

1. Parameter Calibration and Sensitivity Analysis

Model parameters are very important for model effects. Different basins have different parameters and each parameter has its meaning, so parameter calibration is indispensable. Sensitivity analysis can accurately explain which parameters are sensitive in the study area, and these results can provide a basis for selecting the optimal parameter combination. When the optimal parameter combination is selected, the simulation effect will be appropriate. So, parameter calibration and sensitivity analysis play a complementary role in the simulation results.

1.1. Parameter Calibration

The parameters of the VIC model can be divided into two parts; one is directly determined according to the physical meaning of the parameters. The other is closely related to runoff. Due to the complexity of runoff, these parameters are difficult to directly determine and require parameter calibration.

The model parameters that need to be calibrated are the following six (in addition to the thickness of the top thin soil moisture layer $d1$, the default is 0.1m): the infiltration curve parameter, B ; the maximum velocity of the baseflow, Ds_{max} ; the fraction of Ds_{max} where the non-linear baseflow begins, Ds ; the fraction of the maximum soil moisture where non-linear baseflow occurs, Ws ; the thickness of the middle soil moisture layer, $d2$; and the thickness of the lower soil moisture layer, $d3$.

Model parameter calibration methods: parameter calibration methods are divided into manual calibration and automatic calibration [1,2]. Although the accuracy of automatic calibration is higher than that of manual calibration, the calibration process is complicated and takes a long time. In this study, the manual calibration method was used to divide the six parameter intervals into ten equal parts according to the empirical intervals of each parameter, and only one parameter was adjusted at a time to obtain preliminary coarse adjustment results. Then, according to the objective function, the simulated data and the measured data were compared to make detailed adjustments, and finally the optimal parameter combination was obtained.

Table S1 and Table S2 are the result of parameter calibration in the study area. It can be seen that the Kequ River basin, Dari River basin and Jimai River basin in the source region of the Yellow River were adjacent to each other and had similar climatic conditions. Their parameter calibration results were basically the same. Therefore, for areas lacking data, we can adopt parameter transplantation to determine the parameters. Because the Balegen River basin was an arid area, its second and third layers of soil were thicker than those of the other three river basins.

Table S1. Model parameters.

Parameter	Physical meaning	Unit	Numeric range
B	Infiltration curve parameter	/	[0,0.4]
Ds	Fraction of Ds_{max} where the non-linear baseflow begins	/	[0,1]
Ds_{max}	Maximum velocity of the baseflow	mm/day	[0,30]
Ws	Fraction of the maximum soil moisture where non-linear baseflow occurs	/	[0,1]
$d1$	Thickness of the top thin soil moisture layer	m	[0.05,0.1]
$d2$	Thickness of the middle soil moisture layer	m	[0,2]
$d3$	Thickness of the lower soil moisture layer	m	[0,2]

Table S2. Parameter calibration results.

Parameter	Parameter value			
	the Source Region of the Yellow River			the Inland Arid Source Region
	Kequ River basin	Dari River basin	Jimai River basin	Balegen River Basin
B	0.18	0.18	0.18	0.10
Ds	0.10	0.10	0.10	0.10
Dsmax	1.00	1.00	1.00	3.00
Ws	0.80	0.80	0.80	0.80
d1	0.10	0.10	0.10	0.10
d2	0.80	0.80	0.80	0.85
d3	1.10	1.10	1.10	1.50

1.2. Parameter Sensitivity Analysis

The VIC model uses simplified physical equations and empirical equations to describe the changes in energy balance and water balance, so some parameters need to be calibrated to obtain the best results. The interaction of these parameters in the calculation process will have an impact on the simulation results. Due to differences in climatic conditions and underlying surface conditions in different watersheds, the influence of various parameters on the watershed is also different. Therefore, the sensitivity analysis of the parameters helps to understand the characteristics of the model and improve the stability of the model structure [1]. This study quantitatively analyzed the sensitivity of six soil parameters (in addition to the thickness of the top thin soil moisture layer d1, the default is 0.1m), B, Ds, Dsmax, Ws, d2, and d3, in the study area.

We fixed the other five soil parameters and changed the parameters that need to be calibrated between 80% and 120% of the final calibrated value, with a step of 10%. Then, ran the VIC model, calculated NSE and RE, and finally calculated their sensitivity:

$$S_{NSE} = \left| \frac{\Delta Ne / Ne}{\Delta x / x} \right|$$

$$S_{RE} = \left| \frac{\Delta RE / RE}{\Delta x / x} \right|$$

where Δx is the variation of x ; Ne is NSE ; ΔNe is the variation of Ne ; ΔRE is the variation of RE . The larger the absolute value, the more sensitive the calculation parameters are to the objective function. When $|S_{NSE}| > 0.3$, the parameter is considered sensitive to NSE , and when $|S_{RE}| > 5$, the parameter is considered sensitive to RE . When $\Delta x = 0$, this has no mathematical meaning.

