS} when the multi-parameter range selection is performed. "

Specific comment #3

"Page 9, line 24: Seven cases are investigated with different combinations of parameter ranges. What is the rationale behind the chosen combinations? Please specify."

Responses to specific comment #3:

The seven cases were set to demonstrate three primary results. Firstly, the multi-parameter optimal range selection method is superior to the single-parameter one for calibrating hydrologic models with multiple parameters. It can be deduced from higher E_{NS} values of Cases 5-7 than those of Cases 1-4. Secondly, merely using the optimal range of the parameter of relatively higher sensitivity contributes to more efficient calibration when the two parameters have negative effect on each other. It can be concluded by comparing the E_{NS} values of Cases 2-4 referring to the two parameters EX and Im. Thirdly, the combination of optimal ranges of all parameters is not the optimum inasmuch as some parameters like Im have negative effects on other parameters. It can be inferred through analyzing the E_{NS} values of Cases 5-7. The analysis of sensitivity and correlation between parameters is, therefore, very important to determine the optimum ranges combination of all parameters for model calibration.

Specific comment #4

"Figure 1: The chosen color scale makes the figure difficult to read in black and white. Please consider modifying it to facilitate reading the figure in printed form. The elevation units should be "m a.s.l." instead of "m". The lowest elevation in the catchment is reported to be 19 m below the sea level; is that so?"

Responses to specific comment #4:

We will use the gray ribbon for DEM rendering to make Figure 1 easy to read in printed form. The unit "m a.s.l." will be used instead of "m" in revised Figure 1. In addition, there exist dolines (known as sinkholes) in the catchment. It is the reason why the lowest elevation in the catchment is 19 m below the sea level.

Specific comment #5

"Figure 2: Please correct "cure" in the figure caption."

Responses to specific comment #5:

We will change "cure" to "curve" in the caption of Figure 2.

Specific comment #6

"Figure 5: Since the figure represents normalized parameter values on the y-axis, it would be more informative to constrain this axis between 0 and 1."

Responses to specific comment #6:

We will constrain the y-axis of Figure 5 between 0 and 1 in the revised paper. The Fig. 5 modified is presented as follows.

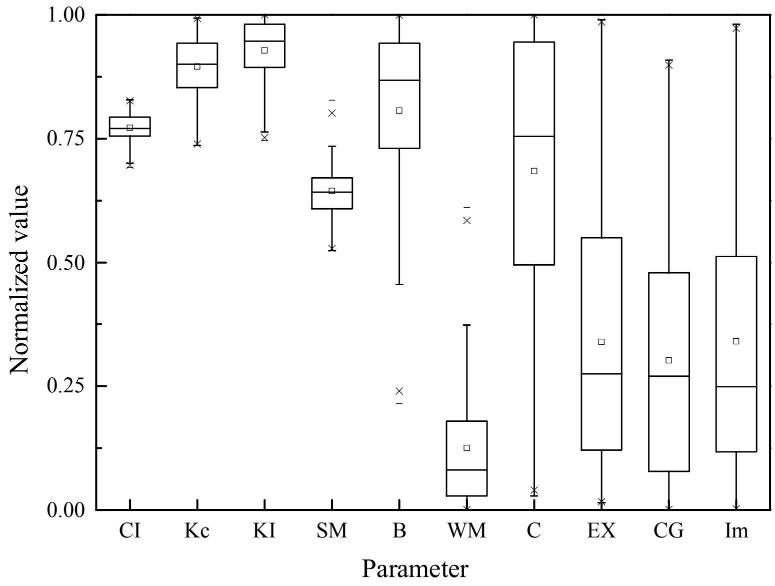

Fig. 5. The box-plot chart of normalized calibrated values for parameters of Xinanjiang model

Specific comment #7

"Table 2: please provide units for all the parameters. In the case of dimensionless parameters indicate so."

Responses to specific comment #7:

We will give units for parameters in a Xinanjiang model, as it is shown in Table 2 below.

Specific comment #8

"Table 2, 3, 4: In order to facilitate the readability of the different tables it might be convenient to order the parameters in the same way in all the tables."

Responses to specific comment #8:

We will modify Tables 2, 5 so that the parameters are ordered in the same way in the related tables. Moreover, the column "range" of Table 2 will be changed as column "Units" because the ranges for parameters are reported in Table 3.

Table 2. Parameters of Xinanjiang model

Parameter	Definition	Units
CI	Recession constants of the lower interflow storage	dimensionless
Kc	Ratio of potential evapotranspiration to pan evaporation	dimensionless
KI	Outflow coefficients of the free water storage to interflow	dimensionless
SM	Areal mean free water capacity of the surface soil layer, which represents the maximum possible deficit of free water storage	mm
B	Exponential parameter with a single parabolic curve, which represents the non-uniformity of the spatial	dimensionless
WM	Averaged soil moisture storage capacity of the whole layer	mm
C	Coefficient of the deep layer, that depends on the proportion of the basin area covered by	dimensionless

	vegetation with deep roots	
EX	Exponent of the free water capacity curve influencing the development of the saturated area	dimensionless
CG	Recession constants of the groundwater storage relationships	dimensionless
KG*	Outflow coefficients of the free water storage to groundwater relationships	dimensionless
Im	Percentage of impervious and saturated areas in the catchment	dimensionless

* the value of KG is calculated by the function 0.7-KI

Table 5. Parameter ranges setting for different cases

Case	Range setting of parameter									
	CI	Kc	KI	SM	B	WM	C	EX	CG	Im
1	I	I	I	I	I	I	I	I	I	I
2	I	I	I	I	I	I	I	I	I	O
3	I	I	I	I	I	I	I	O	I	I
4	I	I	I	I	I	I	I	O	I	O
5	O	O	O	O	O	O	O	O	I	I
6	O	O	O	O	O	O	O	O	O	I
7	O	O	O	O	O	O	O	O	O	O

The symbol ‘I’ represents the initial range of the parameter in Table 3, and ‘O’ the optimal range of the parameter in Table 4.

Responses to Referee #2

Main comment #1

"My main concern is related to the real impact of the proposed methodology. The benefit in terms of NSE is very small: see Fig. 9. Is this improvement relevant for hydrological application? If we focus exclusively on model performances I do not think this methodology shows a significant improvement. I suggest to emphasize more the physical considerations that may rise from the application, for example in terms of sensitivity of specific parameters in relation to the particular nature of the study area, or regarding the evaluation of parameters correlation. From my point of view this methodology may provide additional insights regarding the interactions among model parameters under different hydrological conditions. In other words: since the improvement in terms of NSE seems to be not relevant, what are the added values of this methodology compare to existing ones?"

Responses to main comment #1:

Notwithstanding a small increase in maximum E_{NS}, there is a significant improvement in minimum E_{NS} by using the proposed method. Comparing case 6 (using the optimal combination of ranges) with case 1 (using the initial ranges) in Fig. 9, we find that the maximum E_{NS} increases by 0.001 while the minimum E_{NS} (except outliers) increases by 0.01. The rising minimum E_{NS} with the fixed maximum contributes to the shrinkage of the range of the possible solutions. As a result, the uncertainty of the model performance can be effectively controlled. Moreover, the methodology can be used to analyze the parameter correlation and sensitivity by computing two indexes $R_{\mathrm{C\,Y,X}}$ and S_E. The paper presents the preliminary study of the proposed methodology. In the preliminary study, we adopt a Xinanjiang model with several parameters to evaluate the calibration efficiency of the methodology. Since the parameter Im having negative effect on other parameters is a little bit insensitive in a Xinanjiang model, a modest improvement in calibration efficiency is found after the application of the methodology. In future, we will consider using other complicated hydrologic models with more parameters to further study the application of the methodology.

Main comment #2

"Continuing on the effectiveness of the methodology, the Author do not provide any information regarding the initial GA calibration. Are there benefits from the application of the methodology in terms of NSE values? What are the computational/time efforts required for the implementation of the calibration framework compared to other techniques?"

Responses to main comment #2:

Since the GA method is very common tool for parameter calibration of hydrologic models, we provide a little information about GA calibration. In the study, we carried out trial tests to determine the optimal combination of control parameters: crossover probability of 0.5, mutation probability of 0.7 for the individual, mutation probability of 0.5 for each gene, population size of 21, maximum generation number of 500 and maximum iteration number of 50. These parameters were kept constant for GA calibration in the investigation. The application of the proposed methodology results in an increase of 0.01 in minimum E_{NS}, compared with that of the pure GA method. The rising of minimum E_{NS} with little change of the maximum may shrink the range of the possible solutions. As a result, the uncertainty of the model performance can be effectively controlled.

Through a run of calibration framework, a combination of values of all parameters and the corresponding E_{NS} are obtained. Figure C shows the variation curves of maximum and minimum values of E_{NS} with number of runs by using a GA method and a proposed PRS method, respectively. It is indicated from Figure A that no mater it is maximum or minimum E_{NS}, the value calculated with a proposed method is almost the same as that with a GA method when the number of runs is less than 100. If a proposed method is used for calibration instead of a GA method, there are approximately an increase of 0.001 in maximum E_{NS} and an increase of 0.01 in minimum E_{NS} when the number of runs is greater than 100. Thus, for any particular run number, the value of E_{NS} calculated with a PRS method is not less than that with a GA method. The application of a proposed method, therefore, contributes to a more efficient calibration than that of a GA method does.

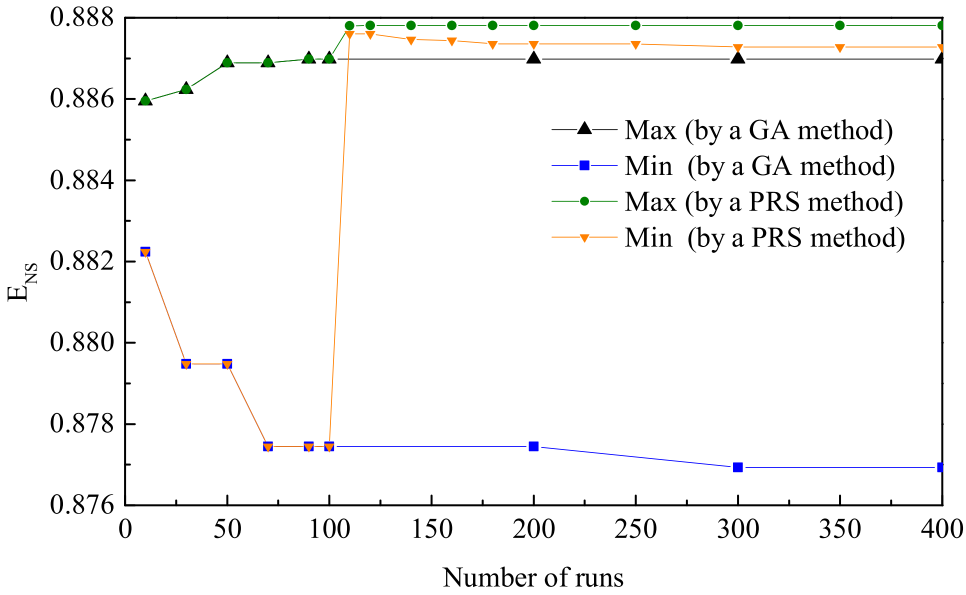

Figure C. the variation curves of maximum and minimum E_{NS} with number of runs by using a GA method and a proposed PRS method

Main comment #3

"Is there a specific reason for considering the MAXR range interval in addition to MINR (see Figure 3). Why a modeler should consider the range of minimum probability density of the parameter values? If it is not necessary I suggest to consider its removal from the analysis."

Responses to main comment #3:

In order to figure out how the selections of two typical ranges, MINR and MAXR, affect respectively the calibration efficiency under different distribution types, we considered the MAXR range internal in Figure 3. From the results shown in Figures 6-7 (referring to parameter CI of a normal distribution and parameter KI of an exponential distribution), it is indicated that MINR is better than MAXR for improving calibration whichever distribution is specified. We removed, therefore, the MAXR range interval from the later analysis presented in Figure 8. As it is one of the main results of the study that MINR is better than MAXR for improving calibration, we would like to keep the MAXR range interval in Figures 3/6/7.

Main comment #4

"At P7, line 25. Why this is obvious? Looking at Fig. 5 this is not. Do the Authors apply statistical tests to evaluate the statistical distribution of the parameters?"

Responses to main comment #4:

There are three types of distribution discussed in the investigation. In order to distinguish them, a simple method in section 3.2.2 was used based on shapes of the cumulative frequency curve and the histogram as well as the sizes of whiskers and box in the box-plot. Despite simplicity, it is subjective and unintelligible to readerships. For avoiding the confusion as described in this comment, a Kolmogorov-Smirnov (K-S) test will be employed to objectively identify each distribution type in the revised paper. Indeed, we carried out K-S tests to evaluate statistical distributions of all parameters in the hydrologic model. The results of K-S tests for parameters CI, Kc, and SM are listed in the following Table B. It is shown that both exponential and uniform distributions are rejected for the three parameters while normal distribution is not. It implies that the three parameters follow normal distributions. Therefore, the simple method used earlier does not change the results of the study, although it is subjective.

Table B. The results of K-S tests for parameters CI, Kc, and SM

	CI			Kc			SM		
	Normal	Exponential （2P）	Uniform	Normal	Exponential （2P）	Uniform	Normal	Exponential （2P）	Uniform
Statistic	0.0623	0.32805	0.1151	0.09199	0.37961	0.10694	0.05983	0.30392	0.10982
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α	0.2	0.01	0.2	0.2	0.01	0.2	0.2	0.01	0.2
Reject?	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes

Main comment #5

"Concerning the 7 scenarios reported in table 5, how have you defined them? Are there specific reasons behind the use of initial or optimal ranges for cases 5, 6 and 7? In addition, I suggest to keep the same column order for parameters, it’s easier to read table 5 in relation to the values of table 4."

Responses to main comment #5:

Case 1 was defined as the initial case using all initial ranges. Cases 2-4 were defined as the single parameter range selection (S-SPR) cases. Cases 5-7 were defined as the multiple parameters ranges selections (M-SPR) cases.

The seven cases were set to demonstrate three primary results. Firstly, the M-SPR method is superior to the S-SPR one for calibrating hydrologic models with multiple parameters. It can be deduced from higher E_{NS} values of Cases 5-7 than those of Cases 1-4. Secondly, merely using the optimal range of the parameter of relatively higher sensitivity contributes to more efficient calibration when the two parameters have negative effect on each other. It can be concluded by comparing the E_{NS} values of

Cases 2-4 referring to the two parameters EX and Im. Thirdly, the combination of optimal ranges of all parameters is not the optimum inasmuch as some parameters like Im have negative effects on other parameters. It can be inferred through analyzing the E_{NS} values of Cases 5-7. The analysis of sensitivity and correlation between parameters is, therefore, very important to determine the optimum ranges combination of all parameters for model calibration.

As for the column order of tables, we will modify Table 2, 5 so that the parameters are ordered in the same way as they do in Table 4.

Main comment #6

"The writing in some part of the manuscript should be improved. I suggest to carefully go through the overall manuscript and check verbs and syntax (here some example: P5, L3; P5, L23; P6, L5, P9, L25-26; ...; P10, L17)."

Responses to main comment #6:

We will revise the manuscript as the suggestion:

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Specific comment #1

"Abstract: in the last part of the abstract, roughly from line 20 on, the Authors report some specific methodological considerations that may not be really clear to one who has not already read the paper. I suggest to focus more on the scope and aims of the analysis, reporting also that the methodology proposes indexes for the evaluation of parameter sensitivity and correlations, as well as a summary of the main outcomes."

Responses to specific comment #1:

According to the comments of the referee, we will rewrite the abstract as follows:

The parameters are usually calibrated to achieve good performance of hydrological models, owing to the highly non-linear problem of hydrology process modelling. However, parameter calibration efficiency has a direct relation with parameter range. Furthermore, parameter range selection is affected by probability distribution of parameter values, parameter sensitivity and correlation. A newly proposed method is employed to determine the optimal combination of multi-parameter ranges for improving the calibration of hydrological models. At first, single-parameter probability distributions were analyzed based on 100 samples obtained from independent Genetic Algorithms (GA) calibration performed on a Xinganjiang model with a corresponding initial parameter range and, the distribution type (i.e. normal, exponential and uniform distributions) was specified for each parameter of the model. Then, the optimal range for each parameter was determined by comparing E_{NS} values calculated separately with the initial range, the minimum and maximum ranges of a given cumulative frequency of 50% (i.e. MINR and MAXR) and the extended range. Next, parameter correlation and sensibility were evaluated by quantifying two indexes $R_{\mathrm{C\,Y,X}}$ and S_E which can be used to coordinate with the negatively correlated parameters to specify the optimal combination of ranges of all parameters for calibrating models. It is shown from the investigation that the probability distribution of calibrated values of any particular parameter in a Xinanjiang model is closely approximated by a normal or exponential distribution. The multi-parameter optimal range selection method is superior to the single-parameter one for calibrating hydrologic models with multiple parameters. The combination of optimal ranges of all parameters is not the optimum inasmuch as some parameters like Im have negative effects on other parameters. The application of the proposed methodology gives a rise to an increase of 0.01 in minimum E_{NS} compared with that of the pure GA method. The rising of minimum E_{NS} with little change of the maximum may shrink the range of the possible solutions, which can effectively reduce uncertainty of the model performance.

Specific comment #2

"P1, L29: is “method” appropriate to indicate hydrological process modelling? I would suggest something like “tools” or similar."

Responses to specific comment #2:

We will replace “method” with “tool” in the first sentence of “Introduction”.

Specific comment #3

"P4, L28: On which base you say that 100 samples are enough? Have you adopted some statistical texts to verify the statistical distribution of the considered parameters."

Responses to specific comment #3:

Before defining sampling size value, we performed a lot of trial tests. Figure D shows the variation curves of maximum and minimum E_{NS} with sample size. It is indicated that both maximum and minimum E_{NS} keep stable when sampling size is greater than 100. Avoiding the time-consuming computation, we assigned sampling size for the study as 100.

With regard to the statistical distribution of the parameters, we performed the K-S tests to define the distribution type for each parameter. The results of some K-S tests are given in the response to main comment #4.

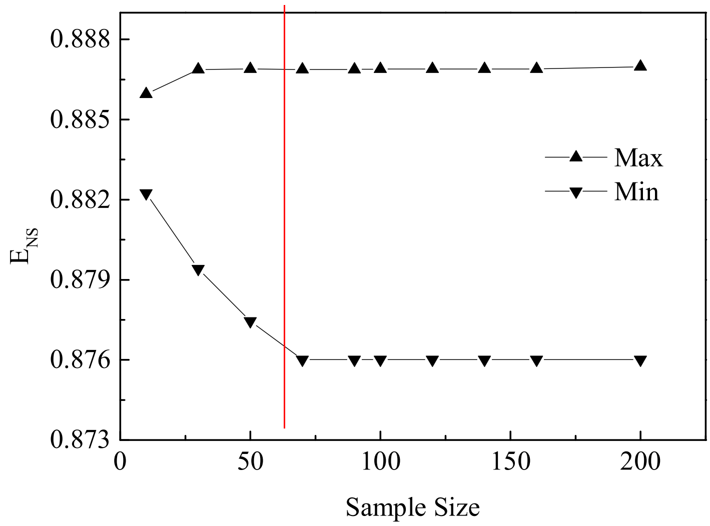

Figure D. Variation curves of maximum and minimum E_{NS} with sample size

Specific comment #4

"P4, L3: “A Genetic Algorithm (GA) was selected”"

Responses to specific comment #4:

Actually, the sentence mentioned above appears in P4, L30. We will modify it as it is suggested.

Specific comment #5

"P9, L6: why do you say that it is obvious?"

Responses to specific comment #5:

According to the values in Table 4, *R*C value in columns of parameters CI and WM are positive, most *R*C values in column of parameter Im are negative. In order to make it easy to read, we will change it to “It is obvious from Table 4 that […]”.

Specific comment #6

"P10, L7: please remove the colon;"

Responses to specific comment #6:

We will remove the colon in Line 7 of Page 10.

Specific comment #7

"Fig. 2: check “curve”; I also suggest to re-word the caption as: [...]; Cumulative frequency and [...] distribution for normal (b), exponential (c) and uniform (d) distributions."

Responses to specific comment #7:

We will replace "cure" with "curve" in the caption of Figure 2. In addition, we will modify the caption of Figure 2 as suggested: “…; Cumulative frequency curve and histogram for normal (b), exponential (c) and uniform (d) distributions”.

Specific comment #8

"Fig. 6, 7 and 8: is it necessary to report the label "schema"?"

Responses to specific comment #8:

We will remove the label "schema" in Figs. 6a, 6b, 6c, 7a, 7b, 7c, 8a, 8b, 8c and 8d.

Specific comment #9

"Table 1: is P the average or the max?"

Responses to specific comment #9:

We will modify the note on Table 1 as follows: "Q_{Max}, Q_{Min} and Q_{Avg} mean the maximum, minimum and average value of daily streamflow, respectively, and P_{Max} means the maximum value of daily precipitation.". Meanwhile, we will modify the corresponding description in section 2 to avoid the misunderstanding.

Specific comment #10

"Table 2: the definition of parameter B seems not complete. Also, the column "range" of Table 2 is reported twice (see Table 3)."

Responses to specific comment #10:

We will complete the definition of parameter B in the modified Table 2 presented below. The column "range" of Table 2 will be changed as column "units" because the ranges of parameters are reported in Table 3.

