Application of SCE-UA Method for Calibrating the Xinanjiang Watershed Model*

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Abstract The difficulties involved in manually calibrating the Xinanjiang watershed model have, in the past been partly attributable to the lack of robust optimization tools. In fact manual calibration process can be a rather frustrating and time-consuming exercise for an inexperienced person. Therefore, in recent years, researchers are exploring ways to incorporate "expert knowledge" of conceptual watershed models into the automatic calibration procedures. This paper presents a brief introduction to the Xinanjiang model and a research work on application of SCE-UA method for calibrating Xinanjiang watershed model using hydrological data of three catchments of different size and climatic conditions. Results show that the overall performance of SCE-UA method for calibrating the Xinanjiang model is very good. On the basis of the results derived from the calibration and verification stages, it seems that SCE-UA is capable of finding a global optimum and conceptually realistic parameter set for the Xinanjiang model.

Key Words Xinanjiang model, conceptual watershed models, model calibration, global optimization, shuffle complex evolution method

The Xinanjiang hydrological model is a conceptual watershed model with distributed parameters developed in 1973 by Prof. R. J. Zhao and other experts of Hohai University. It has been applied to large basins in the humid and semihumid regions of China for daily rainfall runoff and rainstorm flood forecasting. Use of the model has also spread to other fields of application such as water resources estimation, design flood and field drainage, water project programming, hydrological station planning, water quality accounting etc.

The model consists of sixteen parameters that have to be calibrated. Usually the model is calibrated manually. The manual calibration requires detailed understanding of the model, which can only be obtained through many years of calibration experience. With training and good deal of experience, it is possible to obtain very good model calibrations using the manual approach. But, for the inexperienced and untrained persons, manual calibration can be a rather frustrating and time-consuming exercise. This is mainly because the logic by which the parameters should be adjusted to improve the match is difficult to determine. The main weakness of manual calibration is that the absence of generally accepted objective measures of comparison makes it difficult to know when the process should be terminated. Therefore, it is very essential to explore ways to incorporate "expert knowledge" of calibrating Xinanjiang model into the automatic calibration proce-

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dures.

In this research, SCE-UA (Shuffle Complex Evolution) method, developed at the University of Arizona in 1992[1], has been applied to calibrate the Xinanjiang model. This method is based on a synthesis of the best features from several existing methods, including the Genetic Algorithm and Nelder and Mead[2] Simplex downhill search scheme, and introduces the new concept of complex shuffling. According to the literature, SCE-UA method is not problem specific and it is easy to handle. The method was designed specially for the purpose of dealing with the peculiar problems encountered in conceptual watershed model calibration[3,4]. But it can generally be used for nonlinear optimization problems effectively as well. SCE-UA method is capable of handling high parameter dimensionality and it does not rely on the availability of an explicit expression for the objective function or the derivatives. The method has been used in various fields for optimization and reported exact results. Duan et al.[4] indicate that SCE-UA method is both effective and efficient, compared with other existing global optimization methods, including the ARS (Adaptive Random Search) method and the Multi Start Simplex method (MSX).

In this paper, the structure of the SCE-UA algorithm is not discussed in detail. A detailed description of the method can be found in the literature[3].

1 Structure of the Xinanjiang Model

The main feature of the model is the concept of runoff formation on repletion of storage, which means that runoff is not produced until the soil moisture content of the aeration zone reaches the field capacity, and thereafter runoff equals the rain fall excess without further loss. By the definition, field moisture capacity cannot become a runoff component and it can only be depleted by evaporation or transpiration of vegetation. This fact leads the evapotranspiration to become the controlling factor for producing soil moisture deficiency. It is true, that in humid regions, the soil moisture can often reach field capacity within the entire soil cover. Therefore the replenishment in the next period of rainfall will be equal to the evaporation in the intervening period. However, before producing runoff, the rainfall should satisfy the deficiency below field capacity, which in turn is caused by the evaporation since field capacity last occurred. Then the subsequent rainfall will all become runoff since the soil has no more capability to hold water. Basically, the whole basin is divided into a set of sub-basins. The outflow from each sub-basin is first simulated and then routed down through channels to the main basin outlet.

