A parameter estimation scheme of the land surface model VIC using the MOPEX databases

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Abstract A parameter estimation scheme for the land surface model VIC-3L is discussed. VIC-3L parameters, i.e. the variable infiltration curve parameter (B), the baseflow parameters (D_m and D_s) and the depth of the second soil layer (d_2), are chosen for calibration by a systematic manual calibration approach. The VIC-3L parameters are calibrated in the first half of the period of record for 12 MOPEX watersheds in France and used to predict the streamflow for the second half of the record. Comparisons of the simulated results using the *a priori* parameters with those using calibrated parameters show that the calibrated parameters, when evaluated against the *a priori* parameter estimates, are able to reduce the model bias and increase the Nash-Sutcliffe efficiency coefficient of the streamflow simulation. The averaged hourly Nash-Sutcliffe model efficiency coefficient for the 12 watersheds increases from 0.463 to 0.623, and that for the calibrated parameters in predicting the hourly streamflow for the validation period is 0.553. A sensitivity analysis on the calibrated parameters mentioned above shows that the variable infiltration curve parameter (B) and the depth of the second soil layer (d_2) are more sensitive than the other two parameters (D_m and D_s). Therefore, suitable calibration for the parameters of the land surface model VIC-3L, especially for the variable infiltration curve parameter (B) and the depth of the second soil layer (d_2) is very important for simulating land surface behaviour in a specific region.

Key words land surface model; parameter calibration; sensitivity; VIC

INTRODUCTION AND MODEL DESCRIPTION

Land surface models have been widely used for a variety of applications including hydrological forecasting, water resources management, and climate change studies (Dickinson *et al*., 1993; Zeng *et al*., 2002; Dai *et al*., 2003). To properly simulate land surface behaviour in a specific region, the model parameters for the region must be specified *a priori*. Studies have shown that land surface models could perform well if their model parameters are appropriately estimated on the basis of calibration with observations but perform poorly if their model parameters are not calibrated properly. Therefore, a practical parameter estimation method is critical to hydrological modelling (Duan *et al*., 1992; Huang *et al*., 2003). There are two main approaches to estimating the model parameters. The first (*a priori*) approach estimates model parameters by relying on theoretical or empirical relationships that relate such parameters to observable characteristics of the region, such as soil and vegetation properties, regional geomorphology, topographical features, and more. The second approach (model calibration) adjusts model parameter values, so that the model input-output response closely matches the observed input-output response of the region for some historical period in which data have been collected (Nijssen *et al*., 2001). In this work, we discuss parameter estimation of the land surface model VIC-3L using the MOPEX databases. Four VIC-3L parameters, i.e. the variable infiltration curve parameter (B), the baseflow parameters (D_m and D_s) and the depth of the second soil layer (d_2) are chosen to be calibrated by using a systematic manual calibration approach with 12 MOPEX watersheds' data. The VIC-3L parameters are calibrated in the first half of the period of record for 12 MOPEX watersheds in France and are used to predict the hourly streamflow for the second half of the record.

The variable infiltration capacity model (VIC), called VIC-2L, was developed by Liang *et al*. (1994), which includes two different time scales (i.e. fast and slow) for runoff to capture the dynamics of runoff generation. The upper soil layer of the model is designed to represent the dynamic response of the soil to rainfall events, and the lower layer is used to characterize the seasonal soil moisture behaviour. The VIC model uses physically-based formulations for the calculation of the sensible and latent heat fluxes, but uses the conceptual ARNO baseflow model (Franchini *et al.*, 1991; Todini, 1996) to simulate runoff generation from the deepest soil layer. To better represent quick bare soil evaporation following small summer rainfall events, a thin soil layer is included in VIC-2L (Liang *et al.*, 1996), and VIC-2L becomes VIC-3L. Soil moisture diffusion processes between the three soil layers are considered in VIC-3L. Cherkauer & Lettenmaier (1999) improved the representation of processes for cold climates within VIC. Liang & Xie (2001) developed a parameterization to represent the infiltration excess runoff mechanism in VIC-3L and combined it effectively with the original representation of the saturation excess runoff mechanism (Zhao, 1992). Xie *et al.* (2003) developed a surface runoff parameterization with the Philip infiltration formulation as the time compression analysis (TCA) that dynamically represents both the Horton and Dunne runoff generation mechanisms within a model grid cell. In this paper, the VIC-3L with the new runoff parameterization is applied to simulate runoff for the 12 MOPEX watersheds.