Table 2. Parameters of Xinanjiang model

Parameter	Definition	Units
CI	Recession constants of the lower interflow storage	dimensionless
Kc	Ratio of potential evapotranspiration to pan evaporation	dimensionless
KI	Outflow coefficients of the free water storage to interflow	dimensionless
SM	Areal mean free water capacity of the surface soil layer, which represents the maximum possible deficit of free water storage	mm
B	Exponential parameter with a single parabolic curve, which represents the non-uniformity of the spatial	dimensionless
WM	Averaged soil moisture storage capacity of the whole layer	mm
C	Coefficient of the deep layer, that depends on the proportion of the basin area covered by vegetation with deep roots	dimensionless
EX	Exponent of the free water capacity curve influencing the development of the saturated area	dimensionless
CG	Recession constants of the groundwater storage relationships	dimensionless
KG*	Outflow coefficients of the free water storage to groundwater relationships	dimensionless
Im	Percentage of impervious and saturated areas in the catchment	dimensionless

* the value of KG is calculated by the function 0.7-KI

Specific comment #11

"Table 3: the main legend is not really clear, I suggest to re-word it. ** “ratio of calibrated parameter ...”"

Responses to specific comment #11:

The definition of “Ratio” in Table 3 will be modified as follows: “** the ratio is calculated by dividing the parameter range derived from 100 GA calibration by the initial parameter range”.

Part 2 Relevant Changes Following Referees' Comments

1. Following "Referee #1 Main comment #1", "Referee #2 Main comment #4" and "Referee #2 Specific comment #3" comments, we have modified sections 3.2.2 & 4.1 and Table 3. The following were added and/or modified:

a. Page 5, line 8-20:

The probability distributions of calibrated parameters values can be estimated roughly by using box-plot charts, cumulative frequency curves and frequency histograms. The symmetry of the box-plot chart (including one box and two whiskers) and the length ratio of the whisker to the box, the shape of the cumulative frequency curve and the frequency histogram are important indicators for the identification of the distribution type. Based on these indicators, three types of probability distributions are listed as follows: (1) Normal distributions, the box and whiskers are approximately symmetrical along the Y-axis direction, the length of either whisker is longer than half height of the box in a box-plot chart (Fig. 3a), the cumulative frequency curve is S shaped and the histogram bell shaped (Fig. 3b); (2) Exponential distributions, the whole chart is distinctly asymmetrical in the Y-axis direction which means that the average value (marked with a small hollow square) deviates from the median value (marked with a centre line in box), the box is inclined to one side with the extreme shorter whisker (Fig. 3a), the cumulative frequency curve is parabola shaped, and the histogram tends to increase or decline gradually (Fig. 3c); (3) Uniform distribution, the box and whiskers are approximately symmetrical along the Y-axis direction, the length of two whiskers is close to that of the box (Fig. 3a), the cumulative frequency curve tends to a straight line and the histogram varies little along the X-axis (Fig. 3d).

b. Page 5, line 21:

"A Kolmogorov-Simirnov test (K-S test) tries to examine whether a data set fit a reference probability distribution or not (Haktanir, 1991). In a K-S test, for any variable x_i in a data set, the empirical distribution function value (Fi) is calculated by using a plotting position formula, and the cumulative distribution function value ($Fi*$) is computed by using the reference probability distribution. The maximum deviation between the two values, Δ_{Max}, is expressed in Eq. (2).

$$\Delta_{Max} = |F_i^* - F_i| \quad (2)$$

According to the acceptable level of significance α (α=0.2) and the total number of values in a data set n, Δ_{table} can be obtained from the K-S table. If $\Delta_{Max} < \Delta_{table}$, the reference probability distribution is identified to fit to the data set."

c. Page 7, line 25-27:

"It is obvious that the box and whiskers are symmetrical and the length of whiskers is longer than that of box along the direction of Y axis for parameter CI, SM and Kc." >> " It is obvious from Fig. 7 that the box and whiskers are approximately symmetrical and the length of whiskers is longer than that of half box along the direction of the Y axis for parameters CI, SM and Kc."

d. Page 7, line 30:

"Furthermore, K-S tests were employed to determine the probability distributions of parameters and the corresponding results are listed in Table 3. It is shown that only a normal distribution is accepted for parameters CI & SM. Despite the fact that both normal and uniform distributions are accepted for parameter KC, the probability distribution of parameter KC is regarded as a normal distribution. It is because that the Δ_{Max} will become smaller if a normal distribution serves as a reference distribution instead of a uniform distribution. In addition, just an exponential distribution is accepted for the rest of the parameters. Thus, the three parameters follow normal distributions and the others exponential distributions in the Xinanjiang model."

e. Page 23:

Table 3. Range changes and K-S tests (α=0.2) of parameters in schema Initial

Parameter	Initial range	Calibrated range*	Ratio** (%)	Δ_{Max}***		
				Normal distribution	Expoential distribution	Uniform distribution
CI	0–0.9	0.630–0.745	12.78	0.062 (pass)	0.328 (fail)	0.115 (fail)
Kc	0–1.1	0.81–1.09	25.45	0.076 (pass)	0.305 (fail)	0.089 (pass)
KI	0–0.7	0.534–0.7	23.71	0.128 (fail)	0.076 (pass)	0.173 (fail)
SM	10–50	31–39.4	21.00	0.060 (pass)	0.304 (fail)	0.110 (fail)
B	0.1–0.4	0.238–0.4	54.00	0.180 (fail)	0.062 (pass)	0.203 (fail)
WM	120–200	120–150	37.50	0.181 (fail)	0.072 (pass)	0.231 (fail)
C	0.1–0.2	0.1–0.2	100.00	0.163 (fail)	0.082 (pass)	0.217 (fail)
EX	1.0–1.5	1.0–1.5	100.00	0.118 (fail)	0.079 (pass)	0.135 (fail)
CG	0.950–0.998	0.950–0.994	91.67	0.123 (fail)	0.102 (pass)	0.139 (fail)
Im	0.01–0.04	0.01–0.04	100.00	0.134 (fail)	0.076 (pass)	0.148 (fail)

* the calibrated parameter range except the extreme outlier

** the ratio is calculated by dividing the length of the range derived from 100 GA calibration runs by the initial range length

*** the Δ_{Max} is calculated by using the normalnized parameter values

2. Following "Referee #1 Main comment #3" and "Referee #2 Main comment #6" comments, we have revise the manuscript as the suggestion. In addition, we have checked the paper carefully and corrected the other language errors. The following were added and/or modified:

Page 1, line 3: "Qiaofeng." >> "Qiaofeng"

Page 1, line 14: "characteristics of single parameter value was analysed" >> "of single parameter value was analysed"

Page 1, line 17: "corresponding to the distribution" >> "corresponding to the distribution type"

Page 2, line 2: "The hydrological model is a type of black-box model in 1932 originally (Sherman, 1932), and conceptual models and distributed models are subsequently put forward in 1960s (Freeze and Harlan, 1969)." >> "The initial hydrological model was a black-box model in 1932 (Sherman, 1932) and conceptual & distributed models are subsequently put forward in 1960s (Freeze and Harlan, 1969)."

Page 2, line 4: "mechanism of water cycle" >> "mechanism of the water cycle"

Page 2, line 6: "the interflow and base flow are simplified" >> "the interflow and the base flow are simplified"

Page 2, line 9: "the streamflow at catchment outlet" >> "the streamflow at the catchment outlet"

Page 2, line 15-16: "obtain exact optimal solution" >> "obtain an exact optimal solution"

Page 2, line 17: "mathematical methods, having wide application in …" >> "mathematical calculations, having a wide application in …"

Page 2, line 25: "having powerful capability" >> "having a powerful capability"

Page 2, line 27: "search for the optimal solution" >> "search for the an optimal solution"

Page 2, line 30: "of the hydrological model" >> "of a hydrological model"

Page 2, line 31-32: "In general, parameter variables obey some types of probability distribution in the given range after multiple independent repeat calibration by an auto-calibration method" >> "In general, parameter variables obey some special probability distributions within the given range after multiple independent calibration"

Page 2, line 32-33: "Graziani et al. (2008) stated that the shape of the parameter value probability distributions can be significantly affected by their ranges. " >> "Graziani et al. (2008) stated that the shape of a parameter probability distribution can be significantly affected by a parameter range. "

Page 3, line 2: "Although Normal …" >> "Although normal …"

Page 3, line 7-8: "calibration of other parameters correlated with it" >> "calibration of other related parameters"

Page 3, line 9: "varies with catchment characteristic, objective function …" >> "varies with catchment characteristics, objective functions …"

Page 3, line 10: "parameter ranges lead to" >> "parameter ranges could lead to"

Page 3, line 11: "reducing or extending the ranges would affect the parameters sensitivity, making insensitive parameters …" >> "reducing or extending ranges might make insensitive parameters …"

Page 3, line 15-16: "The more deviation between true ranges and given range, the more instability of calculated result." >> "The more deviation between an optimal range and a given range, the more uncertainty of the calculation results."

Page 3, line 16: "Appropriate parameter ranges selection is ..." >> "The selection of appropriate parameter ranges is …"

Page 3, line 16: "few literature reported" >> "few literature covers information on"

Page 3, line 21-23: "At first, probability distribution characteristics of parameter values were analysed based on the parameter value samples that calibrated by using a GA method." >> "At first, probability distribution of each parameter was analysed based on a lot of independent calibrations by using a GA method."

Page 3, line 23-24: "range of single parameter is selected" >> "range of a single parameter was specified"

Page 3, line 30: "in flood reason" >> "in flood season"

Page 3, line 31: "The thickness of soil varies in most karst areas tremendously different with space: limestone exposed in some peak-cluster region, 2-10 m thickness clay covered in the depression and valley bottom." >> "The thickness of soil varies spatially in most karst areas. Limestone is exposed to air in some peak-cluster region. Clay soil with thickness ranging from 2 to 10m is distributed in the depressions and valleies."

Page 4, line 8-10: "The maximum areal precipitation of the studied catchment varies with year, the value is 235 mm/d of 1996 while 107 mm/d of 2000. The average streamflow decreases from 14.38 to 11.37 m3/d during the studied period." >> "The maximum areal daily precipitation varied with years in the studied catchment and reached the value of 235 mm/d in 1996."

Page 4, line 13: "parameters ranges selections" >> "parameters ranges selection"

Page 4, line 18: "from observed streamflow" >> "from the observed streamflow"

Page 4, line 19: "the meaning and the common range of …" >> "the definitions of …"

Page 4, line 20-21: "The proposed PRS method is introduced as follows, taking a Xinanjiang model for example." >> "The proposed PRS method is introduced as follows, when a Xinanjiang model is taken as an example."

Page 4, line 24: "In theory, the results of calibration by using a stochastic-based auto-calibration method are not completely same but similar in a reasonable convergence condition, which obey some probability distributions." >> "In theory, the parameter values calibrated by using a stochastic-based auto-calibration method are not same to each other but obey a certain probability distribution under a reasonable convergence condition."

Page 4, line 28: "… calibrated parameter values" >> "… calibrated parameter values in the investigation"

Page 4, line 30: "because GAs are common …" >> "because GA is a common …"

Page 4, line 31-32: "Many studies showed that the evolutionary algorithms could provide equal or better performance than other algorithms" >> "Many studies show that evolutionary algorithms provide equal or better performance of a model than other algorithms do"

Page 5, line 3: "which representing agreement between observed and simulated data" >> "which represents the agreement between observed and simulated data"

Page 5, line 5-6: "… observed streamflow … observed streamflow … simulated streamflow … mean value …" >> "… the observed streamflow … the observed streamflow … the simulated streamflow … the mean value …"

Page 5, line 11: "whisker to the box" >> "the whisker to the box"

Page 5, line 23: "…, the initial range of parameter is required adjusting properly" >> "…, the initial range of a parameter requires adjusting properly"

Page 5, line 24: "the different ways to adjust specify the optimal ranges for a single parameters" >> "the different ways to adjust specify the optimal ranges for a single parameter"

Page 5, line 25: "For uniform distribution, it is better to keep initial range due to little influence of the range on calibration results." >> "For the parameter of a uniform distribution, it is better to keep the initial range due to little influence of ranges on calibration results."

Page 5, line 25-26: "For normal distribution, the cumulative frequency curve is employed to seek several of reduced ranges …" >> "For the parameter of a normal distribution, the cumulative frequency curve is employed to seek some reduced ranges …"

Page 5, line 28: "represents the ranges …with a given cumulative frequency …" >> "represent the ranges …under a given cumulative frequency …"

Page 5, line 29-30: "As for exponential distribution, the initial range can be doubled from the boundary of high probability density to the outside, if the parameter has reasonable meaning in the new range." >> "As for the parameter of an exponential distribution, the initial range is symmetrically duplicated on one side of high probability density, if the parameter has reasonable meaning in the extended range."

Page 5, line 30-31: "Thus, the exponential distribution can be converted into normal distribution and then the optimal range can be selected by using the method for normal distribution." >> " Then, the optimal range of the parameter can be specified by comparing different ENS calculated separately by using the initial range, the MINR or MAXR of the initial range, the MINR or MAXR of the extended range."

Page 6, line 5: "... values can transform and finally convert into..." >> "... values can be converted into..."

Page 6, line 8-10: "As far as the Xinanjiang model … both parameter WM and B refer to the water storage volume – area curve that representing ..." >> "As far as a Xinanjiang model … parameters WM and B refer to the water storage volume – area curve that represents ..."

Page 6, line 10: "If the curve is fixed, a larger WM results in a smaller B" >> "If the curve is fixed, the larger WM results in the smaller B"

Page 6, line 10-11: "The change of a parameter range may more or less effect the calibration of other parameters." >> "As a result, the range change of parameter WM may affect the range setting and calibration of parameter B."

Page 6, line 11: "if several parameters ranges require adjusting" >> "if the ranges of the related parameters require adjusting"

Page 6, line 13: "If the change of one parameter … other parameters, the selected ranges for the parameter will contributes to ..." >> " If the range change of one parameter … other parameters, using the optimal range of the parameter instead of the initial one can contribute to ..."

Page 6, line 14: "… the negative influence may make the contribution of the selected ranges against model calibration." >> "… the negative impact may result in a worse model calibration, although the optimal ranges of the parameters are used."

Page 6, line 15-16: "The index Rc were quantified quantified to analyse the influencing degree of one parameter range …" >> "The index Rc was quantified to analyse the influence degree of one-parameter range …"

Page 6, line 16-18: "The more close value of $R_{\mathrm{C\,Y,X}}$ to 1, the greater positive influence of range change of parameter X on calibration of parameter Y. If $R_{\mathrm{C\,Y,X}}$ less than 0 ..." >> "When $R_{\mathrm{C\,Y,X}}$ is closer to 1, the range change of parameter X has a greater positive influence on the calibration of parameter Y. If $R_{\mathrm{C\,Y,X}}$ is minus ..."

Page 6, line 20: "the influencing degree of range change … on calibration of parameter Y" >> "the influence degree of the range … on the calibration of parameter Y"

Page 6, line 22-23: "selected range" >> "the optimal range"

Page 6, 24-26: "If there is negative influence between two parameters, the parameter of high sensitivity is ranked as primary one and its selected ranges can be kept in the range combination for all parameters, while the initial range is used in place of the selected range to minimize the negative effect for the other parameter of low sensitivity." >> "If there is a negative influence between two parameters, the optimal range of the parameter of higher sensitivity is used and the initial range of the other parameter kept for calibration generally to mitigate the negative impact."

Page 6, line 26: "It is due to the fact that" >> "It is due to that"

Page 6, line 27: "… parameters do during multi-parameter calibration …" >> "… parameters do in a multi-parameter calibration …"

Page 6, line 28: "by performing S-PRS method" >> "by performing a S-PRS method"

Page 6, line 29-30: "The larger R_{E}, the more concentrated E_{NS} distribution, which means parameter calibration is stable and efficient. Thus, the parameter of high S_{E} is given priority to use the selected range ..." >> "The larger value of R_{E}, the more concentrated distribution of E_{NS} which means more efficient parameter calibration. Thus, the parameter of higher S_{E} is given priority to use the optimal range ..."

Page 7, line 2: "with initial range … with selected range … The statistic analysis …" >> "with an initial range … with an optimal range … The statistical analysis…"

Page 7, line 5: "range selection are investigated" >> "range selection were investigated"

Page 7, line 7: "of one parameter range change" >> "of one-parameter range change"

Page 7, line 6: "ranges is substituted" >> "ranges are substituted"

Page 7, line 8: "the selected one is adopted for calibration of multiple parameters." >> "the optimal ones are adopted for the multi-parameters calibration."

Page 7, line 16: "In stage 3 the ... " >> "In stage 3, the ..."

Page 7, line 20: "of Xinanjiang model" >> "of the Xinanjiang model"

Page 7, line 21: "100 times independent calibration" >> "100 independent calibration runs"

Page 7, line 24-25: "The 100 calibrated values for single parameters were normalized by dividing them by the corresponding initial range, and the box-plot chart of the results is shown in Fig. 5. It is obvious 7 that … " >> "For any particular parameter, calibrated values were normalized by dividing a deviation between a calibrated value and the lower limit of the initial range by the length of the initial range. Based on 100 calibrated values after normalization, a box plot for a parameter is depicted. It is obvious from Fig. 7 that …"

Page 7, line 26: "direction of Y axis" >> "direction of the Y axis"

Page 7, line 30-31: "The ratios of calibrated parameter range to the initial one are less than 30% of parameters CI, SM, and Kc, while the ratio varies from 23% to 100% for parameters such as KI, B, CG, and Im." >> "The ratio of the calibrated range length to the initial range length is less than 30% for parameters CI, SM, and Kc, while the ratio exceeds 30 % for parameters B, WM, C, EX, CG, and Im."

Page 7, line 31: "It suggest that" >> "It implies that"

Page 8: "MINR >> the MINR" & "MAXR" >> "the MAXR" & "in case of" >> "in the case of"

Page 8, line 1-2: "that reducing the ranges is suitable to improve calibration for parameters whose values obey normal distributions, whereas that is not enough for parameters whose values obey exponential distributions." >> "that reducing the initial ranges can improve the calibration for parameters whose values obey normal distributions."

Page 8, line 6: "To normal distribution, reducing the range is generally used to select the appropriate range." >> "For a normal distribution, reducing the range was used to find the optimal range."

Page 8, line 7: "different parameter range are selected" >> "different ranges are selected"

Page 8, line 10-11: "whereas the normal distribution is changed to the exponential one when the range is cut to MAXR." >> "whereas the probability distribution approximates an exponential one when the MAXR is used."

Page 8, line 13: "concentrates at larger value zone" >> "concentrates at a higher value range"

Page 8, line 13-14: "It is indicated that the reduced range of high probability density is helpful to make calibration more steady and efficient." >> "Using the reduced range of high probability density is, therefore, helpful to make calibration more stable and more efficient."

Page 8, line 16-18: "Figure 7 shows the calibration results of parameter KI. Since the initial range of parameter KI can not be extended, the reduced range was searched by using the cumulative frequency curve, the MINR (0.660–0.700) and MAXR (0.522–0.660) were picked out." >> "Figure 9 shows the calibration results under three different input ranges of parameter KI. Since the initial range of parameter KI cannot be extended, the two reduced ranges (i.e. the MINR (0.660 – 0.700) and the MAXR (0.522 – 0.660)) were picked out by using the cumulative frequency curve."

Page 8, line 19-20: "… parameter KI values is converted from exponential distribution to uniform distribution when the initial range is reduced to MINR, whereas the exponential distribution is still kept when the range is cut to MAXR." >> "…parameter KI values is similar to a uniform distribution in the case of the MINR, whereas that is still exponential in the case of the MAXR."

Page 8, line 20-22: "The contribution of parameter ranges to E_{NS} is shown in Fig. 7d. Similar to the results of parameter CI, MINR is best for calibration when compared with MAXR or initial range." >> "The contributions of the three parameter ranges to E_{NS} are shown in Fig. 9d. Thus, the MINR is best for calibration of parameter KI when compared with the MAXR or the initial range, which is similar to the calibration result of parameter CI."

Page 8, lien 24: "Because the parameter values in MINR indicate a high probability to be picked out to achieve high E_{NS}, vice versa." >> "It is because that the parameter values that may achieve a higher E_{NS} can be easily picked out from the MINR of higher probability density."

Page 8, line 31-32: "… the probability distribution of parameter B values is converted into approximate uniform distribution when the range is reduced from initial range to MINR or from the extended range to extension-MINR." >> "… the probability distribution of parameter B approximates a uniform distribution when the MINR or the extension-MINR is used."

Page 8, line 33: "box-plot chart of E_{NS} for different ranges are shown in Fig. 8e" >> "box-plots for different ranges are shown in Fig. 10e"

Page 9, line 5: "The S-PRS method was employed to select the one-parameter optimal range for each parameter, and the optimal ranges, indexed R_C and S_E values are listed in Table 4." >> "The S-PRS method was employed to determine the optimal range for each parameter. According to the optimal ranges and the corresponding initial ranges, indexed R_C and S_E were quantified to understand parameter correlation and sensitivity."

Page 9, line 6: "value in columns of parameter CI and WM" >> "values in the columns of parameters CI and WM".

Page 9, line 10-12: "Parameter CI has the maximum RC_{mean} of 0.465, while parameter Im the minimum RC_{mean} of –0.026. Furthermore, RC mean values for all parameters are positive except for that for parameter Im. It is due to the accumulative negative influence of parameter Im on others." >> "Parameter CI has the maximum $R_{C\ mean}$ of 0.465 and parameter Im the minimum $R_{C\ mean}$ of –0.026. Furthermore, all parameters have positive $R_{C\ mean}$ values except for parameter Im, owing to the accumulative negative correlation between parameter Im and the others."