According to the model structure, runoff was separated to three components as surface runoff, inter flow and ground water flow. Based on the concept of runoff formation on the repletion of storage, the simulation of outflow from each sub-basin is considered of four major parts.

(1) The evapotranspiration, which generates the deficit of the soil storage, which is divided into three layers: upper, lower and deeper.

(2) The runoff production, which produces the runoff according to the rainfall and soil storage deficit.

(3) The runoff separation, which divides the above so determined runoff into three components: surface, subsurface and groundwater.

(4) The flow routing, which transfers the local runoff to the outlet of each sub-basin forming the outflow of the sub-basin.

Normally, the soil moisture deficit often varies from place to place. To provide a non-uniform distribution of tension water capacity throughout the basin, a tension water capacity curve has been introduced in Xinanjiang model.

The inputs to the model are areal mean rainfall (P) and measured pan evaporation (EM). The outputs are the discharge from the whole basin (TQ), the actual evapotranspiration (E) which includes the three components from upper (EU), lower (EL), and deeper (ED) layers. The state variables are the areal mean free water storage (S) and the areal mean tension water storage (W), which is having three components WU, WL, and WD in the upper, lower and deeper layers respectively. RB is the direct runoff from impervious area and FR is the runoff contributing area factor, which is related to W. The runoff produced from pervious area (R) is divided into three components RS, RI and RG referred to as surface runoff, interflow and groundwater flow respectively. The three components are further transferred into QS, QI and QG and together form the total inflow to the channel network of the sub-basin.

There are 16 parameters in Xinanjiang model, including muskingum parameters. These parameters are classified in the following way:

(1)Evapotranspiration para: K, the ratio of potential evapotranspiration to the pan evaporation; WUM, the tension water capacity of upper layer; WLM, the tension water capacity of lower layer; C, the evapotranspiration coefficient of deeper layer.

(2)Runoff production para: WM, the areal mean tension water capacity, B, the exponential of the distribution of tension water capacity; IM, the ratio of impervious area to the total area of the basin.

(3)Runoff separation para: SM, the free water storage capacity; EX, the exponential of distribution water capacity; KG, the out flow coefficient of free water storage to the ground water flow; KI, the out flow coefficient of free water storage to the inter flow.

(4)Runoff concentration para: CG, the recession constant of ground water storage; CI, the recession constant of lower interflow storage; CS, the recession constant of channel network storage.

(5)Muskingum parameters: XE, Muskingum coefficient; KE, the residence time of water.

A detailed description of the model is available in the literature[5].

2 Application of SCE-UA Method

The SCE-UA algorithm contains many parameters that control the probabilistic and deterministic components of the method. These parameters should be carefully selected for the optimal performance of the algorithm. Actually, the optimum values of these parameters depend on the

type of the problem. But practically observed that the following values can be generally used as default: $m=(2n+1)$; $q=(n+1)$; $y=1$, $z=(2n+1)$.
Where m, the number of points in a complex; q, the number of points in a sub complex; p, the number of complexes; y, the number of consecutive offspring generated by each sub complex; z, the number of evolution steps taken by each complex and n, the number of parameters to be optimized on. Hence, the only variable to be specified by the user is the number of complexes p. Theoretically m can be any value greater than one. If m is chosen too large, it may effect in excessive use of the computer processing time with no longer effectiveness. q can be in the range $2 \leqslant q \leqslant m$. The required number of complexes, p depends on the type of the problem. Large number of complexes is needed for highly nonlinear problems.

For the calibration of the Xinanjiang model, the following parameters were kept constant for all catchments: $n=13$; $p=16$, $m=27$; $q=14$; $y=1$; $z=27$.

3 Objective Functions

Three objective functions have been used for the calibration. Previous research works show that the results obtained using absolute error as objective function are more stable than that of least squares. Therefore, here we only consider the absolute error for objective functions.