STUDY DOMAIN AND DATA SETS

Study domain

Twelve MOPEX watersheds in France are chosen for the calibration. Table 1 shows the basic basin information for the 12 MOPEX watersheds. The drainage areas of those basins range from 43.0 to 371.0 km^2. All the watersheds are humid watersheds, with the annual mean precipitation ranging from about 1000 to 2000 mm. The period from November to May of the next year is the wet season, with 70% to 80% of rainfall occurring, while it is hot and dry in the summer and early autumn. Therefore, these watersheds have the typical characteristics of a Mediterranean climate.

Vegetation data

Vegetation related parameters such as architectural resistance, minimum stomatal resistance, leaf-area index, albedo, roughness length, zero-plane displacement, and

Table 1 Watershed information.

Code	Name	Area (km²)
J3024010	Le Guillec à Trézilidé	43.0
V6035010	Le Toulourenc à Malaucène [Veaux]	150.0
Y5615030	Le Loup à Villeneuve-Loubet [Moulin du Loup]	279.0
A1522020	La Lauch à Guebwiller	68.1
H2001020	L'Yonne à Corancy	98.0
H3613020	Le Lunain à Épisy	252.0
J2034010	Le Guindy à Plouguiel	125.0
J4124420	La Rivière de Pont-l'Abbé à Plonéour-Lanvern [Tremillec]	32.1
K0744010	L'Anzon à Débats-Rivière-d'Orpra [Cotes]	181.0
K0753210	Le Lignon du Forez à Boën	371.0
Y3514020	Le Vistre à Bernis	291.0

fraction of root depth of each soil layer are based on the University of Maryland's (UMD) 1 km global land cover classification with 14 unique vegetation types in total (Hansen *et al.*, 2000). For each type of vegetation, the vegetation parameters mentioned above are derived from the literature and the land data assimilation system (LDAS). Since the MOPEX database provides the vegetation data based on the Corine land cover classification for the 12 French watersheds, we regroup it into the UMD classification to use the related vegetation parameters. As shown in Table 2, the area covered with the Corine-based coniferous forest, broad-leaved forest, mixed forest or transitional woodland-scrub is assigned with the corresponding vegetation parameters for the UMD-based deciduous needle-leaf forest, deciduous broadleaf forest, mixed forest, and woodland, respectively. In the same way, the region with the cover of moor and heathland, natural grassland or agricultural area in the Corine land cover classification is assigned with the vegetation parameter values for the open shrubland, grassland and crop land in the UMD classification. Table 2 lists the vegetation parameters in VIC-3L for various vegetation types (Su & Xie, 2003).

Soil data

The soil parameters in VIC-3L, such as, porosity θ_s (m^3 m^{-3}), saturated soil potential ψ_s (m), saturated hydraulic conductivity K_s (m s^{-1}), and the exponent parameter b, are derived according to Cosby *et al*. (1984) and Rawls *et al.* (1993) based on the Food and Agriculture Organization (FAO) soil classification (FAO, 1998). In this study, the soil data provided by MOPEX is based on the French soil texture classification, which are regrouped into the FAO soil classification. Table 3 shows the soil classification and the corresponding values of soil parameters used in the VIC-3L model (Su & Xie, 2003). The French soil texture classification consists of five soil types, which are coarse soil, moderate soil, moderately fine soil, fine soil and very fine soil. The area with the coverage of those five French soil types are set with the corresponding soil parameters for the FAO-based sandy loam, silt loam, silty clay loam, silty clay and clay, respectively.

Table 2 Vegetation-related parameters in the VIC-3L model.