Page 9, line 13: "To coordinate the contradiction between parameters, the index S_E is used to pick parameters of high sensitivity to E_{NS}." >> "To coordinate with negatively related parameters, the index S_E was used to pick out parameters of higher sensitivity to E_{NS}."

Page 9, line 15: "It suggests that parameters CI, B, SM, KI, K_c, WM and CG are highly sensitive to E_{NS}, and parameters C, EX and Im of low sensitivity for E_{NS}. CI is the most sensitive parameter while Im the most insensitive parameter …" >> "It suggests that parameters C, EX and Im are of low sensitivity to E_{NS} and the others highly sensitive to E_{NS}. Parameter CI is the most sensitive while Im the most insensitive …"

Page 9, line 20: "penetrate" >> "penetrability"

Page 9, line 22-23: "It can be deduced that the optimal range of insensitive parameter Im cannot be taken into account when there is a contradiction owing to it, in order to improve calibration." >> "Thus, the optimal ranges of parameters of higher sensitivity should be used to improve calibration."

Page 9, line 24: "seven cases are investigated" >> "seven cases were investigated"

Page 9, line 25: "pf" >> "of"

Page 9, line 25: "The results of seven cases are compared in Fig. 9." >> "The box plots of E_{NS} for different cases are given in Fig. 11."

Page 9, line25-26: "...when Case 4 compared with Case 1, Case 2 and Case 3 It can be explained..." >> "... when Case 4 is separately compared with Case 1, Case 2 and Case 3. It can be explained..."

Page 9, line 27: "As S_E of parameter Im is less than that of parameter EX, parameter EX is given priority to select the optimal range," >> "As the S_E value of parameter Im is less than that of parameter EX, parameter EX is given priority to use the optimal range."

Page 9, line 31-page 10, line 2: "The box and whisker of E_{NS} for Case 6 rise, which means Case 6 has a better performance of calibration than Case 5 does, when the optimal range of parameter CG is included. But the box and whisker of E_{NS} for Case 7 decline when the optimal range of parameter Im is included. Because the mean R_C value of parameter Im is negative and its S_E much less than that of others, using the optimal range of Im is adverse to multi-parameter combined calibration." >> "Case 6 has the most concentrated values of E_{NS} and the largest mean value of E_{NS} among the three cases. It means that the combination of optimal ranges of all parameters (see Case 7) is not the optimum to calibrate a multi-parameter model inasmuch as some parameters like Im have negative correlation on other parameters. Hence, the initial ranges of parameters having negative mean values of R_C and low values of S_E are supposed to be used to calibrate parameters instead of the corresponding optimal ranges."

Page 10, line 4-7: "Considering that there is the relation between the parameter ranges and probability distributions of parameter value, an approach to determine the optimal range combination for multi parameters of hydrological models is put forward by analysing the parameter value probability distribution, parameter sensitivity and parameter correlation. A case of improving the calibration of the GA-based Xinanjiang model for karst areas is studied, and some findings are presented as follows." >> "Considering that there is a relation between the selection of multi-parameter ranges and the calibration effect of a hydrological model, an approach to determine an optimal combination of ranges for the multi-parameter calibration was put forward by analysing parameter probability distribution, parameter sensitivity and correlation between parameters. The newly proposed method was applied for the calibration of a Xinanjiang model for karst areas, and some findings are presented as follows."

Page 10, line 13: "the extension range followed by MINR is recommended" >> "the extension-MINR is recommended"

Page 10, line 17: "to adopted" >> "to be adopted"

Page 10, line 18-19: "The investigation is financially supported by special funds for scientific research on public causes of Chinese Ministry of Water Resources" >> "The investigation is supported by special funds for public welfare industry research projects of the Ministry of Water Resources of the People’s Republic of China"

3. Following “Referee #1 Specific comment #1” and “Referee #2 Specific comment #3” comments, we have expanded sections 3.2.1 & 3.3.1 and add Figures 2 & 5 to clarify more on how to determine the sampling size and cumulative frequency value. The following were added and/or modified:

a. Page 4, line 27-29:

"As far as the sample size is concerned, 100 samples are enough to estimate the probability distribution of calibrated parameter values in the investigation, which is deduced from the results of trial tests as shown in Fig. 2. It can be seen that both maximum and minimum E_{NS} keep stable when sampling size is greater than 100."

b. Page 15:

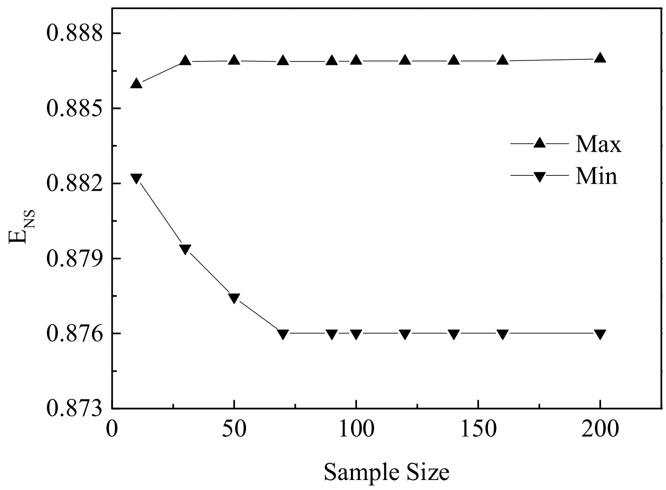

Fig. 2. Variation curves of maximum and minimum E_{NS} with sample sizes

c. Page 6, line 4:

"Figure 5 gives the variation curves of maximum and minimum E_{NS} of a single parameter with cumulative frequency values. It is found that the maximum E_{NS} keeps constant despite a cumulative frequency value varying, while the minimum E_{NS} approaches the peak value of 0.881 when the cumulative frequency value is equal to 50%. Considering that higher minimum E_{NS} contributes to more efficient calibration, the fixed cumulative frequency value of 50% was selected to determine the ranges of maximum and minimum probability density (i.e. MINR and MAXR) for each parameter."

d. Page 16:

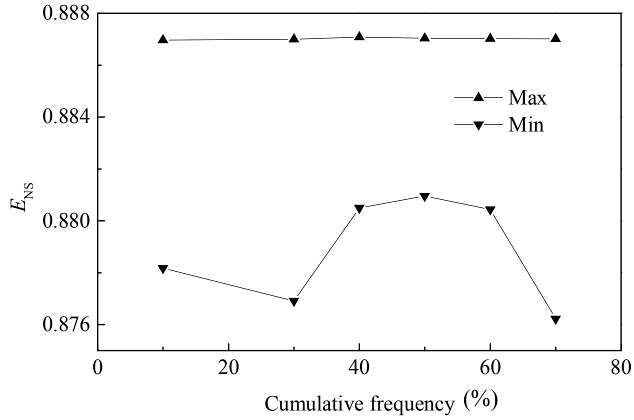

Fig. 5. Variation curves of maximum and minimum E_{NS} of a single parameter with cumulative frequency values

4. Following "Referee #1 Specific comment #2" comments, we have revise the result section as the suggestion. The following were added and/or modified:

a. Page 8, line 12:

"It is found that the minimum E_{NS} except extreme outliers rises convincingly and E_{NS} concentrates at larger value zone when MINR is used instead of the initial range." >> " It is found that the minimum E_{NS} except extreme outliers rises from 0.881 to 0.884 and the E_{NS} concentrates at a higher value range when the MINR is used instead of the initial range."

b. Page 8, line 34:

"It is shown that there is little improvement in maximum E_{NS} when MINR is used for calibration instead of the initial range. There is an increase of 0.0003 in maximum E_{NS} if the initial range is replaced with the extension range or the extension-MINR. As for minimum E_{NS} (except outliers), an increase of 0.001 in the case of the MINR, a decrease of 0.003 in the case of the extension range and an increase of 0.003 in the case of the extension-MINR are found when the initial range is substituted with the three ranges respectively."

c. Page 9, line 29-30:

"As for the cases of multi-parameter range selection (i.e. Case 5, Case 6 and Case 7), the results are much better than of Case 1-4." >> "As for the cases with the multi-parameter range selection (i.e. Cases 5 – 7), the E_{NS} values are much greater than those of cases 1-4. There is approximately an increase of 0.001 in maximum E_{NS} and an increase of 0.01 in minimum E_{NS} when the multi-parameter range selection is performed."

5. Following "Referee #1 Specific comment #3" and "Referee #2 Main comment #5" comments, we have modified section 4.3 & 5. The following were added and/or modified:

Page 9, line 25:

"Case 1 was defined as the initial case using all initial ranges. Cases 2 – 4 were defined as the single parameter range selection (S-SPR) cases. Cases 5 – 7 were set as the multiple parameters ranges selections (M-SPR) cases."

Page 10, line 8-17:

"In the Xinanjiang model for karst areas, parameters CI, Kc, SM and B approximately obey normal probability distributions, and parameters WM, C, EX, KI, CG and Im exponential probability distributions after 100 independent calibration runs. For the parameters of a normal distribution, the MINR defined by using a cumulative frequency curve of calibrated values is preferred to be selected as the optimal parameter range for calibration. For the parameters of an exponential distribution, the extension-MINR is recommended to be used for calibration if the initial range can be extended towards the high-probability side, otherwise the MINR is selected as the optimal range for calibration.

The proposed parameter range selection (PRS) method improves the minimum and mean values of E_{NS}. The application of the proposed methodology results in an increase of 0.01 in minimum E_{NS}, compared with that of the pure GA method. The rising of minimum E_{NS} with little change of the maximum may shrink the range of the possible solutions. As a result, the uncertainty of the model performance can be effectively controlled.

The M-SPR method is superior to the S-SPR one for calibrating hydrologic models with multiple parameters. The R_C and S_E are two important indexes that can help to analyse the sensitivity and correlation between parameters and consequently to coordinate with the negatively related parameters. The initial ranges of parameters of relatively low S_E and negative $R_{C\ mean}$ and the optimal ranges of parameters of positive $R_{C\ mean}$ should be preferred to be chosen for the multi-parameter model calibration."

6. Following "Referee #1 Specific comment #4" comments, we have revise Figure 1 as the suggestion. The following were added and/or modified:
Page 14:

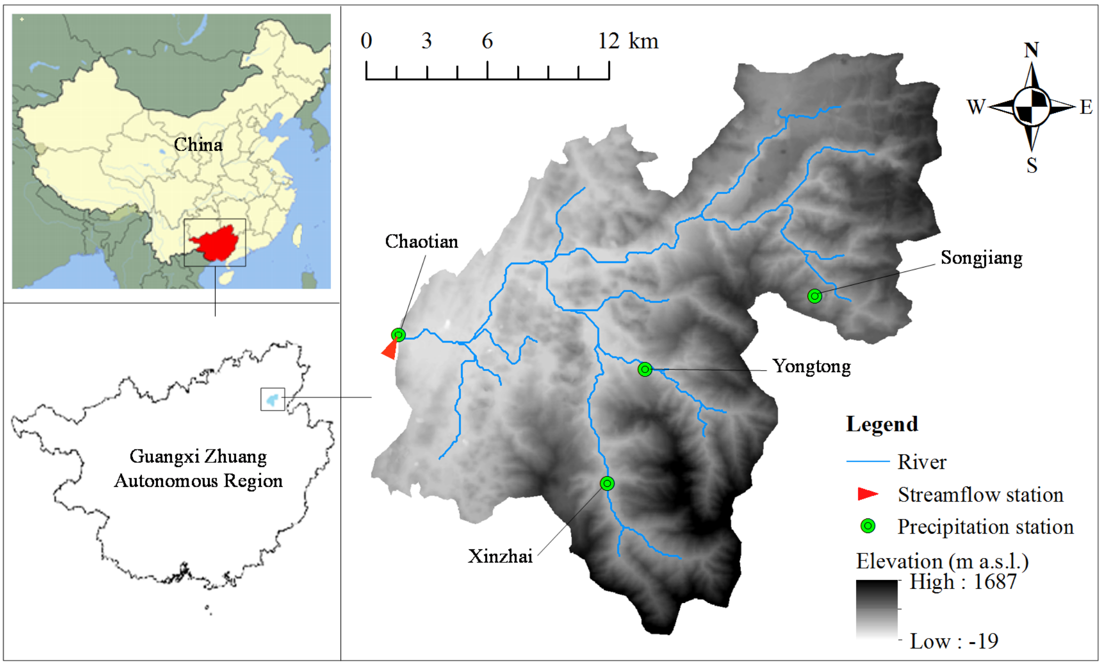

Fig. 1. Location of the study area

7. Following "Referee #1 Specific comment #5" and "Referee #2 Specific comment #7" comments, we have revise the caption of Figure 2 as the suggestion. The following were added and/or modified: Page 15, line 13:

"(a) Box-plot charts of normal, exponential and uniform distribution; Cumulative frequency curve and histogram for normal (b), exponential (c) and uniform (d) distributions"

8. Following "Referee #1 Specific comment #6" comments, we have revise Figure 5 as the suggestion. The following were added and/or modified:
Page 17:

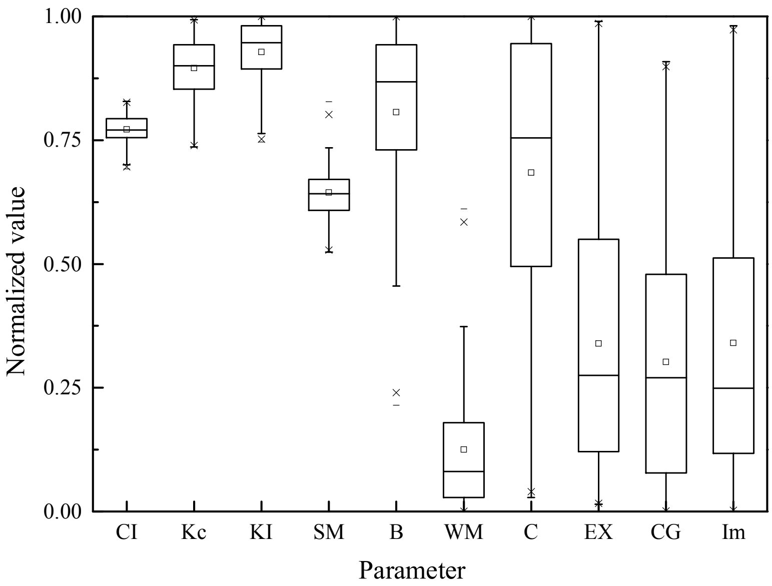

Fig. 7. The box-plot chart of normalized calibrated values for parameters of Xinanjiang model

9. Following "Referee #1 Specific comment #7", "Referee #1 Specific comment #8" and "Referee #2 Specific comment #10" comments, we have modified Table2. The following were added and/or modified:
Page 22:

Table 2. Parameters of Xinanjiang model

Parameter	Definition	Units
CI	Recession constants of the lower interflow storage	dimensionless
Kc	Ratio of potential evapotranspiration to pan evaporation	dimensionless
KI	Outflow coefficients of the free water storage to interflow	dimensionless
SM	Areal mean free water capacity of the surface soil layer, which represents the maximum possible deficit of free water storage	mm
B	Exponential parameter with a single parabolic curve, which represents the non-uniformity of the spatial	dimensionless
WM	Averaged soil moisture storage capacity of the whole layer	mm
C	Coefficient of the deep layer, that depends on the proportion of the basin area covered by vegetation with deep roots	dimensionless
EX	Exponent of the free water capacity curve influencing the development of the saturated area	dimensionless

CG	Recession constants of the groundwater storage relationships	dimensionless
KG*	Outflow coefficients of the free water storage to groundwater relationships	dimensionless
Im	Percentage of impervious and saturated areas in the catchment	dimensionless

* the value of KG is calculated by the function 0.7-KI

10. Following "Referee #2 Main comment #5" comments, we have revise Table 5 as the suggestion. The following were added and/or modified:

Page 24:

Table 5. Parameter ranges setting for different cases

Case	Range setting of parameter									
	CI	Kc	KI	SM	B	WM	C	EX	CG	Im
1	I	I	I	I	I	I	I	I	I	I
2	I	I	I	I	I	I	I	I	I	O
3	I	I	I	I	I	I	I	O	I	I
4	I	I	I	I	I	I	I	O	I	O
5	O	O	O	O	O	O	O	O	I	I
6	O	O	O	O	O	O	O	O	O	I
7	O	O	O	O	O	O	O	O	O	O

The symbol 'I' represents the initial range of the parameter in Table 3, and 'O' the optimal range of the parameter in Table 4.

11. Following "Referee #2 Specific comment #11" comments, we have revise the main legend of Table 3 as the suggestion. The following were added and/or modified:

Page 21, line 3:

"** the ratio is calculated by dividing the parameter range size derived from 100 GA calibration by the initial parameter range size"

12. Following "Referee #2 Main comment #2" comments, we have expanded sections 3.2.1 & 4.3 and add Figure 11 to clarify more on GA parameters and computational/time efforts. The following were added and/or modified:

a. Page 7, line 21:

"Trial tests were employed to determine the optimal GA control parameters: crossover probability of 0.5, mutation probability of 0.7 for the individual, mutation probability of 0.5 for each gene, population size of 21, maximum generation number of 500 and maximum iteration number of 50. These parameters were kept constant for GA calibrations in the investigation."

b. Page 10, line 3:

"Through a calibration run, a set of calibrated values of all parameters and the corresponding E_{NS} are obtained. Figure 12 shows the variation curves of maximum and minimum values of E_{NS} with number of runs by using a GA method and a proposed PRS method, respectively. It is indicated from Figure 12 that no mater it is maximum or minimum E_{NS}, the value calculated by using a proposed method is almost the same as that by using a GA method when the number of runs does not exceed 100. If a proposed method is used for calibration instead of a GA method, there are approximately an increase of 0.001 in maximum E_{NS} and an increase of 0.01 in minimum E_{NS} when the number of runs is greater than 100. Thus, for any particular run number, the value of E_{NS} calculated by using a PRS method is not less than that by using a GA method. The application of a proposed method, therefore, contributes to a relatively efficient calibration."

c. Page 21:

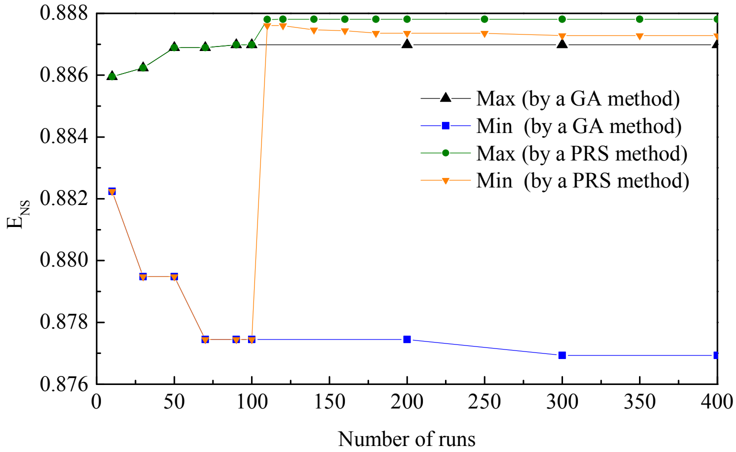

Figure 12. The variation curves of maximum and minimum E_{NS} with number of runs by using a GA method and a proposed PRS method

13. Following "Referee #2 Specific comment #1" comments, we have revise the abstract as the suggestion. The following were added and/or modified:

Page 1:

"The parameters are usually calibrated to achieve good performance of hydrological models, owing to the highly non-linear problem of hydrology process modelling. However, parameter calibration efficiency has a direct relation with parameter range. Furthermore, parameter range selection is affected by probability distribution of parameter values, parameter sensitivity and correlation. A newly proposed method is employed to determine the optimal combination of multi-parameter ranges for improving the calibration of hydrological models. At first, single-parameter probability distributions were analysed based on 100 samples obtained from independent Genetic Algorithms (GA) calibration performed on a Xinganjiang model with a corresponding initial parameter range and, the distribution type (i.e. normal, exponential and uniform distributions) was specified for each parameter of the model. Then, the optimal range for each parameter was determined by comparing E_{NS} values calculated separately with the initial range, the minimum and maximum ranges of a given cumulative frequency of 50% (i.e. MINR and MAXR) and the extended range. Next, parameter correlation and sensibility were evaluated by quantifying two indexes $R_{C\,Y,X}$ and S_E which can be used to coordinate with the negatively correlated parameters to specify the optimal combination of ranges of all parameters for calibrating models. It is shown from the investigation that the probability distribution of calibrated values of any particular parameter in a Xinanjiang model is closely approximated by a normal or exponential distribution. The multi-parameter optimal range selection method is superior to the single-parameter one for calibrating hydrological models with multiple parameters. The combination of optimal ranges of all parameters is not the optimum inasmuch as some parameters like Im have negative effects on other parameters. The application of the proposed methodology gives a rise to an increase of 0.01 in minimum E_{NS} compared with that of the pure GA method. The rising of minimum E_{NS} with little change of the maximum may shrink the range of the possible solutions, which can effectively reduce uncertainty of the model performance."

14. Following “Referee #2 Specific comment #2” comments, we have replaced “method” with “tool” in the first sentence of “Introduction”. The following were added and/or modified:
Page 1, line 1:
"Hydrological process modelling is an important tool for research on water resources management …"

15. Following “Referee #2 Specific comment #4” comments, we have modify it as it is suggested. The following were added and/or modified:
Page 4, line 30:
"A Genetic Algorithm (GA) was selected …"

16. Following “Referee #2 Specific comment #5” comments, we have modify the sentence to make it easy to read. The following were added and/or modified:
Page 9, line 6:
"It is obvious from Table 4 that …"

17. Following “Referee #2 Specific comment #6” comments, we have removed the colon as it is suggested. The following were added and/or modified:
Page 10, line 7:
"… findings are presented as follows:">>"… findings are presented as follows."