First function calculates the relative absolute accumulated volume error over the whole period. This helps to keep the water balance throughout the period. Here Q_{obs}, the observed discharge, Q_{Cal}, the calculated discharge, and n, number of days per year.

$$\mathrm{Obj}_1 = \left| \frac{\sum_{i=1}^{n} Q_{\mathrm{Obs}}(i) - \sum_{i=1}^{n} Q_{\mathrm{Cal}}(i)}{\sum_{i=1}^{n} Q_{\mathrm{Obs}}(i)} \right|$$

Second objective function indicates the mean relative absolute error, being the sum of the absolute error of prediction normalized by dividing by the measured discharge.

$$\mathrm{Obj}_2 = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{Q_{\mathrm{Obs}}(i) - Q_{\mathrm{Cal}}(i)}{Q_{\mathrm{Obs}}(i)} \right|$$

Third objective function calculates the absolute mean logarithmic error. This can treat the lagging of the hydrograph. Also it enhances the base flow agreement. One is introduced in the equation for eliminating the log value becoming undefined.

$$\mathrm{Obj}_3 = \frac{1}{n} \sum_{i=1}^{n} \log\left(\left| \frac{Q_{\mathrm{Obs}}(i) - Q_{\mathrm{Cal}}(i)}{Q_{\mathrm{Obs}}(i)} \right| + 1 \right)$$

The main objective function (F), is defined as the combination of above mentioned three objective functions.

$$F = \sum_{i=1}^{y} (\mathrm{Obj}_1(i) + \mathrm{Obj}_2(j) + \mathrm{Obj}_3(i))$$

Where y is the number of years.

4 Statistical Indices

Two statistical indices selected to compare the performance of the model calibrated with SCE-UA method are D_y and % Err.

$$D_y = 1 - \left[\frac{\sum_{i=1}^{n}(Q_{Obs}(i) - Q_{Cal}(i))^2}{\sum_{i=1}^{n}[Q_{Obs}(i) - \bar{Q}_{Obs}(i)]^2}\right]$$

Where $\bar{Q}_{Obs}$ is daily mean observed discharge. %Err is for checking the water balance throughout the year. The error is obtained as a percentage and depending on the sign (positive or negative), the calculated discharge can be lower or higher than the observed discharge.

$$\%Err = \left[\frac{\sum_{i=1}^{n}Q_{Obs}(i) - \sum_{i=1}^{n}Q_{Cal}(i)}{\sum_{i=1}^{n}Q_{Obs}(i)}\right] \times 100$$

5 Stopping Criteria of Iterations

Three stopping criteria have been used for the termination of the iterative process. The calibration process is terminated if one or more of the following criteria are satisfied.

(1) The search is stopped when the algorithm is unable to appreciably improve 0.01 percent of the value of the objective function over five iterations. It could mean that a very flat region of the response surface has been reached.

(2) The search is stopped when the algorithm is unable to appreciably change the parameter values and simultaneously improve the function value over five iterations. While this can indicate arrival an optimum, it could also mean only that a region of high parameter interaction (long narrow valley) on the response surface has been reached.

(3) Since the computer time is limited and, to ensure that the algorithm does not somehow enter a finite loop, the search is terminated if the maximum number of iterations (10000) is exceeded, unless the parameter or function convergence criteria are met first.

6 Test Catchments Characteristics

Three catchments of different size and climatic conditions were chosen (see Table 1). Two of them known as Bagmathi and Tamor are located in Nepal and Misai is located in China. Bagmathi and Tamor basins were calibrated with four years of hydrological data and for Misai, five years hydrological data have been used. Two years of hydrological data were used in the validation stage for all catchments.

The Bagmathi River is the principal river of the Bagmathi watershed and lies between the Koshi and Gandaki watersheds in central Nepal. Nearly 45% of the watershed area lies in the

Mountain physiographic zone. Approximately 30% of the watershed lie in the Siwalik zone and the remaining 25% represents the Terai zone. Soils on the mountain slopes of Upper and Middle Bagmathi basins are relatively stable and thick (0.5 to 1.5m). Soils are better developed in the valley floor of Kathmandu in the Upper Bagmathi Basin. Nearly 42% of the watershed area is under agriculture, 46% under forest cover and 14% occupied by degraded shrub land and grazing land. Nearly over 60% of the river discharge takes place in the wet monsoon season and the dry season contribution is less than 40%. It is estimated th at more than 90% of the monsoon rain is diverted to the streams.