Figure S1 is the result of parameter sensitivity analysis in the study area. It can be seen that in the three basins of the source region of the Yellow River, the three parameters B, d2, and Dsmax were relatively sensitive. However, in the Balegen River basin of the inland arid source region, the two parameters B and d2 were relatively sensitive. The infiltration curve parameter B represents uneven spatial distribution of soil water content, which affects the distribution of rainfall infiltration and runoff, so B is more sensitive. The thickness of the middle soil moisture layer, d2, reflects the redistribution of soil to rainfall, and the root system of vegetation is mostly distributed in the second layer of soil, which has a great influence on the transpiration of vegetation [3]. Therefore, d2 directly affects the generation of surface runoff and base flow and has a direct impact on soil water content. In a word, d2 is more sensitive. The maximum velocity of the baseflow,

Dsmax, represents the maximum value of the base flow generated by the soil in a day, mainly affecting the base flow, not directly affecting the runoff, so Dsmax is more sensitive than several other insensitive parameters.

According to the above sensitivity analysis, we can see that various parameters have complex interrelationships in the process of hydrological simulation, and they directly or indirectly affect the simulation effect. Therefore, the influence of each parameter should be comprehensively considered according to the geographical location of each river basin and hydrogeological differences and other factors, and the optimal parameter should be determined.

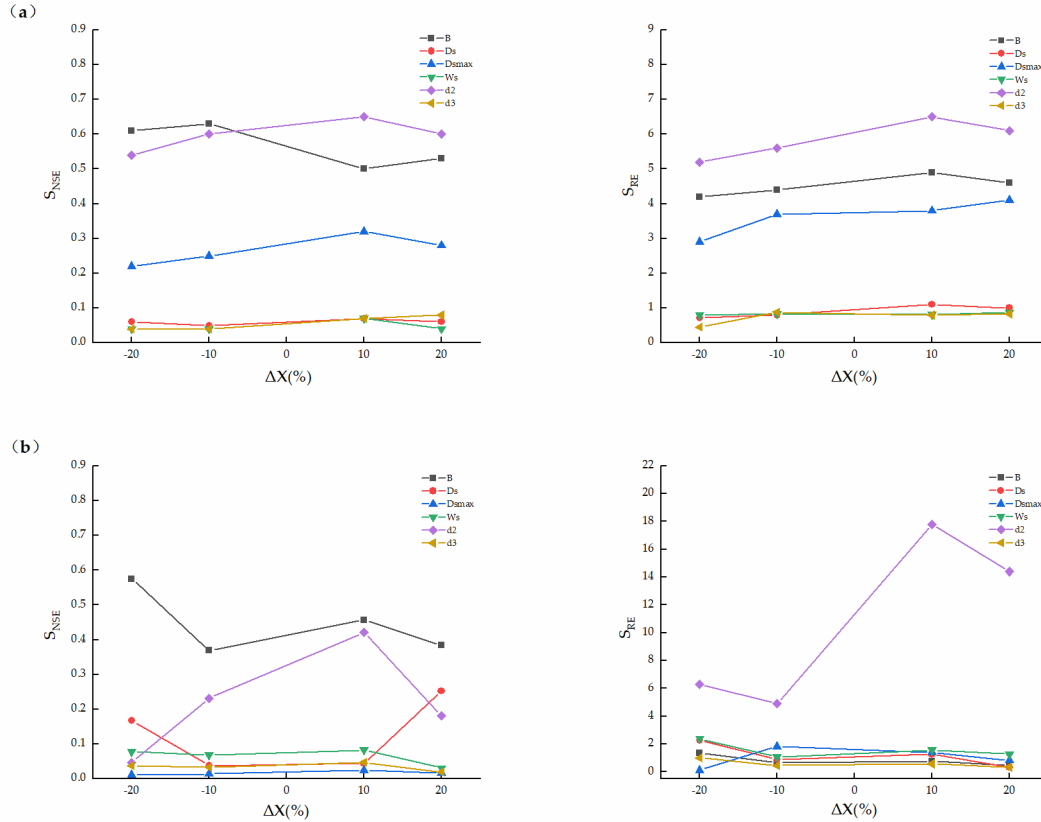


Figure S1. Sensitivity analysis of parameters in the study area. (a) The Kequ River basin, Dari River basin and Jimai River basin in the source region of the Yellow River; (b) The Balegen River basin in the inland arid source region.

References

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