18. Following “Referee #2 Specific comment #8” comments, we have the label “schema” in Figs. 6a, 6b, 6c, 7a, 7b, 7c, 8a, 8b, 8c and 8d. The following were added and/or modified:

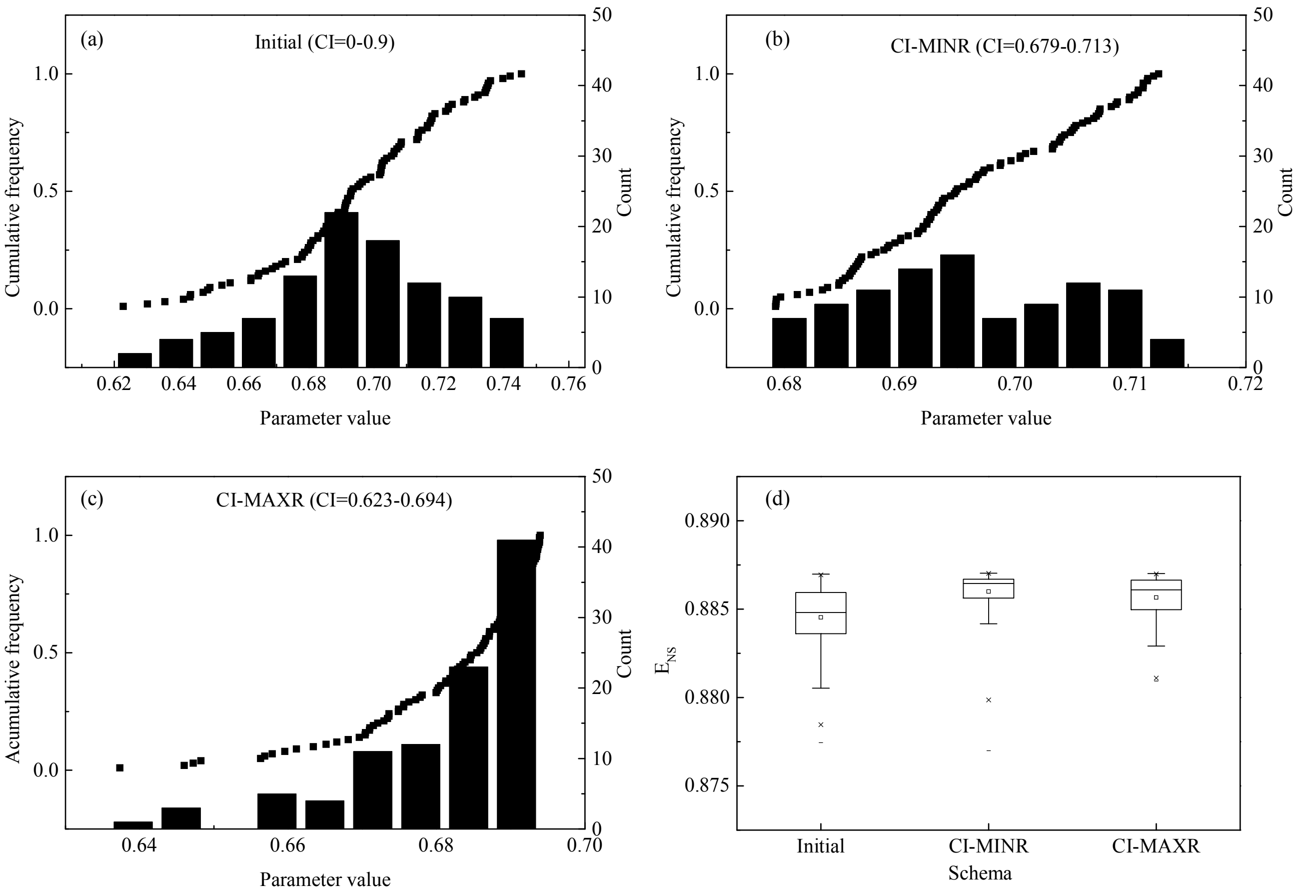

Fig. 8. Results of range selection of parameter CI

Probability distribution of parameter values for schema initial range (a), CI-MINR (b) and CI-MAXR (c);

(d) Box-plot chart of E_{NS} for three schemas

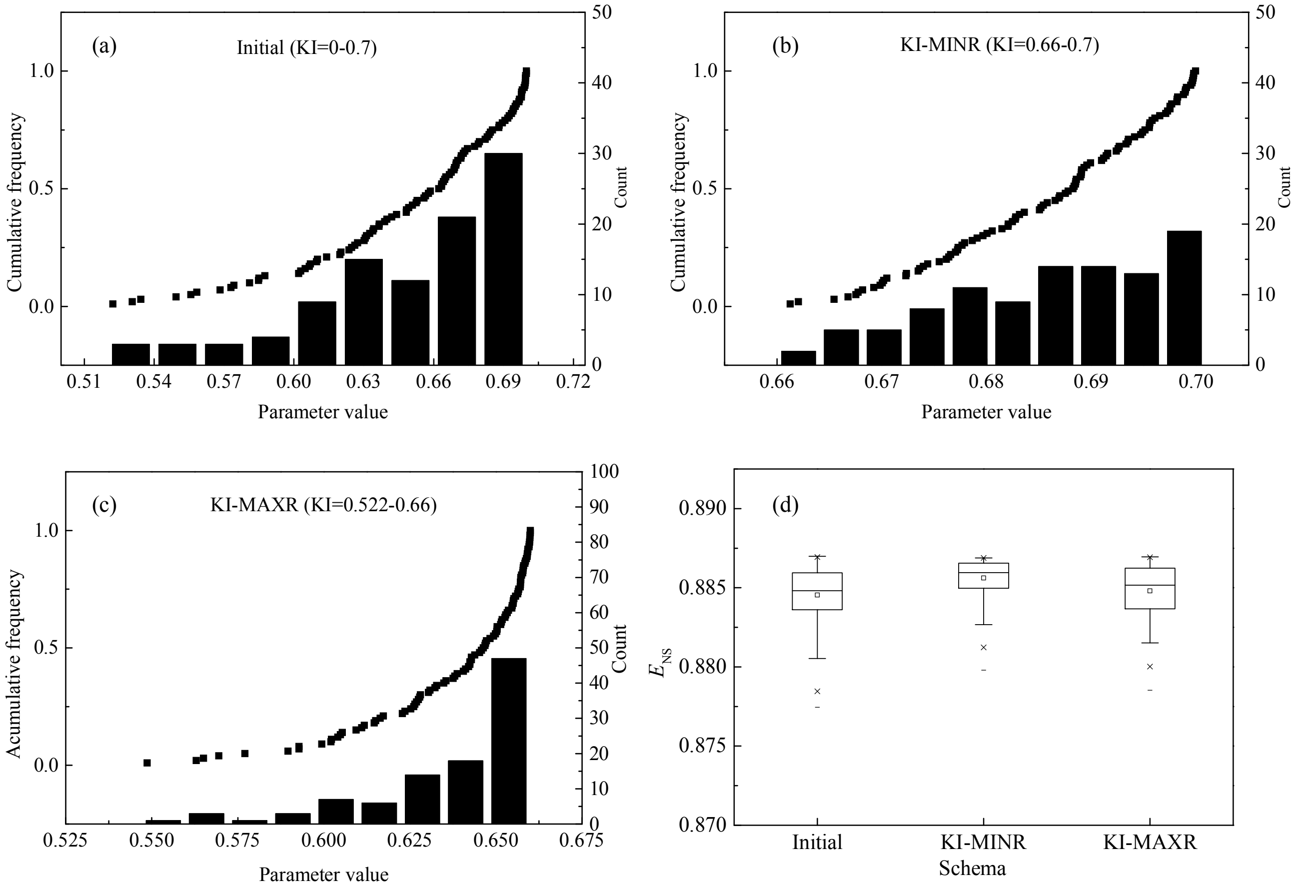

Fig. 9. Results of range selection of parameter KI

Probability distribution of parameter values for schema initial range (a), KI-MINR (b) and KI-MAXR (c);

(d) Box-plot chart of E_{NS} for three schemas

5

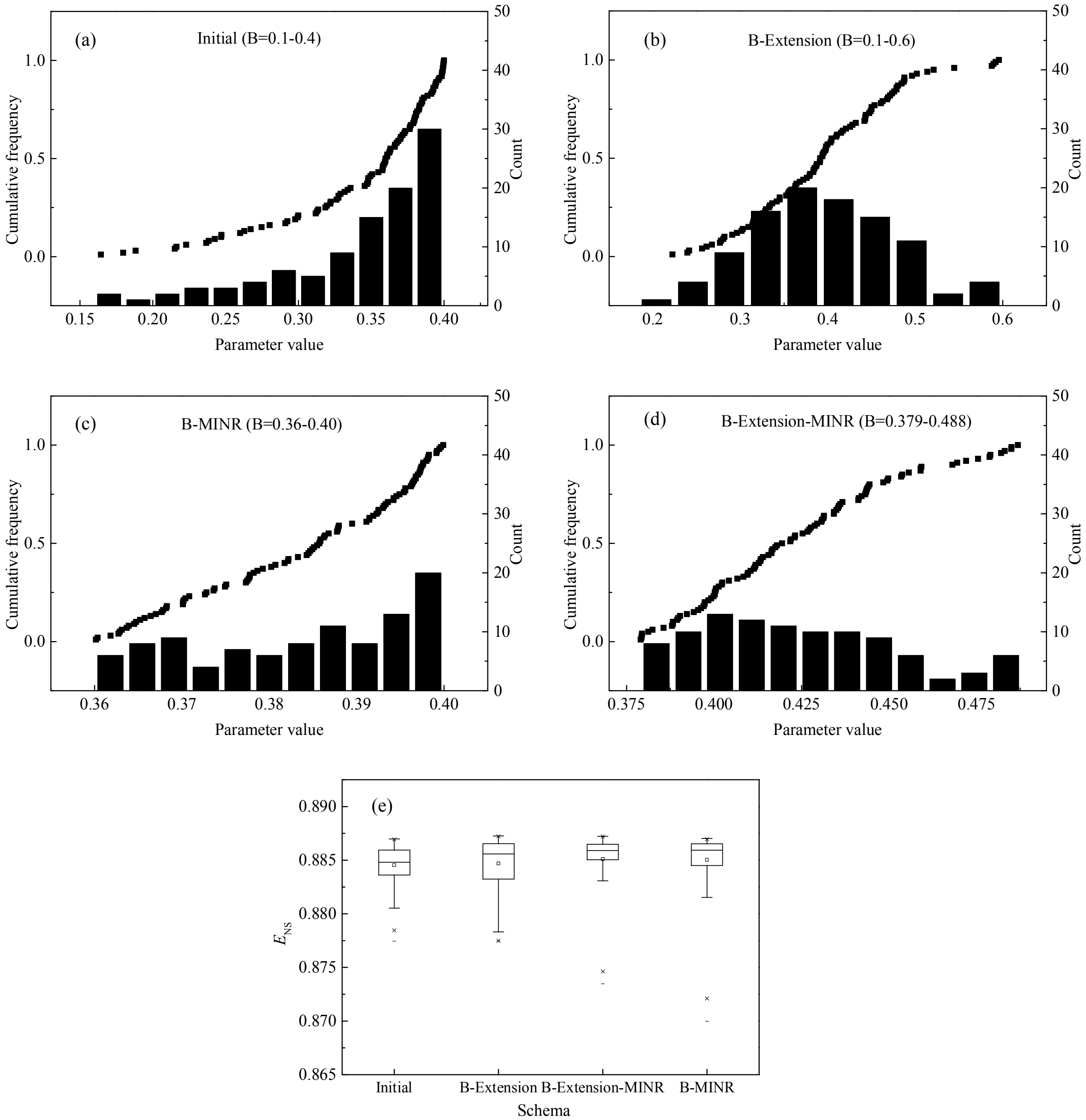

Fig. 10. Results of range selection of parameter B

Probability distribution for schema initial range (a), B–Extension (b), B–MINR (c) and B–Extension–MINR (d);

(e) Box–plot chart of E_{NS} for four schemas

19. Following "Referee #2 Specific comment #9" comments, we have modify the note on Table 1 to make it easy to read. The following were added and/or modified:

Page 22, note on Table 1:

"Q_{Max}, Q_{Min} and Q_{Avg} mean the maximum, minimum and average value of daily streamflow, respectively, and P_{Max} means the maximum value of daily precipitation."

Part 3 Marked-up manuscript version

Improvement of hydrological model calibration by selecting multiple parameter ranges

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Abstract. The parameters ~~of hydrological models~~ are usually calibrated to achieve ~~a~~ good performance of hydrological ~~the~~ models, owing to the highly non-linear problem of hydrology process modelling. However, parameter calibration efficiency has a direct relation with parameter range. Furthermore, parameter range selection is affected by probability distribution of parameter values, parameter sensitivity and correlation. A newly proposed method is employed ~~introduced~~ to determine ~~select~~ the optimal combination of multi-parameter ~~and coordinate parameter~~ ranges for improving the calibration of hydrological models~~ with multiple parameters~~. At first, single-parameter probability distributions were~~the probability distribution characteristics of single parameter value was~~ analysed based on 100 samples obtained from independent Genetic Algorithms (GA) calibration performed on a Xinganjiang model with ~~initial~~a corresponding initial parameter range and, the distribution type (i.e. normal, exponential and uniform distributions) was specified for each parameter of the model~~determined for single parameter~~. Then, the optimal range for each parameter was determined by comparing E_{NS} values calculated separately with the initial range, the minimum and maximum ranges of a given cumulative frequency of 50% (i.e. MINR and MAXR) and the extended range.~~the way to select the optimal range for single parameter was demonstrated by comparing different reduced and extended ranges corresponding to the distribution.~~ Next, parameter correlation and sensibility were evaluated by quantifying two indexes $R_{C\,Y,X}$ and S_E which can be used to coordinate with the negatively correlated parameters to specify the optimal combination of ranges of all parameters for calibrating models.~~parameter correlation and sensibility were estimated to coordinate range selection of single parameter and the optimal combination of ranges for all parameters obtained. The results show that the probability of calibrated parameter values of Xinanjiang model takes on the normal or exponential distributions. For normal distribution, selecting the range of high probability density from the initial range is much more efficient for calibration. For exponential distribution, if the initial range can not be extended, selecting the range of high probability density contributes to high objective function. If the initial range can be extended, it is better to make the exponential distribution convert into normal distribution by doubling the range along X-axis direction and subsequently select the range according to normal distribution. Moreover, the coordination of range selection of single parameters makes the calibration of models with multiple parameters more efficient and effective.~~ It is shown from the investigation that the probability distribution of calibrated values of any particular parameter in a Xinanjiang model is closely approximated by a normal or exponential distribution. The multi-parameter optimal range selection method is superior to the single-parameter one for calibrating hydrological models with multiple parameters. The combination of optimal ranges of all parameters is not the optimum inasmuch as some parameters like Im have negative effects on other parameters. The application of the proposed methodology gives a rise to an increase of 0.01 in minimum E_{NS} compared with that of the pure GA method. The rising of minimum E_{NS} with little change of the maximum may shrink the range of the possible solutions, which can effectively reduce uncertainty of the model performance.

Key words: hydrological model, calibration, parameter ranges, probability distribution

1. Introduction

Hydrological process modelling is an important ~~method~~ tool for research on water resources management, flood control and disaster mitigation, water conservancy project planning and design, hydrological response to climate change and so on (Zanon et al., 2010;Papathanasiou et al., 2015). The initial hydrological model ~~is~~ was a ~~kind of~~ black-box model in 1932 ~~originally~~ (Sherman, 1932)~~,~~ and conceptual ~~models and~~& distributed models are subsequently put forward in 1960s (Freeze and Harlan, 1969). The three kinds of hydrological models have been significantly improved in recent years and their structures become more and more mature. Theoretically, distributed models have definite physical mechanism of the water cycle and all parameters can be measured in-situ (Abbott et al., 1986;Huang et al., 2014). Conceptual models express hydrological processes in form of some abstract models which come from some physical phenomenon and experience. For example, the interflow and the base flow are simplified as the flow from linear reservoirs (Caviedes-Voullième et al., 2012;Lü et al., 2013). As a result, some parameters of conceptual models need calibrating. In general, conceptual models have better performance of modelling the streamflow at the catchment outlet than distributed models do, especially for catchments lacking sufficient data (Bao et al., 2010;Cullmann et al., 2011). Thus, many conceptual models such as HBV model, TOPMODEL, Tank model and Xinanjiang model are of strong vitality (Abebe et al., 2010;Vincendon et al., 2010;Hao et al., 2015; Xie et al., 2015). Additionally, the performance of distributed models can be improved after calibration of some parameters. Therefore, all of the hydrological models should be calibrated before engineering applications.

There are two kinds of calibration methods for hydrological models, the trial-error method and auto-calibration method. The trial-error method depends on plenty of trials for reducing the error of the objective. However, it is difficult to obtain an exact optimal solution due to limited enumeration (Boyle et al., 2000). The auto-calibration method is based on stochastic or mathematical ~~methods~~calculations, having a wide application in the non-linear parameter optimization. Compared with the trial-error method, it is more efficient and effective, avoiding the interference of anthropogenic factors (Madsen, 2000;Getirana, 2010). The initial automatic optimization methods, such as the Rosenbrock Method (Rosenbrock, 1960) and the Simplex Method (Nelder and Mead, 1965), are classical and useful methods, but has its limitation of initial value ranges of parameters.

Therefore, it can only be regarded as local optimization algorithms (Gupta and Sorooshian, 1985). Different from classical methods above, the Genetic Algorithm (GA) is of random search strategy that avoids problem of local search, being a global optimization algorithm in a real sense (Wang, 1991, 1997;Sedki et al., 2009;Chandwani et al., 2015). After that, many global optimization algorithms have been proposed inheriting the random search strategy. The Shuffled Complex Evolution (SCE-UA) method combines many advantages of Genetic Algorithm and Simplex Method, having a powerful capability of calibrating the rainfall-runoff model (Duan et al., 1994;Zhang and Shi, 2011). The Particle Swarm Optimization (PSO) based on random solution can directly obtain the identification parameters through the iterative search for an~~the~~ optimal solution (Kennedy, 1997;Zambrano-Bigiarini and Rojas, 2013). Though the auto-calibration method has been intensively employed to calibrate parameters in the field of hydrology, the most advanced algorithm inevitably falls into local solution because of the strong non-linear problem of ~~the~~ a hydrological model and parameter correlation (Chu et al., 2010;Jiang et al., 2010;Jiang et al., 2015).

In general, parameter variables obey some ~~types of~~special probability distributions within~~in~~ the given range after multiple independent ~~repeat~~ calibrations ~~by an auto-calibration method~~ (Viola et al., 2009;Jin et al., 2010;Li et al., 2010). Graziani et al. (2008) stated that the shape~~s~~ of ~~the~~ a parameter ~~value~~ probability distribution~~s~~ can be significantly affected by ~~their~~ a parameter range~~s~~. Ben et al. (2013) studied the effect~~s~~ of different probability distributions (e.g., Normal distribution and uniform distribution) of parameters values on parameter sensitivity, and found that the probability distribution can be provide a clue to realize parameter sensitivity. Although ~~Normal~~ normal and uniform distributions are greatly studied in practice, other types of probability distributions seldom were investigated in previous researches (Kucherenko et al., 2012;Esmaeili et al., 2014).

Most hydrological models contain many parameters of different sensitive characteristics and correlation behaviour. Some researchers believe that the sensitive parameter should be calibrated, but the insensitive parameter can be set as a fixed value by experience (Beck, 1987;Cheng et al., 2006). Inappropriate parameter ranges or fixed values may result in the instability of calibrated results. Furthermore, the range setting of one parameter may influence the calibration of other related ~~other~~ parameters ~~correlated with it~~ (Song et al., 2015). The model parameter sensitivity analysis has been a growing concern in recent years. Parameters sensitivity varies with catchment characteristics, objective functions and parameter ranges (van Griensven et al., 2006). Wang et al. (2013) noted the different parameter ranges could lead to changes - in parameter sensitivity. Shin et al. (2013) reported that reducing or extending ~~the~~ ranges ~~would~~ might make~~affect the parameters sensitivity, making~~ insensitive parameters become sensitive ones or vice versa. Thus, parameter ranges and correlation should be taken into considered when the calibration of multi-parameters models is performed.

Parameter ranges are generally given roughly due to lack of knowledge concerning physical settings of a local catchment (Song et al., 2013;Hao et al., 2015). The more deviation between an ~~true~~ optimal range~~s~~ and a given range, the more ~~instability~~ uncertainty of the ~~calculated~~calibration result~~s~~. The selection of ~~A~~appropriate parameter ranges ~~selection~~ is critical for calibrating the model efficiently. However, few literature ~~reported~~ covers information on how to select the appropriate parameter range for improving the calibration of hydrological models. Furthermore, the calibration of multiple parameters is more complex due to the parameter sensitivity and correlation. Hence, it is necessary to find a way to coordinate the range settings of all parameters.

Considering the effect of parameter ranges on calibration efficiency of hydrological models, an approach of parameter ranges selection (PRS) is put forward to improve the calibration of hydrological models with multiple parameters. At first, probability distribution characteristics of each parameter values were was analysed based on a lot of the parameter value samples that calibrated independent calibrations by using a GA method. Then the optimal range of a single parameter wasis selected specified for calibration according to its probability distribution. Finally, parameter correlation and sensitivity were estimated to determine the optimal combination of multiple parameters ranges. The proposed method is expected to be helpful for an effective and efficient calibration of hydrological models with multiple parameters.