Tab.1 General information about the three catchments

Catchment	Area (km^2)	Test mode	Total No. of days	Mean Rainfall (mm/d)	Mean pan Evaporation (mm/d)	Mean Discharge (mm/d)	Country	Catchment condition
Misai	797.0	C	1826	4.87	2.06	3.14	China	Semi wet
		V	731	4.91	2.14	3.37		
Tamor	5797.7	C	1461	8.64	4.38	5.27	Nepal	Semi wet
		V	730	8.64	4.38	5.50		
Bagmathi	2817.6	C	1461	4.71	3.09	3.67	Nepal	Semi wet
		V	730	5.30	3.09	4.23		

C:Calibration; V:Verification.

Tamor River is located in the Lesser (middle hills) and Higher Himalayas (high mountains) of eastern Nepal. The river has the highest flow of $920m^3$ in the month of July and the lowest flow of $52m^3$ in March. The annual precipitation is about 1100 mm in the southern part of the valley and 1000 mm in the upstream areas. Above, 3000-m elevation, precipitation is characterized by drizzling and snows fall. Above 80% of the annual rainfall occurs between June and September. Land use distribution shows that 35% of the total area is covered by forest, 25% by the cultivated land, 15% by the water bodies and 25% by the rocks. The mountain areas in the north exceed an altitude of 3000 m. The hilly areas consist of ridges and steep slopes including the Mahabharat range and Siwalik hills.

Misai watershed (29°30′N, 118°30′E) is located in Zhejiang Province, China. The area is mountainous and with thick vegetation cover. The upper layer soil is highly permeable. Therefore the infiltration capacity is higher. Normally, the ground water flow is high and it covers about 40% of yearly runoff.

The area is semi-humid and the precipitation is fairly high. Yearly average rainfall is about 1500−2000mm. Yearly runoff coefficient is about 0.7−0.8. Monsoon period is from April to June. The amount of precipitation during this period is about 60% of yearly precipitation. Mid summer begins from July. It is comparatively dry season and sometimes, it might occur heavy rainfalls with high intensity for a short period. Rainfall distribution is uneven over the catchment. There is very less rain during November to February, next year.

7 Results

Three independent trials were conducted for each catchment with different initial conditions and different initial seeds. The parameters K, IM, B, WUM, WLM, C, SM, EX, CG, CI, CS, KG, XE were calibrated by using the SCE-UA method while WM and TT were kept constant. Since we use the daily model, $TT = 24$h for all iterations. WM value was chosen in such a way that $WUD = WM - (WUL + MUM)$ value would not become negative. KI value was chosen according to the relationship, $KI + KG = 0.7$. All the iterations were stopped satisfying the function convergence stopping criteria. That is the objective function value has not been improved 0.01% in consecutive five iterations.

Tab.2 Calibrated values for Xinanjiang model parameters using SCE-UA method

Trial No.	Misai			Tamor			Bagmathi		
	1#	2#	3#	1#	2#	3#	1#	2#	3#
K	0.922	0.922	0.922	1.275	1.268	1.274	0.554	0.553	0.544
IM	0.001	0.001	0.001	0.123	0.124	0.123	0.129	0.114	0.151
B	0.080	0.080	0.080	0.700	0.700	0.700	0.091	0.105	0.07
WUM	34.999	34.996	34.986	16.368	20.529	15.648	10.735	10.500	11.402
WLM	64.997	65.012	65.026	64.993	64.986	64.982	31.905	28.050	28.231
C	0.350	0.350	0.350	0.019	0.018	0.020	0.136	0.138	0.128
SM	9.372	9.595	9.330	27.999	27.997	27.997	24.088	21.529	25.571
EX	0.800	0.815	0.801	0.775	0.758	0.767	0.710	0.689	1.671
CG	0.999	0.999	0.999	0.989	0.990	0.989	0.998	0.998	0.998
CI	0.890	0.890	0.891	0.941	0.942	0.941	0.947	0.948	0.949
CS	0.281	0.276	0.286	0.242	0.242	0.240	0.064	0.065	0.195
KG	0.119	0.117	0.117	0.302	0.299	0.302	0.055	0.058	0.063
XE	0.485	0.488	0.488	0.120	0.122	0.118	0.318	0.330	0.301
KI	0.581	0.583	0.583	0.398	0.401	0.398	0.645	0.642	0.637
WM	125	125	125	125	125	125	125	125	125
TT	24	24	24	24	24	24	24	24	24

Tab.3 Calibration and validation results of Misai watershed

Trial		1#		2#		3#	
	Year	%Err	D_y	%Err	D_y	%Err	D_y
Calibration	1982	5.143	0.922	5.119	0.923	5.079	0.921
	1983	−1.252	0.891	−1.247	0.891	−1.291	0.890
	1984	0.000	0.894	0.000	0.894	0.000	0.893
	1985	0.339	0.851	0.343	0.849	0.348	0.851
	1986	−0.001	0.909	0.000	0.911	−0.001	0.908
Validation	1987	−4.471	0.875	−4.491	0.874	−4.539	0.875
	1988	6.903	0.860	6.913	0.862	6.889	0.859

8 Discussion of Results

Two statistical indices (D_y and %Err) as mentioned above, have been used to compare the performance of the SCE-UA method. A careful inspection of tables 2, 3, 4 & 5 reveals that statistics and parameter values give nearly similar results in all three trials in each catchment. Even though the parameter values are not the same, the error bound is negligible. In fact the accuracy can be enhanced by changing the tolerance of stopping criteria as appropriate.

Tab. 4 Calibration and validation results of Tamor watershed

Trial		1#		2#		3#	
	Year	%Err	D_y	%Err	D_y	%Err	D_y
Calibration	1989	11.726	0.934	11.819	0.934	11.774	0.935
	1990	3.467	0.940	3.513	0.940	3.486	0.940
	1991	−3.459	0.947	−3.721	0.947	−3.915	0.947
	1992	−4.883	0.915	−5.215	0.914	−5.457	0.914
Validation	1993	2.800	0.932	2.835	0.931	2.754	0.932
	1994	6.425	0.950	6.766	0.949	6.302	0.950

Tab. 5 Calibration and validation results of Bagmathi watershed

Trial		1#		2#		3#	
	Year	%Err	D_y	%Err	D_y	%Err	D_y
Calibration	1989	0.000	0.861	0.007	0.848	0.000	0.895
	1990	−6.949	0.885	−6.883	0.881	−6.837	0.884
	1991	0.000	0.855	0.000	0.855	0.000	0.859
	1992	0.000	0.842	0.000	0.835	0.000	0.837
Validation	1993	−1.992	0.919	−1.775	0.910	−1.728	0.926
	1994	0.787	0.833	0.770	0.817	0.780	0.836

Considering the Misai basin (Tab. 2), the parameter values obtained in three trials are almost similar. But the best statistics are shown in the Bagmathi (Tab. 5) basin. Both the calibration and validation results are acceptable only except year 1990 data. It may happen due to the data errors. But it is worth to note that achieving better statistics as the calibration stage does not guarantee getting parameter sets always with a stronger physical basin. In the calibration stage, Misai also has performed well. But validation results are not very good compared to Bagmathi basin. Topographic conditions and accuracy of discharge data might cause this difference. Considering the topography, Bagmathi basin is located in mountainous area, whereas Misai is comparatively in flat area.