2. Study area and data collection

The Chaotianhe River catchment is located in the northeast of Guangxi Zhuang Autonomous Region in Southwest China (Fig. 1). The Chaotianhe River is the major tributary of the Lijiang River of well-known karst landscape. The total catchment area is 476.24 km^2. The annual precipitation is approximately 1704 mm and 78% precipitation concentrates in flood sreasons (March to August).The thickness of soil varies spatially in most karst areas. tremendously different with space: l Limestone is exposed to air in some peak-cluster region., 2-10 m thickness cClay soil with thickness ranging from 2 to 10m is distributedcovered in the depressions and valleyies bottom. In clastic rock mountain areas, the thickness of the soil is usually less than 0.5 m. Thus, the soil moisture storage capacity varies significantly with space. Moreover, the underground rivers are very well developed in the karst area, which makes the flood gather rapidly and recess slowly due to higher underground flow rate.

The daily data concerning precipitation, evaporation and streamflow were collected from national gauging stations for the 5-year period of 1996–2000. Four precipitation stations, one streamflow gauging station and one evaporation station are selected for the investigation. Areal precipitation was calculated using data from the four precipitation stations by using a Thiessen polygon method under GIS environment (Cai et al., 2014). The streamflow gauging station is at the catchment outlet. Some metro-hydrological statistical data of the studied catchment are summarized in Table 1. From 1996–2000, the maximum of daily streamflow is about 719 m^3/sd, the minimum 0.53 m^3/ds and the average is 13.31 m^3/sd at the outlet. The maximum areal daily precipitation of the studied catchment varies varied with years in the studied catchment and reached the value of , the value is 235 mm/d inof 1996. while 107 mm/d of 2000. The average streamflow decreases from 14.38 to 11.37 m^3/s during the studied period.

3. Methodology

3.1 Hydrological model selection

The method of parameters ranges selection~~s~~ (PRS) is designed for most of hydrological models. At present, there have been many hydrological models for hydrological processes simulation. Considering the climate characteristics of the study area, the Xinanjiang model which is suitable for humid regions was chosen to serve as ~~the~~ a hydrological model for the investigation. The Xinanjiang model mainly includes three evapotranspiration layers and three runoff components (i.e. surface-, subsurface runoff and groundwater) (Zhao et al., 1980;Zhao, 1992). The surface runoff is routed by the Unit Hydrograph (UH) which is derived from the observed streamflow and other runoff components are simplified as linear reservoirs (Ju et al., 2009). With regard to the Xinanjiang model, there are 10 parameters that should be calibrated. The ~~meaning~~ definitions ~~and the common range~~ of the parameters are given in Table 2 (Lin et al., 2014;Hao et al., 2015). The proposed PRS method is introduced as follows, ~~taking~~ when a Xinanjiang model is taken as an~~for~~ example.

3.2 Probability distribution analysis of calibrated parameter value

3.2.1 Sample collection of calibrated parameter value

In theory, the parameter values calibrated ~~results of calibration~~ by using a stochastic-based auto-calibration method are not ~~completely~~ same to each other but obey a certain probability distribution ~~similar~~ under ~~in~~ a reasonable convergence condition.~~, which obey some probability distributions~~ (Jiang et al., 2015). In order to analyse the probability distribution of ~~calibrated~~ parameter values, a stochastic-based auto-calibration is used to calibrate the model, and samples of calibrated parameters values are obtained. As far as the sample size is concerned, 100 samples are enough to estimate the probability distribution of calibrated parameter values in the investigation, which is deduced from ~~plenty~~ the results of trial tests as shown in ~~by comparing the similitude of distributions and computing efficiency.~~ Fig. 2. It can be seen that both maximum and minimum E_{NS} keep stable when sampling size is greater than 100.

A Genetic Algorithm (GA) was selected as the auto-calibration method in the investigation, because GA~~s~~ ~~are~~ is a common and widespread used global optimization algorithm based on stochastic and evolutionary optimization ~~technique~~. Many studies show~~ed~~ that ~~the~~ evolutionary algorithms ~~could~~ provide equal or better performance of a model than other algorithms do (Cooper et al., 1997;Jha et al., 2006;Zhang et al., 2009). The Nash–Sutcliffe efficiency (E_{NS}) was chosen as ~~the~~ an objective function (Eq. (1)) for GA, which ~~representing~~ represents the agreement between observed and simulated data.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(Q_{\mathrm{obs,i}} - Q_{\mathrm{sim,i}})^2}{\sum_{i=1}^{n}(Q_{\mathrm{obs,i}} - Q_{\mathrm{mean}})^2} \quad (1)$$

where E_{NS} is Nash–Sutcliffe efficiency, i serial number of the step; n total number of the observed streamflow data, $Q_{\mathrm{obs,i}}$ the observed streamflow at step i, $Q_{\mathrm{sim,i}}$ the simulated streamflow at step i, and Q_{mean} is the mean value of observed streamflow.

3.2.2 Determination of probability distribution types

The probability distributions of calibrated parameters values can be ~~determined~~ estimated roughly by using box-plot charts, cumulative frequency curves and frequency histograms. ~~Figure 2 shows the three types of probability distribution based on 100 samples of parameter values of the Xinanjiang model.~~ The symmetry of the box-plot chart (including one box and two whiskers) and the length ratio of the whisker to the box, the shape~~s~~ of the cumulative frequency curve and the frequency histogram are important indicators ~~to determine~~for the identification of the distribution type~~s~~. Based on these indicators, three types of probability distributions are listed as follows: (1) Normal distributions, the box and whiskers are approximately symmetrical along the Y-axis direction, the length of either whisker~~s~~ is longer than ~~the~~ half height of the box in a box-plot chart (Fig. ~~2a~~3a), the cumulative frequency curve is S shaped and the histogram ~~is~~ bell shaped (Fig. ~~2b~~3b); (2) Exponential distributions, the whole chart is distinctly asymmetrical in the Y-axis direction which means that the average value (marked with a small hollow square) deviates from the median value (marked with a centre line in box), the box ~~close~~is inclined to one side with the extreme shorter~~where the~~ whisker ~~is extreme shorter than that on the opposite side~~ (Fig. ~~2a~~3a), the cumulative frequency curve is parabola shaped, and the histogram tends to increase or decline gradually (Fig. ~~2c~~3c); (3) Uniform distribution, the box and whiskers are approximately symmetrical along the Y-axis direction, the length of two whiskers is ~~approximates~~ close to that of the box (Fig. ~~2a~~3a), the cumulative frequency curve tends to a straight line and the histogram varies little along the ~~x~~X-axis (Fig. ~~2d~~3d).

A Kolmogorov-Simirnov test (K-S test) tries to examine whether a data set fit a reference probability distribution or not (Haktanir, 1991). In a K-S test, for any variable x_i in a data set, the empirical distribution function value (Fi) is calculated by using a plotting position formula, and the cumulative distribution function value (Fi^*) is computed by using the reference probability distribution. The maximum deviation between the two values, Δ_{Max}, is expressed in Eq. (2).

$$\Delta_{Max} = |F_i^* - F_i| \qquad (2)$$

According to the acceptable level of significance α (α=0.2) and the total number of values in a data set n, Δ_{table} can be obtained from the K-S table. If $\Delta_{Max} < \Delta_{table}$, the reference probability distribution is identified to fit to the data set.

3.3 Parameters ranges selections

3.3.1 Single parameter range selection (S-PRS)

In order to improve E_{NS}, the initial range of a parameter ~~is required~~ requires adjusting properly. In consideration of the three probability distribution types mentioned above, the different ways to ~~adjust~~ specify the optimal range~~s~~ for a single parameter~~s~~ are presented in the investigation. For the parameter of a uniform distribution, it is better to keep the initial range due to little influence of ~~the~~ ranges on calibration results. For the parameter of a normal distribution, the cumulative frequency curve is employed to seek ~~several of~~some reduced ranges with a given cumulative frequency (e.g. 50%), and the minimum and maximum ranges (namely MINR and MAXR) are obtained as depicted in Fig. ~~3~~4. The MINR and MAXR represent~~s~~ the ranges of maximum and minimum probability density of parameter values ~~with~~under a given cumulative frequency, respectively. As for the parameter of an exponential distribution, the initial range can be extended appropriately towards one side of high probability density, if the parameter has reasonable meaning in the extended range. Then, the optimal range of the parameter can be specified by comparing different E_{NS} calculated separately by using the initial range, the MINR or MAXR of the initial range, the MINR or MAXR of the extended range. ~~As for exponential distribution, the initial range can be doubled from the boundary of high probability density to the outside, if the parameter has reasonable meaning in the new range. Thus, the exponential distribution can be converted into normal distribution and then the optimal range can be selected by using the method for normal distribution.~~ If the initial range cannot be extended, the MINR and MAXR are sought out according to the cumulative frequency curve. ~~Through plenty of tests, a cumulative frequency value of 50% was adopted to search the MINR and MAXR, which reduces sampling errors in case of smaller percentage, and increases difference between MINR and MAXR in case of larger percentage.~~ Figure 5 gives the variation curves of maximum and minimum E_{NS} of a single parameter with cumulative frequency values. It is found that the maximum E_{NS} keeps constant despite a cumulative frequency value varying, while the minimum E_{NS} approaches the peak value of 0.881 when the cumulative frequency value is equal to 50%. Considering that higher minimum E_{NS} contributes to more efficient calibration, the fixed cumulative frequency value of 50% was selected to determine the ranges of maximum and minimum probability density (i.e. MINR and MAXR) for each parameter. In short, the optimal range of a single parameter can be determined by properly extending or reducing the initial range to make calibrated parameter values distributed quite closely to a uniform distribution.~~Through extending or reducing the ranges, the probability distribution of calibrated parameter values can transform and finally convert into approximate uniform distribution.~~

3.3.2 Multiple parameters ranges selection~~s~~ (M-PRS)

In general, there is more or less correlation between parameters for most hydrological models. As far as ~~the~~ a Xinanjiang model is concerned, ~~both~~ parameters WM and B refer to the water storage volume – area curve that ~~representing~~ represents the spatial variability of soil moisture storage. If the curve is fixed, ~~the~~ a larger WM results in ~~the~~ a smaller B (Zhao et al., 1980). As a result, ~~T~~the range change of ~~a~~ parameter WM ~~range~~ may ~~more or less effect~~affect the range setting and calibration of ~~other~~ parameter~~s~~ B. The correlations among parameters, therefore, should be taken into account, if the~~several parameters~~ ranges of the related parameters require adjusting. If the range change of one parameter ~~range~~ has positive influence on calibration of other parameters, using the ~~selected~~ optimal range~~s~~ ~~for~~of the parameter instead of the initial one can ~~will~~ contribute~~s~~ to better calibration results. On the contrary, the negative ~~influence~~impact may result in a worse model calibration, although the optimal ranges of the parameters are used. ~~make the contribution of the selected ranges against model calibration.~~ Thus, some coordination measures should be taken to deal with such a contradiction. The index R_C (Eq. (3~~2~~)) ~~were~~ was quantified to analyse the influence~~ing~~ degree of one-parameter range change on~~to~~ the calibration of other parameters. When ~~The more close value of~~ $R_{C\,Y,X}$ is closer to 1, ~~the greater positive influence of~~the range change of parameter X has a greater positive influence on the calibration of parameter Y. If $R_{C\,Y,X}$ is minus~~less than 0~~, it means ~~the~~ a negative influence.

$$R_{C\,Y,X} = 1 - \frac{L_{Y,X} - L_{Y,Y}}{L_{Y,Initial} - L_{Y,Y}} \quad (~~2~~3)$$

Where $R_{\mathrm{C\,Y,X}}$ is the influence~~ing~~ degree of the range change of parameter X on the calibration of parameter Y; $L_{\mathrm{Y,X}}$ the range of parameter Y calibrated with ~~selected~~ the optimal range of parameter X and initial ranges of other parameters, $L_{\mathrm{Y,Y}}$ the range of parameter Y calibrated with the ~~selected~~ optimal range of parameter Y and initial ranges of other parameters, and $L_{\mathrm{Y,Initial}}$ is the range of parameter Y calibrated with initial ranges of all parameters. The calibrated range of ~~the~~ any parameter is calculated except extreme outliers.

If there is a negative influence between two parameters, the optimal range of the parameter of higher sensitivity is used and ~~ranked as primary one and its selected ranges can be kept in the range combination for all parameters, while~~ the initial range of the other parameter kept for calibration generally ~~is used in place of the selected range~~ to mitigate the negative impact~~minimize the negative effect for the other parameter of low sensitivity~~. It is due to ~~the fact~~ that sensitive parameters play more important roles than insensitive parameters do ~~during~~ in a multi-parameter calibration. In order to assess the sensitivity of parameter range change to E_{NS}, index S_{E} as expressed in Eq. (~~3~~4) is computed by performing an S-PRS method on each parameter. The larger value of R_{E}, the more concentrated ~~E_{NS}~~ distribution of E_{NS}, which means more efficient parameter calibration ~~is stable and efficient~~. Thus, the parameter of higher S_{E} is given priority to use the ~~selected~~ optimal range when the R_{C} of two parameters is minus.

$$S_E = 1 - \frac{E'_{\mathrm{NS\,Max}} - E'_{\mathrm{NS\,Min}}}{E_{\mathrm{NS\,Max}} - E_{\mathrm{NS\,Min}}} \qquad (~~3~~4)$$

where S_{E} is sensitivity of parameter range change to E_{NS}, $E_{\mathrm{NS\,Max}}$ and $E_{\mathrm{NS\,Min}}$ maximum and minimum E_{NS} calibrated with an initial range, ~~and~~ $E'_{\mathrm{NS\,Max}}$ and $E'_{\mathrm{NS\,Min}}$ are maximum and minimum E_{NS} calibrated with an ~~selected~~ optimal range. The statistical analysis of E_{NS} excludes extreme outliers.

Considering there are more than two parameters in most hydrological models, the accumulative influence and the coordination of range selection ~~are~~ were investigated in the study. ~~Parameters of positive influence on other parameters can be taken into account, while the selected ranges is substituted for the initial ranges for the parameters of negative influence.~~ The mean value of R_{C} ($R_{\mathrm{C\,mean}}$) is the index to judge the accumulative influence of one-~~-~~parameter range change on the calibration of ~~the~~ other parameters. Thus, for parameters of a negative $R_{\mathrm{C\,mean}}$, the initial ranges instead of the ~~selected~~ optimal ones ~~is~~ are adopted for the multi-parameters calibration ~~of multiple parameters~~.

The flow chart of the parameter range selection method is shown in Fig. ~~4~~6. In stage 1, a set of initial ~~parameter~~ ranges of parameters is given for a hydrological model and the probability distribution for each parameter analysed based on the 100 independent parameters values calibrated by an auto-calibration method. In stage 2, there are three range adjustment methods with response to a ~~parameter value~~ probability distribution of parameter values: for a normal distribution, the optimal range ~~for~~ of a single parameter is obtained by reducing the initial range; for an exponential distribution, the initial range of a single parameter is extended to ~~convert to the normal distribution and~~ specify the optimal range ~~determined according to normal distribution~~, or the initial range is reduced to seek the optimal range for calibration ~~in the case of~~ when the extension of the parameter range is limited~~the limitation on range extension~~; for a uniform distribution, the initial range is kept. In stage 3, the

~~method of~~ single-~~-~~parameter range selection (S-PRS) is performed on each parameter. Based on the indexes S_E and R_C estimated, the optimal combination of ranges is determined by coordinating the range~~s~~ selection ~~for~~ of all parameters.

4. Results and discussion

4.1 Probability distribution characteristics of calibrated parameter values of the Xinanjiang model

A series of calibrated parameters values were obtained through 100 ~~times~~ independent calibration runs by using a GA method. Trial tests were employed to determine the optimal GA control parameters: crossover probability of 0.5, mutation probability of 0.7 for the individual, mutation probability of 0.5 for each gene, population size of 21, maximum generation number of 500 and maximum iteration number of 50. These parameters were kept constant for GA calibrations in the investigation. The initial and calibrated ranges of parameters are presented in Table 3. The ratio of the calibrated ~~parameter~~ range length ~~range~~ to the initial one in Table 3 is less than 60% for most parameters (i.e. parameter CI, Kc, KI, SM, B, and WM), which implies that reducing the ranges can help calibrate most parameters ~~the parameter~~ efficiently. For any particular parameter, ~~The 100~~ calibrated values ~~for single parameters~~ were normalized by dividing a deviation between a calibrated value and the lower limit of the initial range ~~them~~ by ~~the corresponding~~the length of the initial range.~~, and~~Based on ~~the box-plot chart of the results~~ 100 calibrated values after normalization, a box-plot for a parameter is ~~shown~~ depicted.~~in Fig. 5.~~ It is obvious from Fig. 7 that the box and whiskers are approximately symmetrical and the length of whiskers is longer than that of ~~the~~ half box along the direction of the Y axis for parameters CI, SM and Kc. But for other parameters, it is shown from the box-plot charts that the mean value deviates from the median one, which means an ~~considerably~~ asymmetric chart. According to the~~se~~ characteristics of the box-plots ~~chart~~, it is ~~indicated~~ shown that the probability distributions of the calibrated values ~~is~~ are normal ~~distribution~~ for parameters CI, SM, and Kc, while ~~that~~ those are~~is~~ exponential ~~distribution~~ for other parameters. Furthermore, K-S tests were employed to determine the probability distributions of parameters and the corresponding results are listed in Table 3. It is shown that only a normal distribution is accepted for parameters CI & SM. Despite the fact that both normal and uniform distributions are accepted for parameter KC, the probability distribution of parameter KC is regarded as a normal distribution. It is because that the Δ_{Max} will become smaller if a normal distribution serves as a reference distribution instead of a uniform distribution. In addition, just an exponential distribution is accepted for the rest of the parameters. Thus, the three parameters follow normal distributions and the others exponential distributions in the Xinanjiang model. The ratio of the calibrated ~~parameter~~ range length to the initial range length~~one~~ is less than 30% for parameters CI, SM, and Kc, while the ratio ~~varies from 23% to 100%~~exceeds 30% for parameters ~~such as KI,~~ B, WM, C, EX, CG, and Im. It ~~suggest~~ implies that reducing the initial ranges ~~is suitable to~~can improve the calibration for parameters whose values obey normal distributions.~~, whereas that is not enough for parameters whose values obey exponential distributions.~~

4.2 Effect of range adjustment pattern on calibration results

Since the probability distribution of a single parameter ~~value~~ has a direct relation with the parameter range selection, the range adjustment pattern of a single parameter~~s for calibration is~~ was discussed on the basis of the parameter probability distribution ~~type of parameters~~ in the investigation.

~~To~~ For a normal distribution, reducing the range ~~is generally~~was used to ~~select~~ find the ~~appropriate~~ optimal range. Figure ~~6~~ 8 shows the calibration results of parameter CI when the different ~~parameter~~ ranges are selected. The MINR (0.679–0.713) and the MAXR (0.623–0.694) were picked out based on the cumulative frequency curve derived from calibrations with the initial range (0–0.900). From the cumulative curves and the histograms in Fig. ~~6a~~8a, ~~6b~~ 8b and ~~6c~~8c, it is found that the probability distribution of parameter CI values is converted from a normal distribution to a uniform distribution when the initial range is reduced to the MINR, whereas the ~~normal~~ probability distribution ~~is changed~~approximates ~~to the~~an exponential one when the ~~range is cut to~~ MAXR is used. Figure ~~6d~~ 8d reveals ~~that~~ the contribution of the parameter range~~s~~ selection to E_{NS}. It is found that the minimum E_{NS} except extreme outliers rises from 0.881 to 0.884 and the E_{NS} concentrates at a higher value range when the MINR is used instead of the initial range.~~It is found that the minimum E_{NS} except extreme outliers rises convincingly and E_{NS} concentrates at larger value zone when MINR is used instead of the initial range.~~ ~~It is indicated that~~Using the reduced range of high probability density is, therefore, helpful to make calibration more ~~steady~~ stable and more~~and~~ efficient.