Based on the results, it is clear that Xinanjiang hydrological model can be successfully applied to the selected Bagmati basin, and Tamor basin (Nepal) that represent various climatic and geographical zones of Nepal. In fact, compared to the other two basins, Tamor basin calibration results are not good (Tab. 4). Tamor River is a snow-fed river and originates entirely within the territory of Nepal. The northern area (approximately 27°30′N) lies in the higher Himalayan Zone and has a very rugged topography, steep slopes and dominated by glacial-per glacial geomorphology. A number of glacier and high altitude lakes are located in this basin. Snow-fed area comprises about 20% of the total basin area. These facts may cause for the poor calibration results

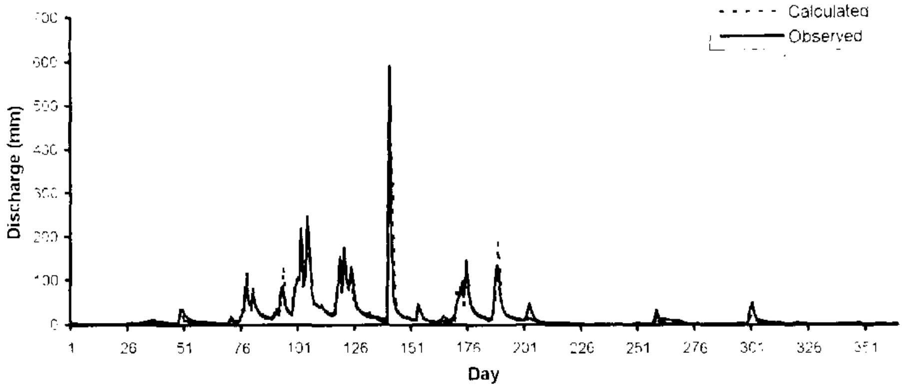

Fig. 1 Discharge hydrograph of Misai watershed for the data from Jan. 1986 to Dec. 1986

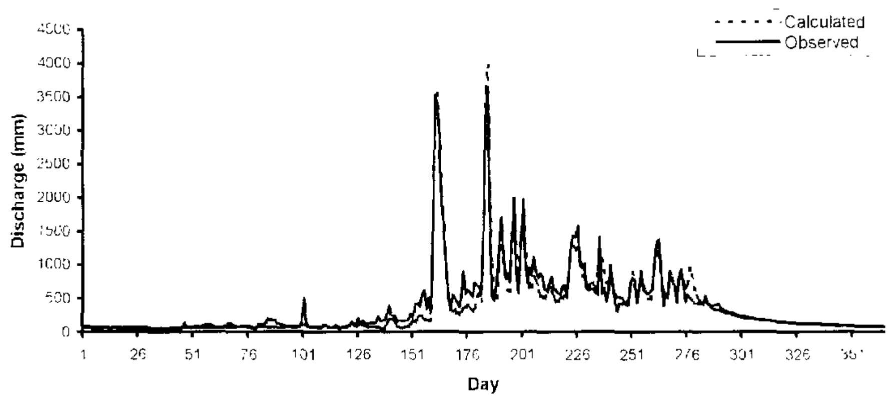

Fig. 2 Discharge hydrograph of Tamor watershed for the data from Jan. 1990 to Dec. 1990

since Xinanjiang model is incapable of accounting snow. However, the model should be applied with much caution in the areas with extreme geographical features like Tamor basin even though the failure to use the model can partly be attributed to the inaccuracy of the observed discharge data.

Figure 1, 2 and 3 shows the fit of the calculated and observed river discharges. Only selected period (one year) of the hydrograph is shown for the convenience. It is clear that modeled discharge fits well with observed discharge in the three catchments.

These results may lead to conclude that the SCE-UA method is capable of finding a conceptually realistic and global optimum parameter set for the Xinanjiang watershed model. Also our results clearly show that SCE-UA can handle high parameter dimensions and achieve the global convergence in the presence of multiple regions of attraction.

Additionally, in the calibration process, initial conditions of the watershed (W, WUM,

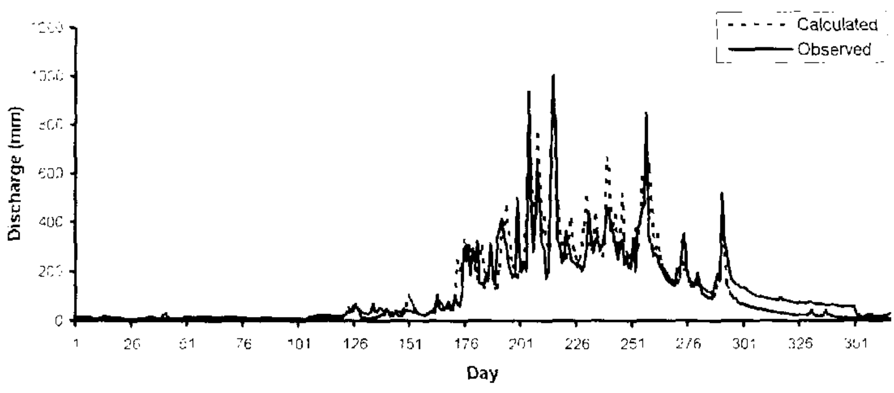

Fig. 3 Discharge hydrograph of Bagmathi watershed for the data from Jan. 1992 to Dec. 1992

WUL, *S*, *FR*, *QS*, *QI*, *QG*) should be carefully selected such that the calculated discharge at the beginning of the year is nearly equal to the observed discharge. Invalid initial data may lead *W* to become negative in the ierative process. As a result the search may trap in local optimums or the computational time may be longer.

9 Conclusions

A brief review of the essential concepts of the Xinanjiang model and the application results of SCE-UA method for calibrating the Xinanjiang model using hydrological data of three catchments of different size and climatic conditions, are presented in this paper. Based on the results obtained, the following conclusions can be drawn.

(1) Overall performance of SCE-UA method for calibrating the Xinanjiang model is very good. On the basis of the results derived from the calibration and verification stages, it seems that SCE-UA is capable of finding a global optimum and conceptually realistic parameter set for the Xinanjiang model.

(2) The Xinanjiang model can be successfully appliwed in semi wet catchments of Nepal. However more attention should be paid when applying the model in the areas with extreme geographical features and Snow-fed areas like Tamor basin. In such situations, modifications should be added to the model as appropriate.

(3) The objective function plays a major roll in calibrating Xinanjiang watershed model. Therefore a combination of proper objective functions is recommended. Changes in objective function may direct the search process in certain direction.

(4) The Xinanjiang model parameter boundary values should be carefully selected such that they represent the possible smallest range that could reach the global optimum. Especially the boundary values of paramters like *K*, *IM* etc. that have a physical meaning, should be selected by considering the real situation of the watershed. More attention should be paid for fixing the

value of WM such that the value of W would not be negative in the iterative process.

(5) SCE-UA method is capable of handling high paramter dimensionality and it does not rely on the availability of an explicit expression for the objective function or the derivatives. On the other hand, in the SCE-UA algorithm, only p, number of complexes, is the main variable. All other parameters can be fixed as default values. But other optimization algorithms like genetic algorithms, Simplex method etc. have many parameters to be chosen it self. Therefore less knowledeable user would be better of choosing SCE-UA for calibrating the Xinanjiang model.

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SCE-UA方法在新安江模型参数优化中的应用

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提 要 以前在使用新安江模型时人们遇到的最大困难可归因于缺乏有效的参数全局优化的数学方法.事实上对于一个缺乏经验的人来说,模型参数的人工试错计算的过程是一个相当不容易的过程,并且耗时颇多.为此,近些年来研究者们正在探索把概念性水文模型中的专家经验与自动优化计算相结合的方法或者数学优化中的全局优化方法,如SEC-UA方法.本文首先简述新安江模型,而后采用3个大小和气候条件各不相同的流域对SCE-UA算法就在新安江模型计算的参数优化进行了研究.研究结果表明,SCE-UA算法用来进行新安江模型的参数优化所取得的效果是好的.从率定和检验的结果来看,SCE-UA算法可以使得率定的新安江模型的参数达到全局最优并且从概念上也合理.

关键词 新安江模型 概念性模型 模型率定 全局优化 基因算法

分类号 P333.9