To an exponential distribution, both reduced ranges and ~~the~~ extended ranges of reasonable meaning ~~can be~~were used to select the ~~appropriate~~ optimal range for parameter calibration. Figure 9~~7~~ shows the calibration results~~ of parameter KI~~ under three different input ranges of parameter KI. Since the initial range of parameter KI cannot be extended, the two reduced ranges (i.e. the MINR (0.660-0.700) and the MAXR (0.522-0.660)) were picked out~~ was searched~~ by using the cumulative frequency curve.~~, the MINR (0.660–0.700) and MAXR (0.522–0.660) were picked out.~~ From the cumulative curves and the histograms in Fig. ~~7a~~9a, ~~7b~~ 9b and ~~7c~~9c, it is found that the probability distribution of parameter KI values is~~ converted from exponential distribution~~ similar to a uniform distribution~~ when the initial range is reduced to~~ in the case of the MINR, whereas~~ the~~ that is still exponential ~~distribution is still kept when the range is cut to~~in the case of the MAXR. The contributions of the three parameter ranges to E_{NS} ~~is~~ are shown in Fig. ~~7d~~9d. Thus, the ~~Similar to the results of parameter CI,~~ MINR is best for calibration of parameter KI when compared with the MAXR or the initial range, which is similar to the calibration result of parameter CI. In general, ~~It is demonstrated that~~ the MINR is better than the MAXR ~~to improve~~for parameter calibration ~~for parameters whose value obeys normal or exponential distribution.~~ because the parameter values that may achieve a higher E_{NS} can be easily picked out from the MINR of higher probability density.~~Because the parameter values in MINR indicate high probability to be pick out to achieve high E_{NS}, vice versa.~~

Figure ~~8~~ 10 shows the calibration results of parameter B whose initial range can be extended.~~ The initial range (B=0.1–0.4) of p~~Parameter B generally ranges from 0.1 to 0.4 ~~is common~~ for most areas, but it is quite different for karst areas where the soil moisture storage varies remarkably with space~~, and~~. A~~a~~s a result, the value of parameter B ~~could~~ can be ~~larger~~ greater than 0.4. From Fig. ~~8a~~ 10a and ~~8b~~10b, it is shown that the probability distribution of parameter B is converted from an exponential distribution to a normal distribution when the initial range is extended to new one (B=0.1–0.6). After the MINR selection ~~is~~ was performed on the initial range and the extended range respectively, the two ranges, i.e. the MINR (B=0.36–0.40) and the extension-MINR (B=0.379–0.488) ~~are~~ were obtained and then used to calibrate parameter B. From Fig. ~~8c~~ 10c and ~~8d~~10d, it is found that the probability distribution of parameter B ~~values is converted into~~ approximates a uniform distribution when the ~~range is reduced from initial range to~~ MINR or the ~~from the extended range to~~ extension-MINR is used. The box-plots ~~chart~~ of E_{NS} for different ranges are shown in Fig. 10~~8~~e. It is shown that there is little improvement in maximum E_{NS} when MINR is used for calibration instead of the initial range. There is an increase of 0.0003 in maximum E_{NS} if the initial range is replaced with the extension range or the extension-MINR. As for minimum E_{NS} (except outliers), an increase of 0.001 in the case of the MINR, a decrease of 0.003 in the case of the extension range and an increase of 0.003 in the case of the extension-MINR are found when the initial range is substituted with the three ranges respectively.~~It is indicated that there is a considerable improvement of both maximum and minimum E_{NS} when extension-MINR is used for calibration.~~ It suggests that an appropriate range extension followed by a MINR selection is helpful to improve calibration for the parameter~~s~~ whose probability distribution is exponential and initial range~~s~~ can be extended.

4.3 Effect of multiple parameters ranges combination on calibration results

The S-PRS method was employed to ~~select~~ determine the ~~one-parameter~~ optimal range for each parameter. ~~,~~ According to ~~and~~ the optimal ranges and the corresponding initial ranges, indexed R_C and S_E ~~values are listed in Table 4~~were quantified to understand parameter correlation and sensitivity. It is obvious from Table 4 that R_C values in the columns of parameters CI and WM are positive, but most R_C values in the column of parameter Im are negative. The negative R_C ~~value between~~related to two parameters ~~indicates~~ means that using the optimal range of one parameter is adverse to ~~calibration of~~calibrate the other. ~~parameter. Specially, b~~ Both $R_{C\ EX,Im}$ and $R_{C\ Im,EX}$ are negative in spite of small values, ~~.~~ ~~It means~~which implies that using the optimal ranges of parameters EX and Im simultaneously is not conductive to calibrate these two~~multi~~ parameters ~~combined calibration~~. The mean of R_C ($R_{C\ mean}$) varies with parameters. Parameter CI has the maximum $R_{C\ mean}$ of 0.465~~, while~~ and parameter Im the minimum $R_{C\ mean}$ of –0.026. Furthermore, ~~$R_{C\ mean}$ values for~~ all parameters ~~are~~have positive $R_{C\ mean}$ values except for ~~that for~~ parameter Im, ~~.~~ ~~It is due~~owing to the accumulative negative ~~influence of~~correlation between parameter Im and the ~~on~~ others.

To coordinate ~~the contradiction between~~with negatively related parameters, the index S_E ~~is~~ was used to pick out parameters of higher sensitivity to E_{NS}. From Table 4, it is found that parameter CI has the maximum S_E of 54.7%~~,~~ and parameter Im the minimum S_E of 0.3%. Most S_E values are more than 20% except those of parameters C, EX and Im. It suggests that parameters ~~CI, B, SM, KI, K_e, WM and CG~~C, EX and Im are of low sensitivity to E_{NS} and the others highly sensitive to E_{NS}.~~are of high sensitive to E_{NS}, and parameters C, EX and Im of low sensitivity for E_{NS}.~~ Parameter CI is the most sensitive ~~parameter~~ while Im the most insensitive ~~parameter~~, which agrees with the work of Lü et al. (2013) and Song et al. (2013). For the well-developed karst areas, the thin layer of soil and strong permeability of limestone make rainfall easy to penetrate into the ground. Moreover, the existence of karst caves and subsurface streams contribute to great interflow storage which accounts for a large proportion of streamflow. As a result, the calibration of parameters KI (representing ~~penetrate ability~~the penetrability of free water to interflow)~~,~~ and ~~parameter~~ CI (representing recession capacity of interflow storage) has a~~have~~ significant influence on rainfall-runoff simulation results. Hence, parameters KI and CI are ~~very~~ highly sensitive in the investigation. Thus, ~~It can be deduced that~~ the optimal ranges of ~~insensitive~~ parameters ~~Im~~of higher sensitivity should be used to~~cannot be taken into account when there is contradiction owing to it, in order to~~ improve calibration.

In order to determine the optimal range combination of multiple parameters, seven cases ~~are~~ were investigated with different range combinations ~~p~~of parameters (Table 5). Case 1 was defined as the initial case using all initial ranges. Cases 2–4 were defined as the single parameter range selection (S-SPR) cases. Cases 5–7 were set as the multiple parameters ranges selections (M-SPR) cases. The ~~results~~ box-plots of E_{NS} for ~~seven~~ different cases are ~~compared~~ given in Fig. ~~9~~11. There is a little decrease in E_{NS} when Case 4 is separately compared with Case 1, Case 2 and Case 3. It can be explained that both $R_{C\ EX,Im}$ and $R_{C\ Im,EX}$ are negative and the combination of the optimal ranges corresponding to the two parameters leads to a worse calibration result. As the S_E value of parameter Im is less than that of parameter EX, parameter EX is given priority to ~~select~~ use the optimal range~~,~~. ~~that~~ It is the reason why the calibration result of Case 3 is better than that of Case 2. As for the cases with the multi-parameter range selection (i.e. Cases 5–7), the E_{NS} values are much greater than those of cases 1-4. There is approximately an increase of 0.001 in maximum E_{NS} and an increase of 0.01 in minimum E_{NS} when the multi-parameter range selection is performed.~~As for the cases of multi-parameter range selection (i.e. Case 5, Case 6 and Case 7), the results are much better than that of Case 1–4.~~ There are some differences in E_{NS} ~~between~~ with the comparison between Cases 5–~~, Case 6 and Case~~ 7 ~~when~~ in a magnified~~their~~ box-plot chart~~s are magnified~~. Case 6 has the most concentrated values of E_{NS} and the largest mean value of E_{NS} among the three cases. It means that the combination of optimal ranges of all parameters (see Case 7) is not the optimum to calibrate a multi-parameter model inasmuch as some parameters like Im have negative correlation on other parameters. Hence, the initial ranges of parameters having negative mean values of R_C and low values of S_E are supposed to be used to calibrate parameters instead of the corresponding optimal ranges. ~~The box and whisker of E_{NS} for Case 6 rise, which means Case 6 has a better performance of calibration than Case 5 does, when the optimal range of parameter CG is included. But the box and whisker of E_{NS} for Case 7 decline when the optimal range of parameter Im is included. Because the mean R_C value of parameter Im is negative and its S_E much less than that of others, using the optimal range of Im is adverse to multi-parameter combined calibration.~~

Through a calibration run, a set of calibrated values of all parameters and the corresponding E_{NS} are obtained. Figure 12 shows the variation curves of maximum and minimum values of E_{NS} with number of runs by using a GA method and a proposed PRS method, respectively. It is indicated from Figure 12 that no mater it is maximum or minimum E_{NS}, the value calculated by using a proposed method is almost the same as that by using a GA method when the number of runs does not exceed 100. If a proposed method is used for calibration instead of a GA method, there are approximately an increase of 0.001 in maximum E_{NS} and an increase of 0.01 in minimum E_{NS} when the number of runs is greater than 100. Thus, for any particular run number, the value of E_{NS} calculated by using a PRS method is not less than that by using a GA method. The application of a proposed method, therefore, contributes to a relatively efficient calibration.

5. Conclusions

Considering that there is ~~the~~ a relation between the ~~parameter~~ selection of multi-parameter ranges and the ~~probability distributions of parameter value~~calibration effect of a hydrological model, an approach to determine ~~the~~ an optimal ~~range~~ combination of ~~for multi parameters~~ ranges for the multi-parameter calibration~~of hydrological models~~ ~~is~~ was put forward by analysing ~~the~~ parameter ~~value~~ probability distribution, parameter sensitivity and ~~parameter~~ correlation between parameters. ~~A case of~~ The newly proposed method was applied for the ~~improving the~~ calibration of ~~the GA-based~~a Xinanjiang model for karst areas ~~is studied~~, and some findings are presented as follows.~~:~~

~~The proposed parameter range selection (PRS) method improves the minimum E_{NS} and the maximum E_{NS}, which makes the results concentrate at high E_{NS}. The PRS-based calibration is, therefore, more efficient and effective.~~ In the Xinanjiang model for karst areas, ~~the~~ parameters CI, Kc, SM and B approximately obey normal probability distributions, and parameters WM, C, EX, KI, CG and Im ~~obey~~ exponential probability distributions after 100 independent calibration runs. For the parameters of a normal distribution, the ~~minimum ranges (~~MINR~~)~~ defined by using a cumulative frequency curve of calibrated values ~~with a given cumulative frequency of the parameter~~ is preferred to be selected as the optimal parameter range for calibration. For the parameters of an exponential distribution, ~~if the parameter range can be extended outside the boundary of high probability,~~ the ~~extension~~ extension-MINR ~~range followed by MINR~~ is recommended to be ~~selected~~used for calibration if the initial range can be extended towards the high-probability side, otherwise the MINR ~~of the initial range~~ is selected as the optimal range for calibration.

The proposed parameter range selection (PRS) method improves the minimum and mean values of E_{NS}. The application of the proposed methodology results in an increase of 0.01 in minimum E_{NS}, compared with that of the pure GA method. The rising of minimum E_{NS} with little change of the maximum may shrink the range of the possible solutions. As a result, the uncertainty of the model performance can be effectively controlled.

The M-SPR method is superior to the S-SPR one for calibrating hydrologic models with multiple parameters. The R_C and S_E are two important indexes that can help to analyse the sensitivity and correlation between parameters and consequently to coordinate with the negatively related parameters. The initial ranges of parameters of relatively low S_E and negative $R_{C\ mean}$ and the optimal ranges of parameters of positive $R_{C\ mean}$ should be preferred to be chosen for the multi-parameter model calibration.

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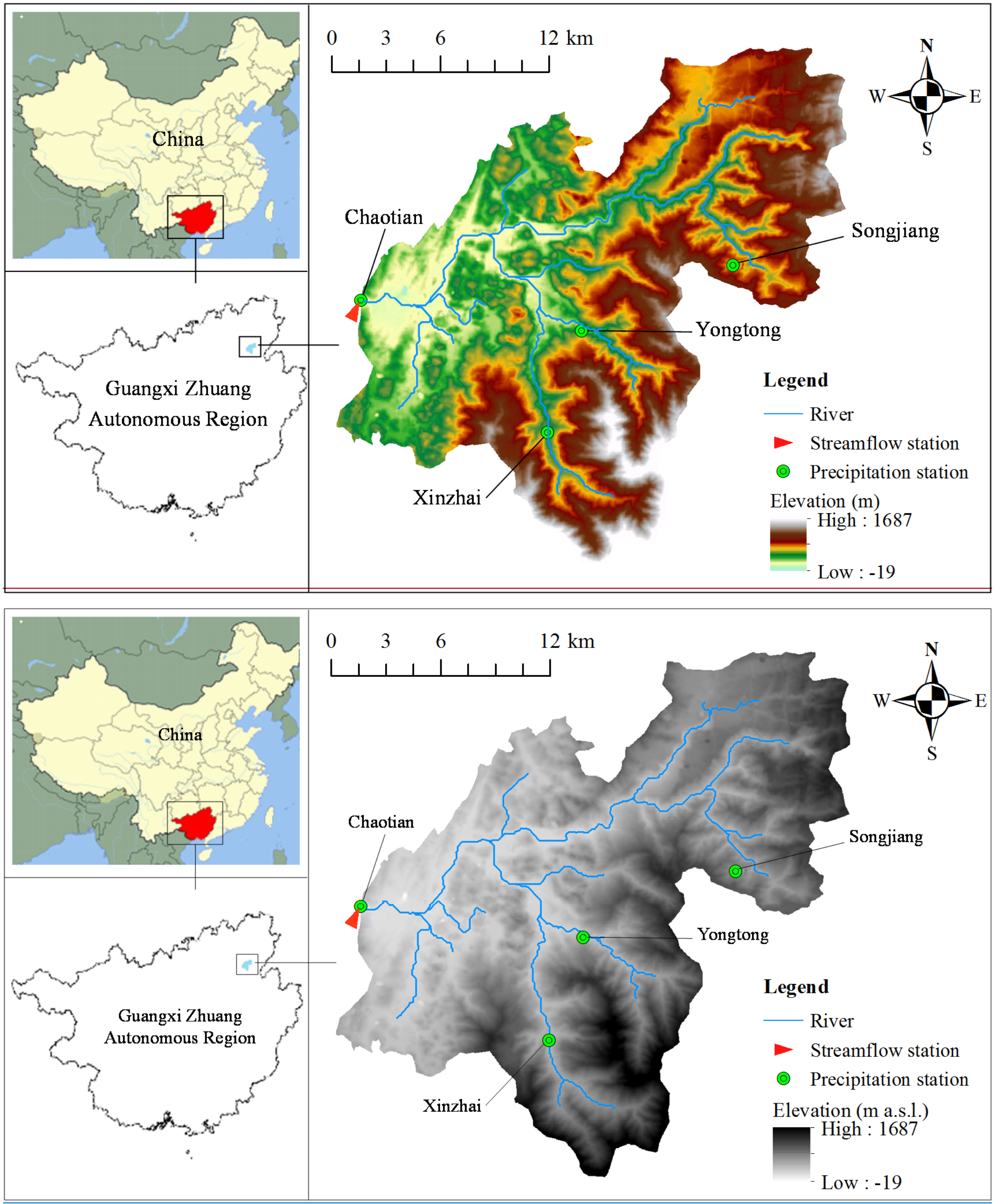


Fig. 1. Location of the study area

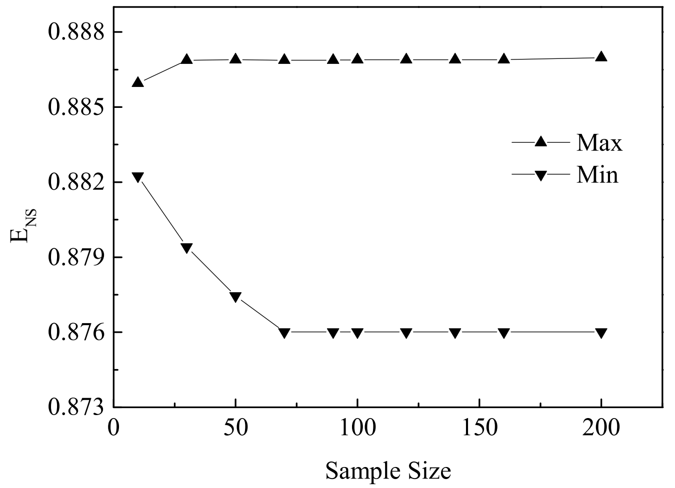


Fig. 2. Variation curves of maximum and minimum E_{NS} with sample sizes

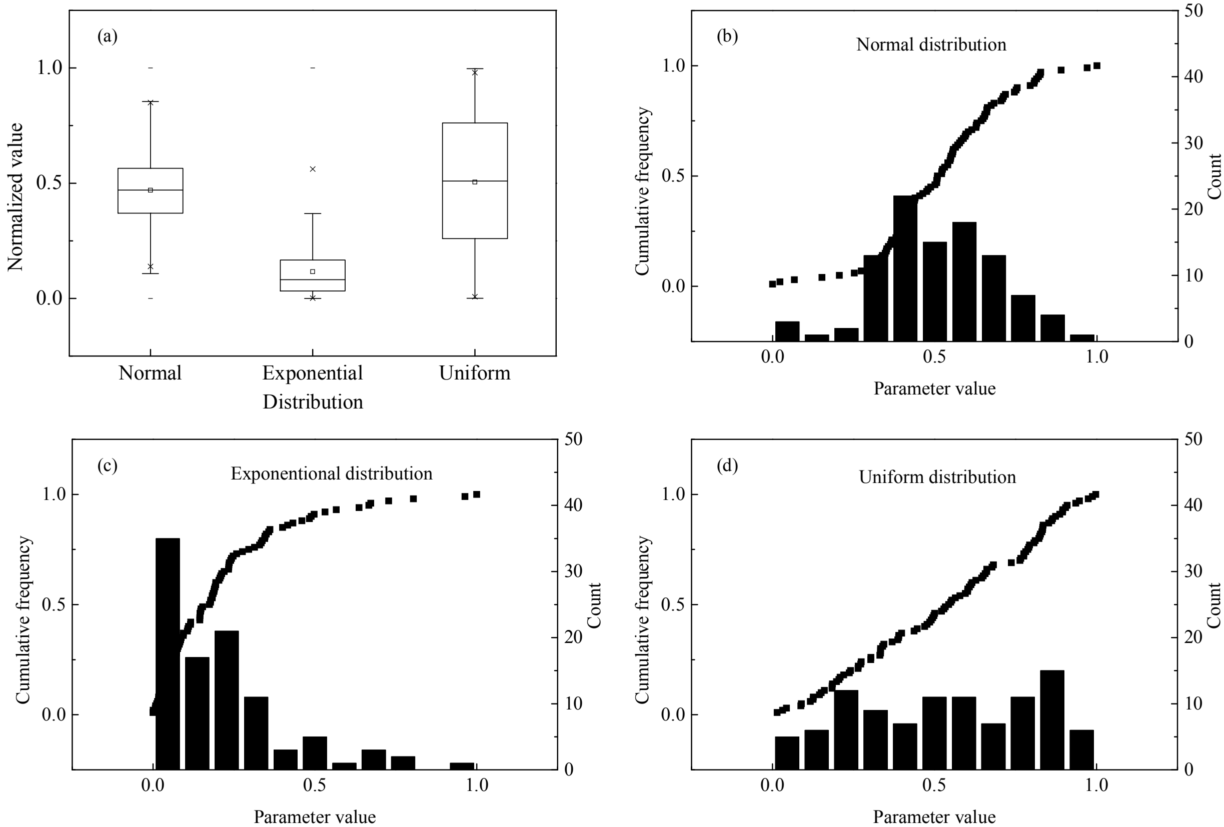


Fig. 23. Different probability distribution types of calibrated parameter values

(a) Box-plot charts of normal, exponential and uniform distribution;

Cumulative frequency curve and histogram for normal (b), exponential (c) and uniform (d) distributions

(a) Box-plot charts of normal, exponential and uniform distribution (b) Cumulative frequency cure and histogram of normal distribution (c) Cumulative frequency cure and histogram of exponential distribution (d) Cumulative frequency cure and histogram of uniform distribution

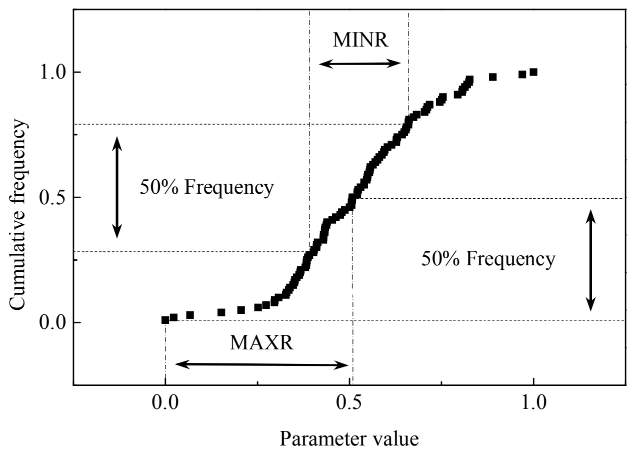


Fig. ~~3~~4. Selection of minimum and maximum range (MINR and MAXR) with a cumulative frequency of 50%

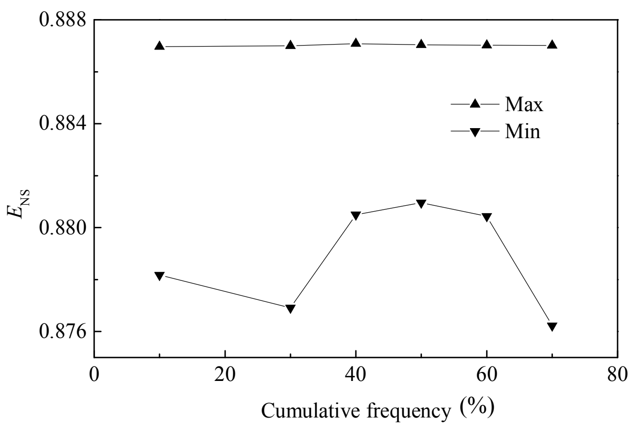


Fig. 5. Variation curves of maximum and minimum E_{NS} of a single parameter with cumulative frequency values

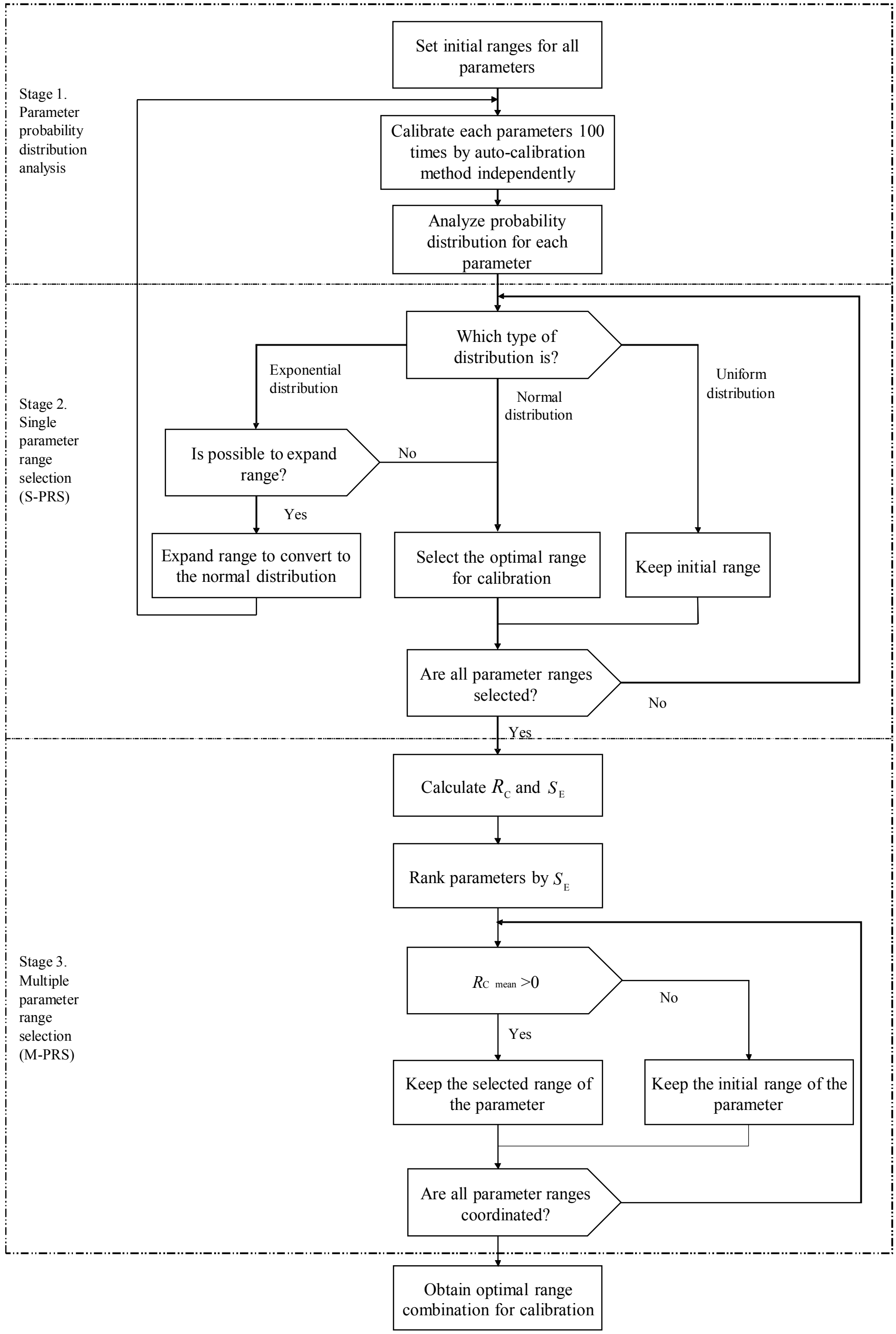
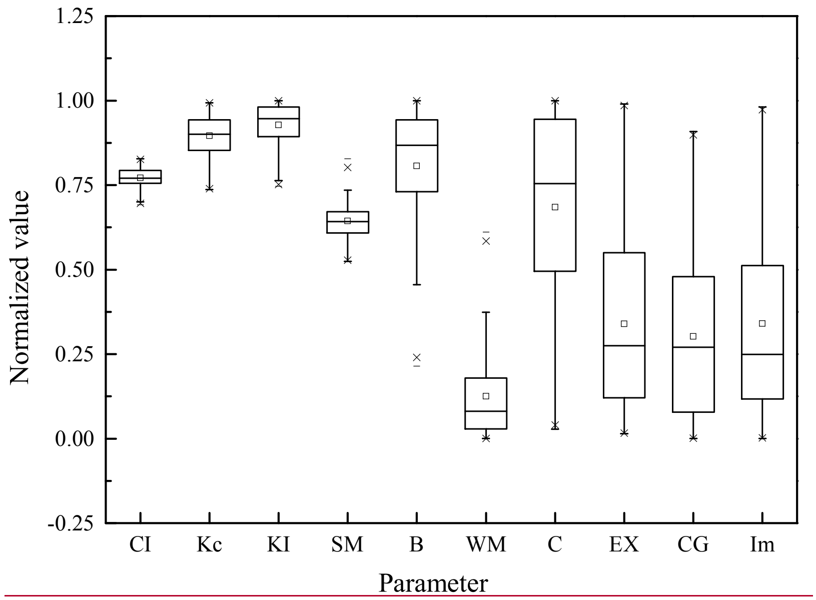


Fig. ~~4~~6. The ~~F~~flow chart of multiple parameters ranges selections



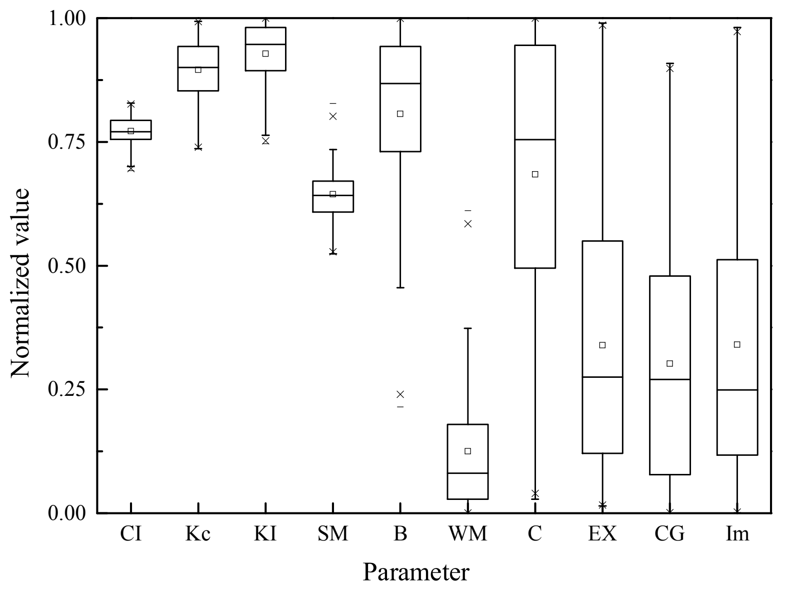


Fig. ~~5~~7. The box-plot chart of normalized calibrated values for parameters of Xinanjiang model

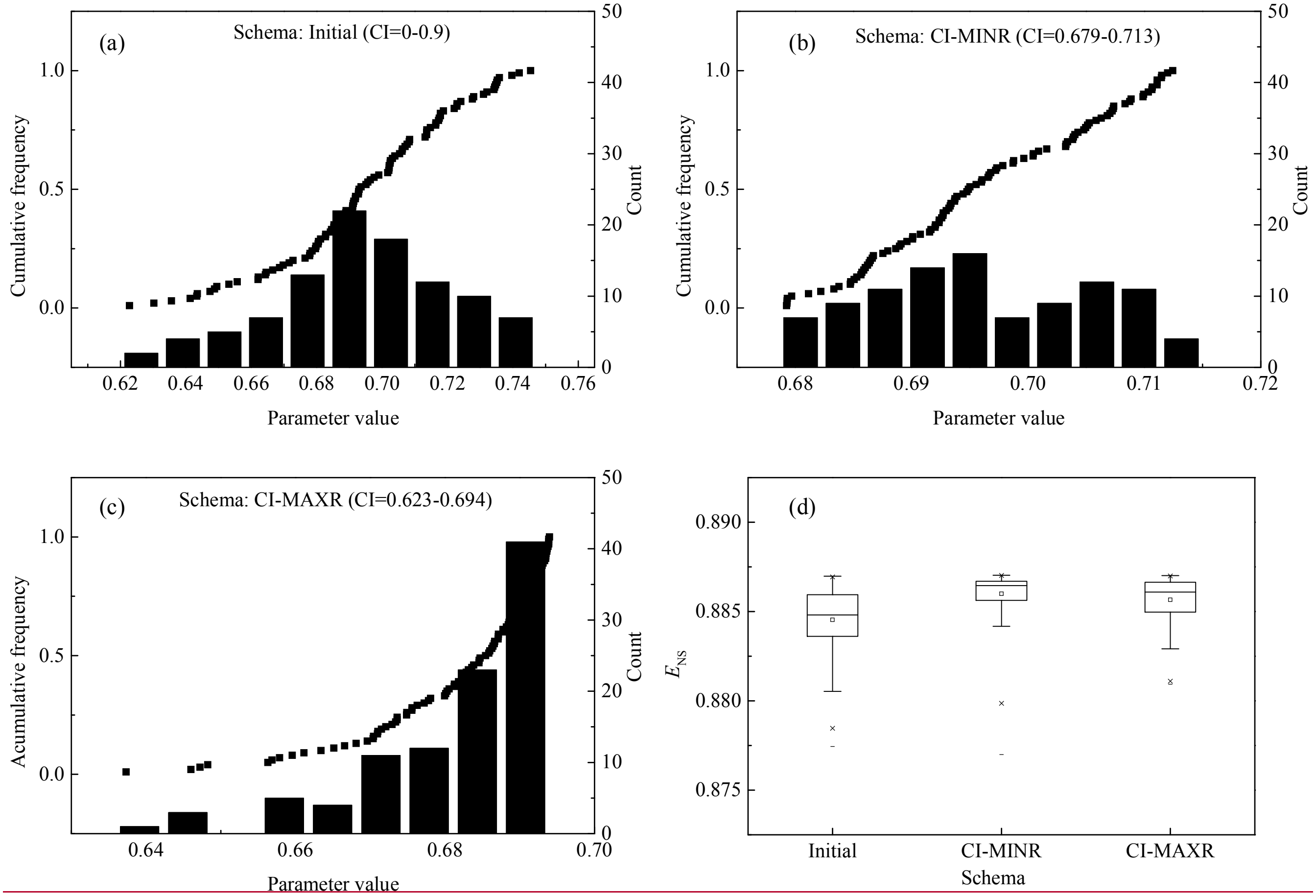


Fig. 6. Results of range selection of parameter CI

(a) probability distribution of parameter values for schema initial range (b) probability distribution of parameter value for schema CI-MINR (c) probability distribution of parameter values for schema CI-MAXR (d) box-plot chart of E_{NS} for three schemas

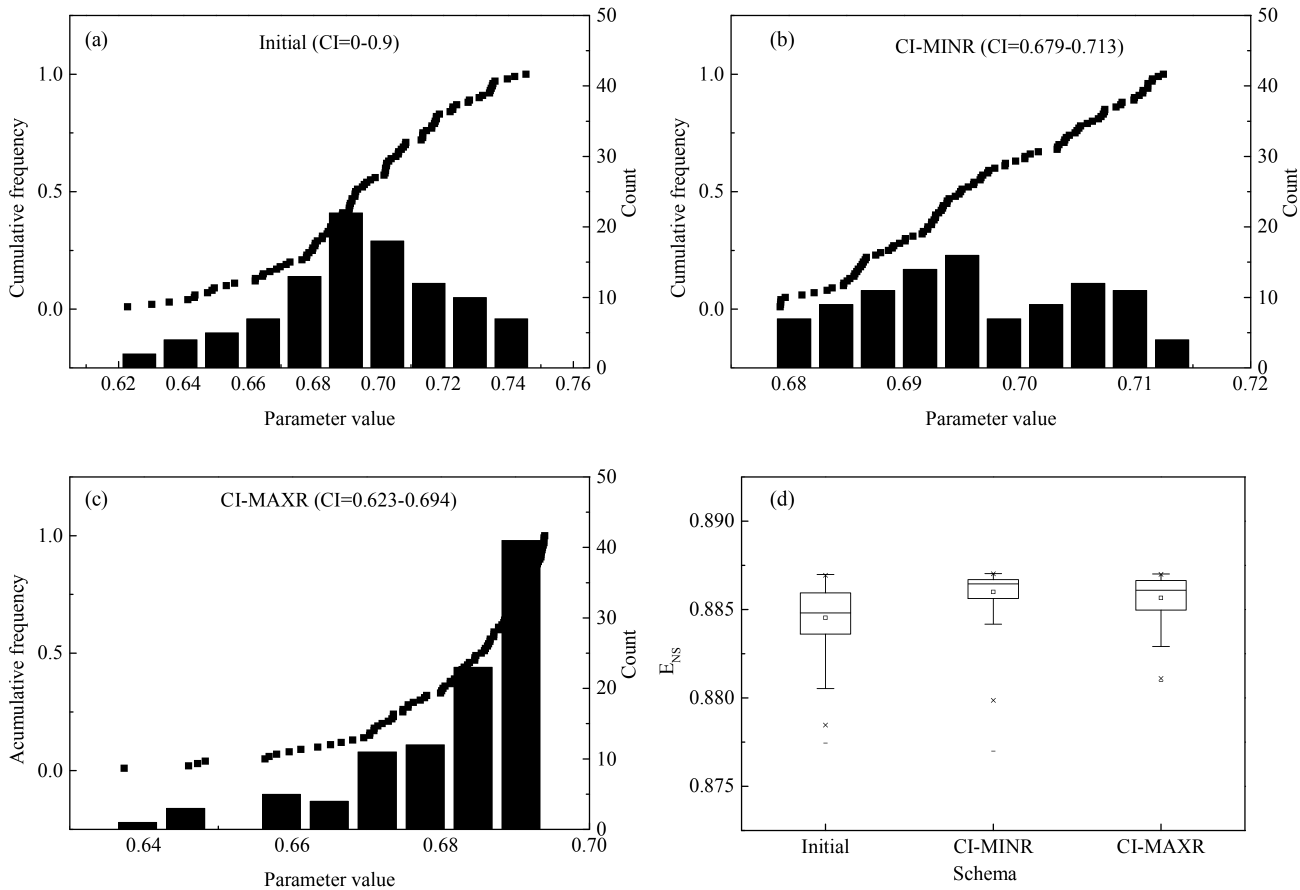
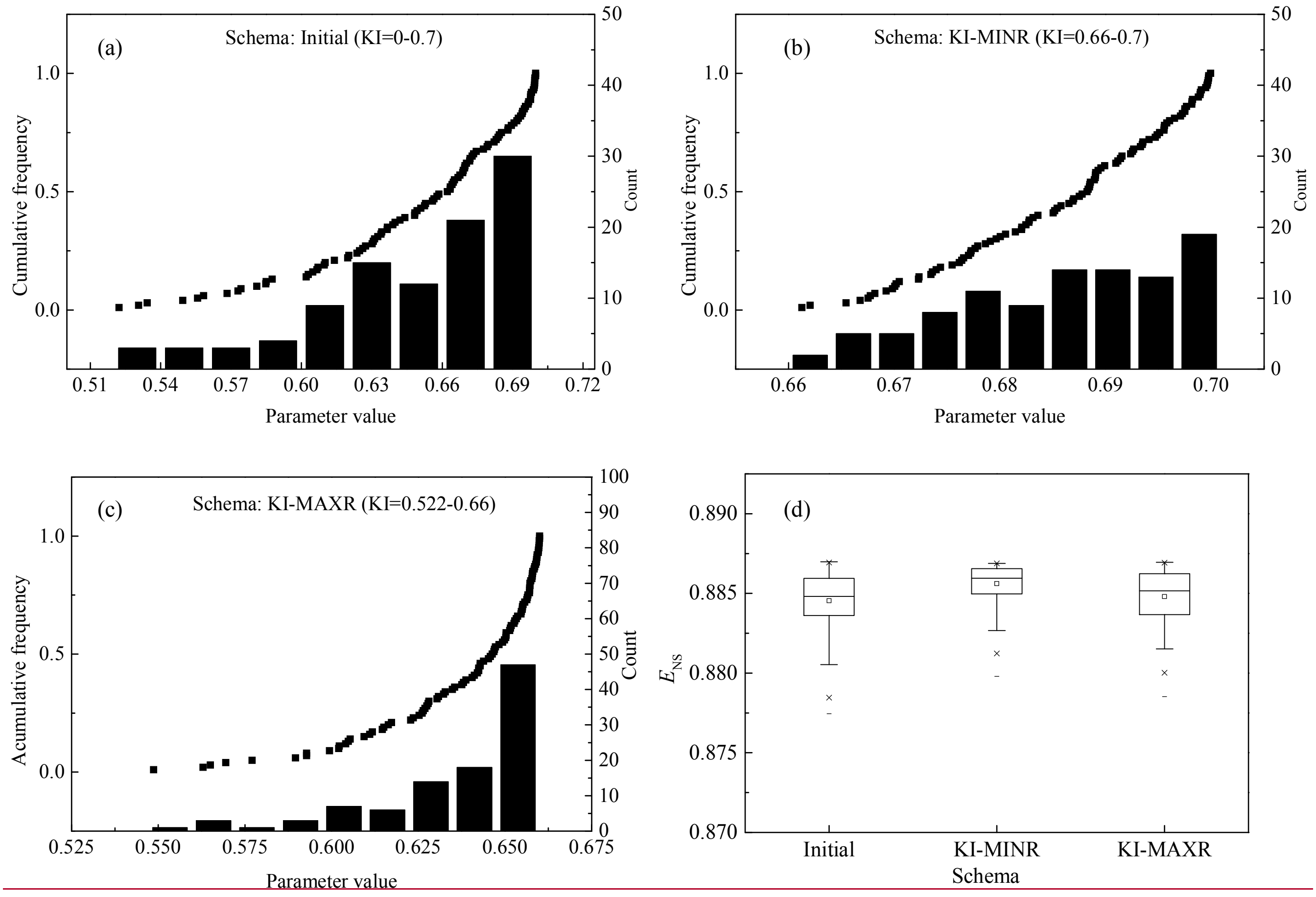


Fig. 8. Results of range selection of parameter CI

Probability distribution of parameter values for schema initial range (a), CI-MINR (b) and CI-MAXR (c);

(d) Box-plot chart of E_{NS} for three schemas



~~Fig. 7. Results of range selection of parameter KI~~

~~(a) probability distribution of parameter values for schema initial range (b) probability distribution of parameter values for schema KI-MINR (c) probability distribution of parameter values for schema KI-MAXR (d) box-plot chart of E_{NS} for three schemas~~

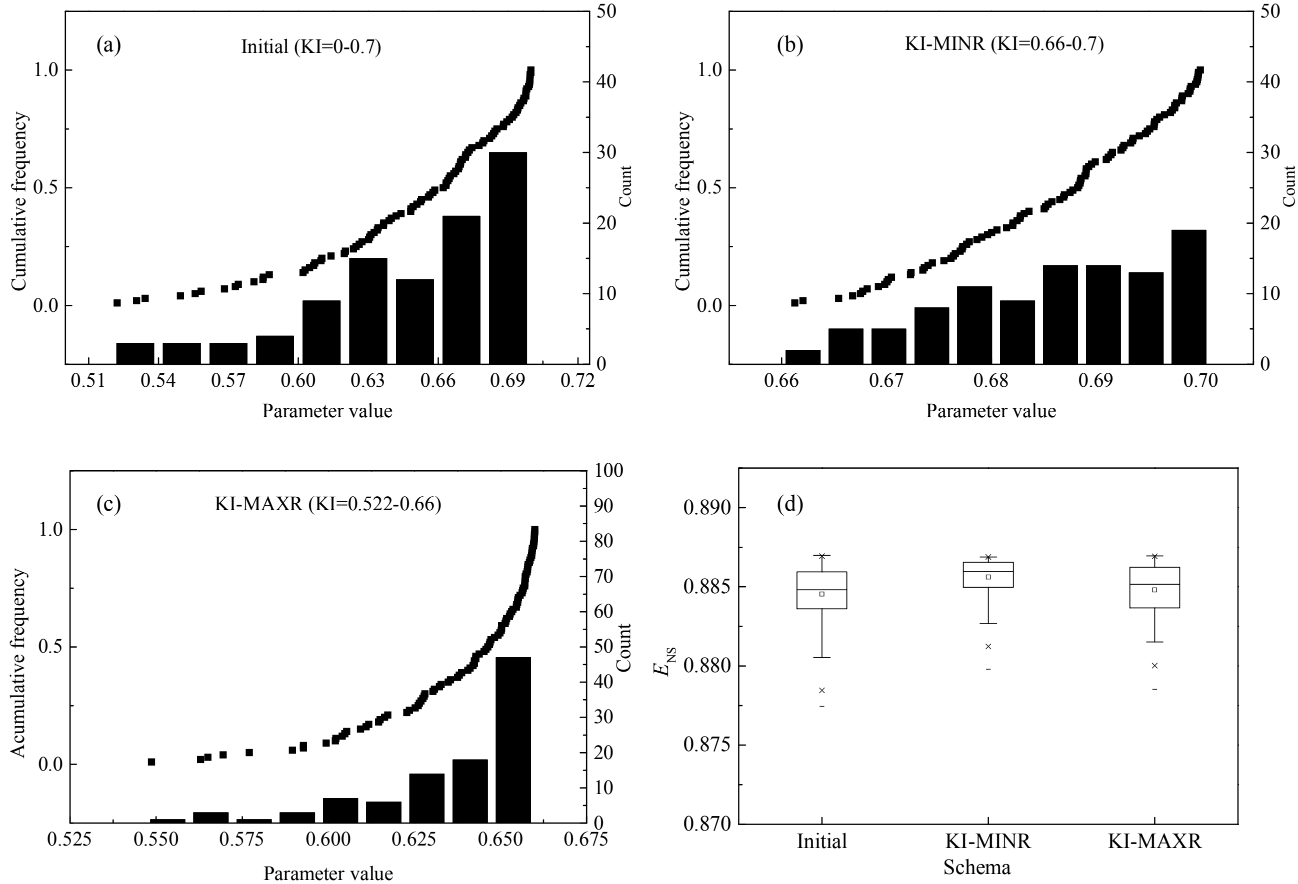
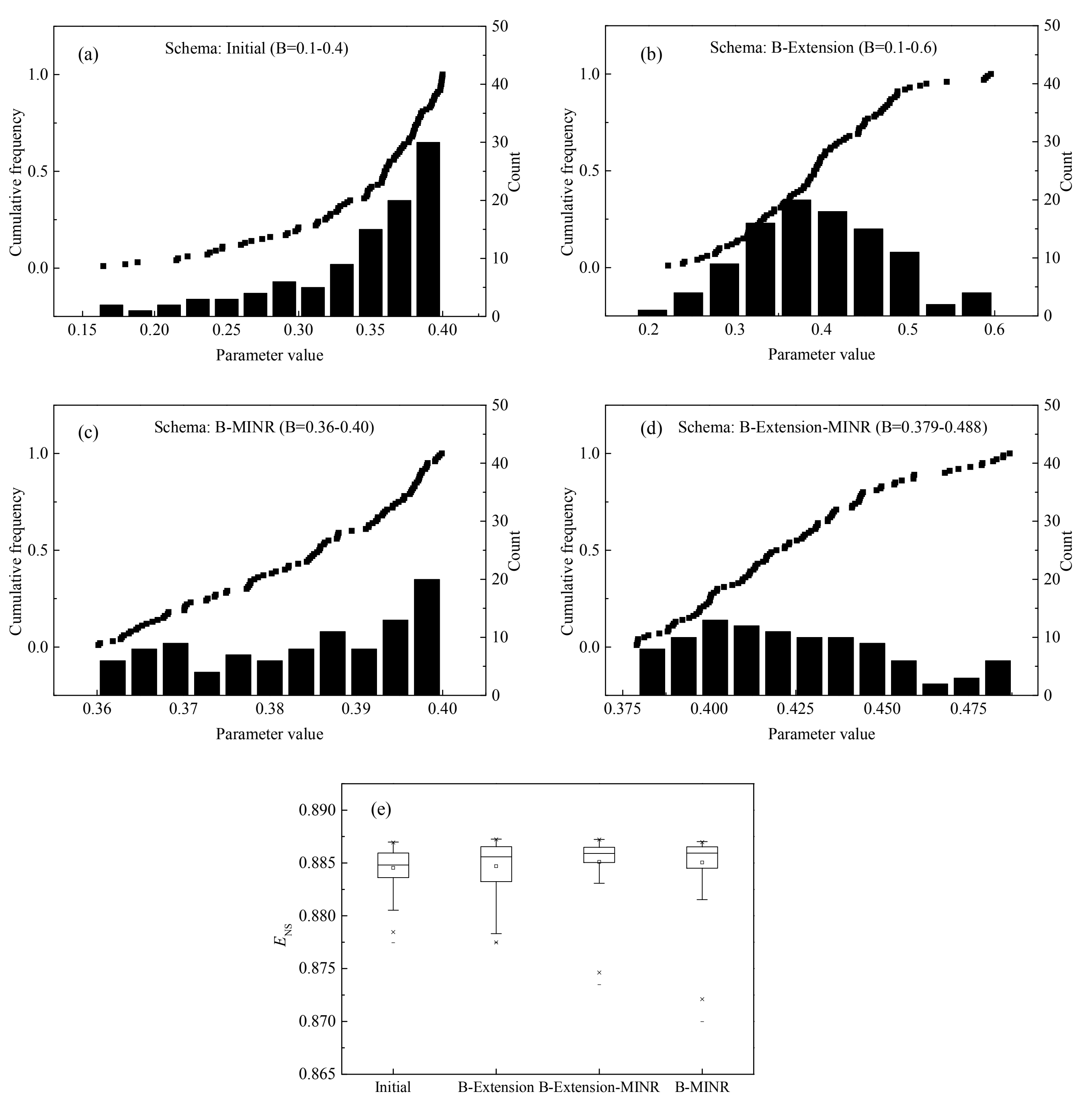


Fig. 9. Results of range selection of parameter KI

Probability distribution of parameter values for schema initial range (a), KI-MINR (b) and KI-MAXR (c);

(d) Box-plot chart of E_{NS} for three schemas



~~Fig. 8. Results of range selection of parameter B~~

~~(a) probability distribution for schema initial range (b) probability distribution for schema B- Extension (c) probability distribution for schema B- MINR (d) probability distribution for schema B- Extension- MINR (e) box- plot chart of E_{NS} for four schemas~~

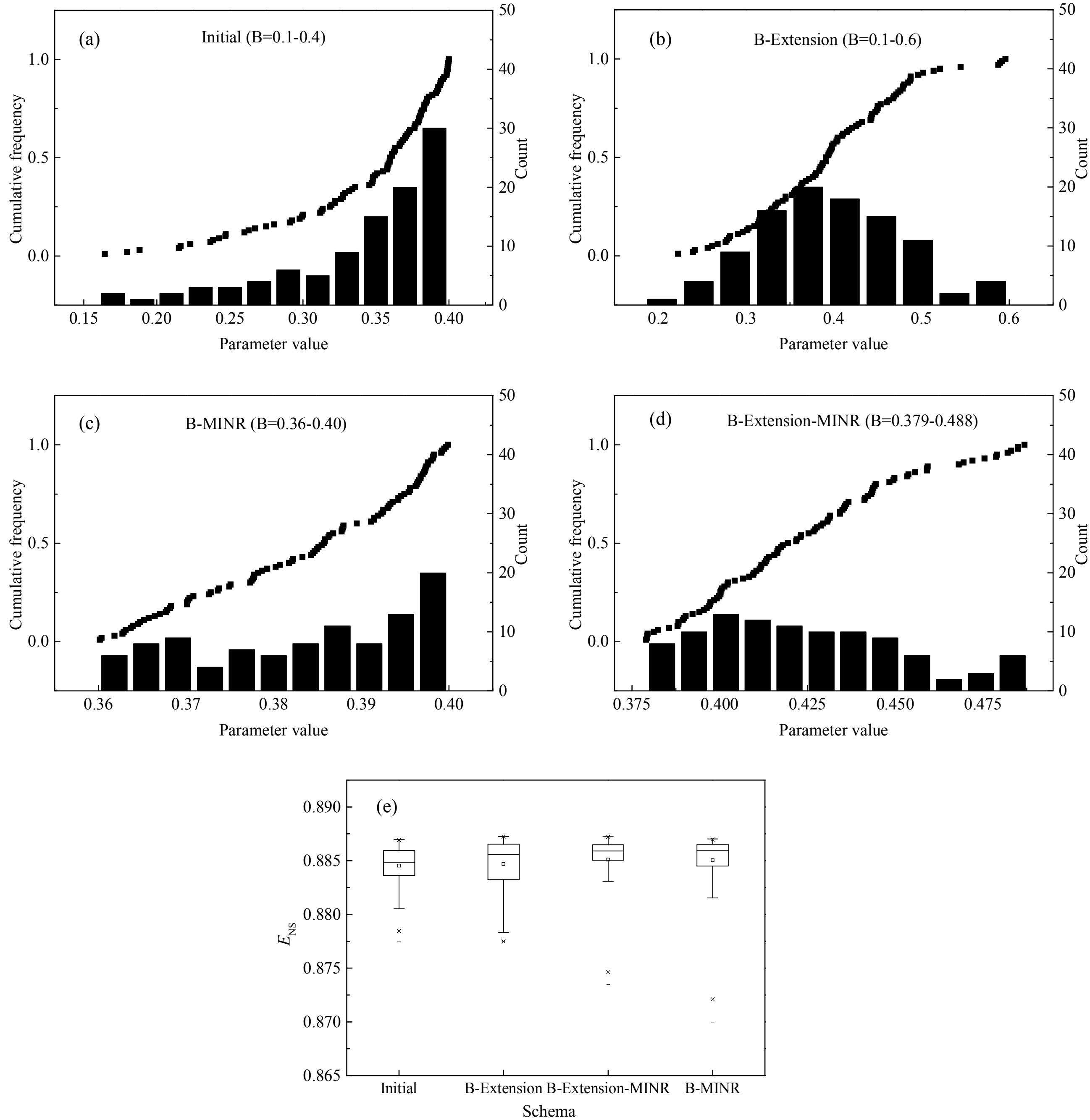


Fig. 10. Results of range selection of parameter B

Probability distribution for schema initial range (a), B–Extension (b), B–MINR (c) and B–Extension–MINR (d); (e) Box–plot chart of E_{NS} for four schemas

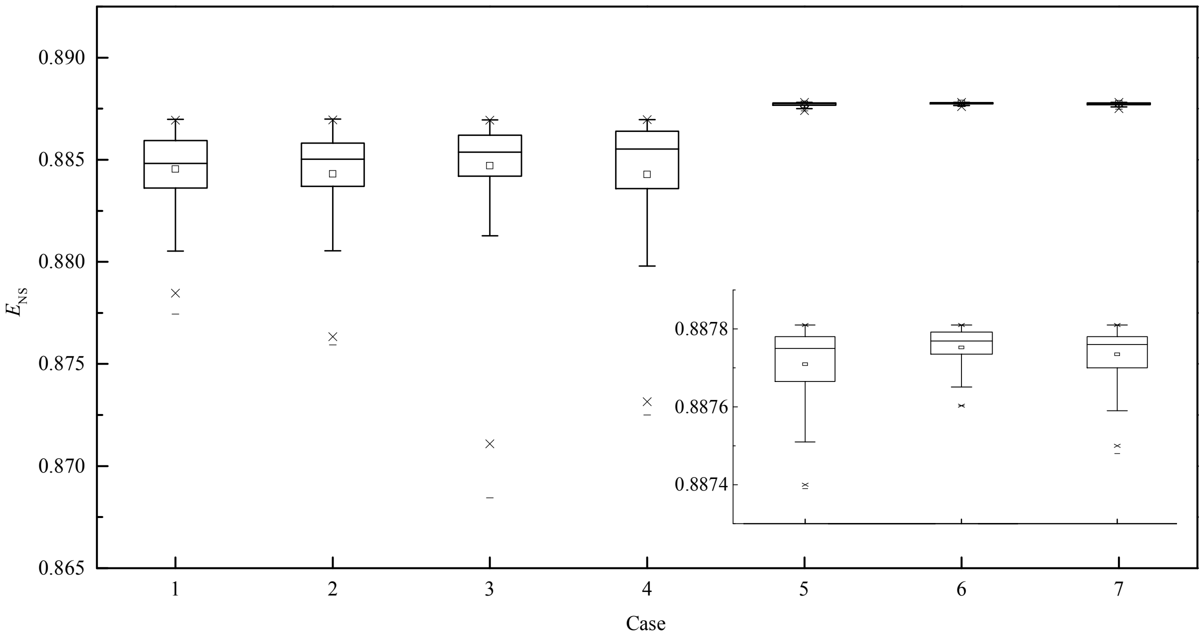


Fig. ~~9~~11. The ~~B~~box–plot chart of E_{NS} for different cases

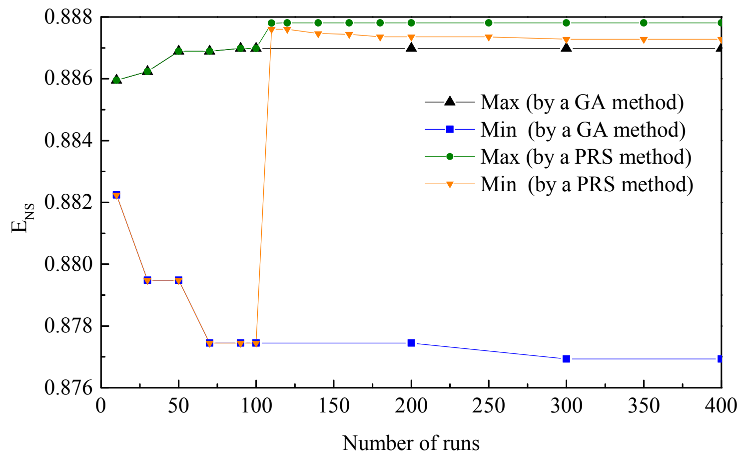


Figure 12. The variation curves of maximum and minimum E_{NS} with number of runs by using a GA method and a proposed PRS method

Table 1. Metro-hydrological statistical data of the study area

Year	Q_{Max} （m^3/s）	Q_{Min}（m^3/s）	Q_{Avg}（m^3/s）	P_{Max}（mm/d）
1996	719	0.76	14.38	235
1997	308	0.76	14.32	155
1998	369	0.66	13.67	157
1999	282	0.53	12.81	144
2000	339	1.14	11.37	107

Q_{Max}, Q_{Min} and Q_{Avg} mean the maximum, minimum and average value of daily streamflow, respectively, and P_{Max} means the maximum value of daily precipitation. ~~*Q* means streamflow and *P* means average precipitation.~~

~~Table 2. Parameters of Xinanjiang model~~

~~Parameter~~	~~Definition~~	~~Range~~
~~Kc~~	~~Ratio of potential evapotranspiration to pan evaporation~~	~~0–1.1~~
~~C~~	~~Coefficient of the deep layer, that depends on the proportion of the basin area covered by vegetation with deep roots~~	~~0.1–0.2~~
~~WM~~	~~Averaged soil moisture storage capacity of the whole layer~~	~~120–200 (mm)~~
~~B~~	~~Exponential parameter with a single parabolic curve, which represents the non-uniformity of the spatial~~	~~0.1–0.4~~
~~Im~~	~~Percentage of impervious and saturated areas in the catchment~~	~~0.01–0.04~~
~~SM~~	~~Areal mean free water capacity of the surface soil layer, which represents the maximum possible deficit of free water storage~~	~~10–50 (mm)~~
~~EX~~	~~Exponent of the free water capacity curve influencing the development of the saturated area~~	~~1.0–1.5~~
~~KI~~	~~Outflow coefficients of the free water storage to interflow~~	~~0–0.7~~
~~KG~~	~~relationships Outflow coefficients of the free water storage to groundwater relationships~~	~~KG+KI=0.7~~
~~CG~~	~~Recession constants of the groundwater storage~~	~~0.950–0.998~~
~~CI~~	~~Recession constants of the lower interflow storage~~	~~0–0.9~~

Table 2. Parameters of Xinanjiang model

Parameter	Definition	Units
CI	Recession constants of the lower interflow storage	dimensionless
Kc	Ratio of potential evapotranspiration to pan evaporation	dimensionless
KI	Outflow coefficients of the free water storage to interflow	dimensionless
SM	Areal mean free water capacity of the surface soil layer, which represents the maximum possible deficit of free water storage	mm
B	Exponential parameter with a single parabolic curve, which represents the non-uniformity of the spatial	dimensionless
WM	Averaged soil moisture storage capacity of the whole layer	mm
C	Coefficient of the deep layer, that depends on the proportion of the basin area covered by vegetation with deep roots	dimensionless
EX	Exponent of the free water capacity curve influencing the development of the saturated area	dimensionless
CG	Recession constants of the groundwater storage relationships	dimensionless
KG*	Outflow coefficients of the free water storage to groundwater relationships	dimensionless
Im	Percentage of impervious and saturated areas in the catchment	dimensionless

* the value of KG is calculated by the function 0.7-KI

~~Table 3. Range changes of parameters in schema Initial~~

Parameter	Initial parameter range	Calibrated parameter range*	Ratio** (%)
CI	0–0.9	0.630–0.745	12.78
Kc	0–1.1	0.81–1.09	25.45
KI	0–0.7	0.534–0.7	23.71
SM	10–50	31–39.4	21.00
B	0.1–0.4	0.238–0.4	54.00
WM	120–200	120–150	37.50
C	0.1–0.2	0.1–0.2	100.00
EX	1.0–1.5	1.0–1.5	100.00
CG	0.950–0.998	0.950–0.994	91.67
Im	0.01–0.04	0.01–0.04	100.00

~~* the calibrated parameter range except the extreme outlier~~

~~** the ratio is the ratio of calibrated parameter range to initial parametere range~~

Table 3. Range changes and K-S tests (α=0.2) of parameters in schema Initial

Parameter	Initial range	Calibrated range*	Ratio** (%)	Δ_{Max}***		
				Normal distribution	Expoential distribution	Uniform distribution
CI	0–0.9	0.630–0.745	12.78	0.062 (pass)	0.328 (fail)	0.115 (fail)
Kc	0–1.1	0.81–1.09	25.45	0.076 (pass)	0.305 (fail)	0.089 (pass)
KI	0–0.7	0.534–0.7	23.71	0.128 (fail)	0.076 (pass)	0.173 (fail)
SM	10–50	31–39.4	21.00	0.060 (pass)	0.304 (fail)	0.110 (fail)
B	0.1–0.4	0.238–0.4	54.00	0.180 (fail)	0.062 (pass)	0.203 (fail)
WM	120–200	120–150	37.50	0.181 (fail)	0.072 (pass)	0.231 (fail)
C	0.1–0.2	0.1–0.2	100.00	0.163 (fail)	0.082 (pass)	0.217 (fail)
EX	1.0–1.5	1.0–1.5	100.00	0.118 (fail)	0.079 (pass)	0.135 (fail)
CG	0.950–0.998	0.950–0.994	91.67	0.123 (fail)	0.102 (pass)	0.139 (fail)
Im	0.01–0.04	0.01–0.04	100.00	0.134 (fail)	0.076 (pass)	0.148 (fail)

* the calibrated parameter range except the extreme outlier

** the ratio is calculated by dividing the length of the range derived from 100 GA calibration runs by the initial range length

*** the Δ_{Max} is calculated by using the normalnized parameter values

Table 4. The indexed R_C and S_E of parameters when the optimal range ~~for~~ of ~~single~~ each parameter is ~~performed~~ used for calibration

Parameter*		CI	Kc	KI	SM	B	WM	C	EX	CG	Im
Optimal range of a single parameter		0.679–0.713	0.95–1.05	0.66–0.7	35–39	0.379–0.488	105–110	0.175–0.2	1–1.118	0.95–0.966	0.01–0.0245
R_C	CI	1.000	0.334	0.371	0.462	0.322	0.113	0.105	0.115	–0.128	0.272
	Kc	0.689	1.000	0.467	0.429	0.504	0.503	0.389	0.102	0.284	0.150
	KI	0.778	0.315	1.000	0.445	0.574	0.268	0.456	0.328	0.060	0.258
	SM	0.508	–0.199	0.422	1.000	–0.089	0.009	–0.063	0.383	0.218	–0.032
	B	0.914	0.560	0.698	–0.017	1.000	0.972	–0.175	0.007	–0.319	–0.722
	WM	0.575	0.311	0.439	0.553	0.325	1.000	0.229	0.360	–0.069	–0.235
	C	0.208	0.273	0.083	0.151	0.277	0.335	1.000	0.077	0.200	0.210
	EX	0.054	0.047	–0.011	0.018	0.371	0.045	0.009	1.000	–0.021	–0.025
	CG	0.221	0.246	–0.135	0.022	0.010	0.198	–0.034	–0.009	1.000	–0.112
	Im	0.238	0.073	–0.025	0.045	0.031	0.030	–0.026	–0.020	0.001	1.000
Mean of R_C		0.465	0.218	0.257	0.234	0.258	0.275	0.099	0.149	0.025	–0.026
S_E (%)		54.7	47.9	36.6	41.7	48.1	39.9	10.8	14.7	21.9	0.3

* The parameter represents ~~the~~ parameter X in Eq. 2.

~~Table 5. Parameter ranges setting for different cases~~

~~Case~~	~~Range setting of parameter~~									
	~~WM~~	~~C~~	~~B~~	~~SM~~	~~EX~~	~~KI~~	~~CI~~	~~CG~~	~~Kc~~	~~Im~~
~~1~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~
~~2~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~	~~O~~
~~3~~	~~I~~	~~I~~	~~I~~	~~I~~	~~O~~	~~I~~	~~I~~	~~I~~	~~I~~	~~I~~
~~4~~	~~I~~	~~I~~	~~I~~	~~I~~	~~O~~	~~I~~	~~I~~	~~I~~	~~I~~	~~O~~
~~5~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~I~~	~~O~~	~~I~~
~~6~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~I~~
~~7~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~	~~O~~

~~The symbol ‘I’ represents the initial range of the parameter in Table 3, and ‘O’ the optimal range of the parameter in Table 4.~~

Table 5. Parameter ranges setting for different cases

Case	Range setting of parameter									
	CI	Kc	KI	SM	B	WM	C	EX	CG	Im
1	I	I	I	I	I	I	I	I	I	I
2	I	I	I	I	I	I	I	I	I	O
3	I	I	I	I	I	I	I	O	I	I
4	I	I	I	I	I	I	I	O	I	O
5	O	O	O	O	O	O	O	O	I	I
6	O	O	O	O	O	O	O	O	O	I
7	O	O	O	O	O	O	O	O	O	O

The symbol ‘I’ represents the initial range of the parameter in Table 3, and ‘O’ the optimal range of the parameter in Table 4.