UMD classification	Corine land cover legend	Albedo	Minimum stomatal resistance (sm^{-1})	Leaf-area index	Roughness length (m)	Zero-plane displacement (m)
Evergreen needleleaf forest		0.12	250	3.40~4.40	1.476	8.04
Evergreen broadleaf forest		0.12	250	3.40~4.40	1.476	8.04
Deciduous needleleaf forest	3.1.2 Coniferous forest	0.18	150	1.52~5.00	1.23	6.7
Deciduous broadleaf forest	3.1.1 Broad leaved forest	0.18	150	1.52~5.00	1.23	6.7
Mixed forest	3.1.3 Mixed forest	0.18	200	1.52~5.00	1.23	6.7
Woodland	3.2.4 Transitional woodland-scrub	0.18	200	1.52~5.00	1.23	6.7
Wooded grassland		0.19	125	2.20~3.85	0.495	1
Closed shrubland		0.19	135	2.20~3.85	0.495	1
Open shrubland	3.2.2 Moor and heathland	0.19	135	2.20~3.85	0.495	1
Grassland	3.2.1 Natural grassland	0.2	120	2.20~3.85	0.0738	0.402
Crop land (corn)	2 Agricultural area	0.1	120	0.02~5.00	0.006	1.005

Table 3 Soil-related parameters in the VIC-3L model.

FAO soil texture	French soil texture	θ_s (m^3m^{-3})	ψ_s (m)	K_s (mm day^{-1})	$2b$+3	Bulk density (kg m^{-3})
Sand		0.445	0.069	92.45	11.2	1490
Loamy sand		0.434	0.036	1218.24	10.98	1520
Sandy loam	1 Coarse	0.415	0.141	451.87	12.68	1570
Silt loam	2 Moderate	0.471	0.759	242.78	10.58	1420
Silt		0.523	0.759	242.78	9.1	1280
Loam		0.445	0.355	292.03	13.6	1490
Sandy clay loam		0.404	0.135	384.48	20.32	1600
Silty clay loam	3 Moderately fine	0.486	0.617	176.26	17.96	1380
Clay loam		0.467	0.263	211.68	19.04	1430
Sandy clay		0.415	0.098	623.81	29	1570
Silty clay	4 Fine	0.497	0.324	115.78	22.52	1350
Clay	5 Very fine	0.482	0.468	84.15	27.56	1390

Forcing and streamflow data

In this study, the forcing data were provided by the Meteo-France, which include the hourly precipitation, atmospheric pressure, water vapour pressure, wind speed, short wave radiation and long wave radiation in the period from 1 August 1995 to 31 July 2002. Hourly streamflow data were also provided for the same period.

PARAMETER ESTIMATION SCHEME

Although most of vegetation and soil parameters in VIC-3L can be estimated according to the literature, some soil parameters are subject to calibration based on the agreement between simulated and observed hydrographs. These include the infiltration parameter (B), which controls the amount of water that can infiltrate into the soil; the depths of the three soil layers d_i (i = 1, 2, 3), which affect the maximum storage available for transpiration; the three parameters in the baseflow scheme including the maximum velocity of baseflow (D_{m}), the fraction of maximum baseflow (D_{s}), and the fraction of maximum soil moisture content of the third layer (W_{s}) at which a nonlinear baseflow response is initiated, which determines how quickly the water stored in the third layer is depleted. *A priori* estimates for those parameters over a humid region, the Huaihe River basin in China, are presented in Su & Xie (2003). In this study, the related parameters for the Huaihe River basin are used as the *a priori* values for the 12 humid French watersheds, which are shown in Table 4. The hourly streamflow simulation is conducted for the whole period of record (1 August 1995–31 July 2002), called the ungauged simulation mode. Among the seven VIC-3L parameters, the variable infiltration capacity curve parameter (B), baseflow parameter (D_{m} and D_{s}) and the depth of the second soil layer (d_2) are the more sensitive, and hence they are chosen for calibration by a systematic manual calibration approach. The other three parameters are assigned with the *a priori* values mentioned above. Calibration is made manually and the Nash-Sutcliffe model efficiency coefficient (Nash & Sutcliffe, 1978) is used as the objective function, which describes the matching extent of the hydrograph between the simulated and observed values:

$$C_e = \frac{\sum (Q_{i,o} - \overline{Q}_o)^2 - \sum (Q_{i,c} - Q_{i,o})^2}{\sum (Q_{i,o} - \overline{Q}_o)^2}$$

where $Q_{i,o}$ is the observed streamflow (m^3 s^{-1}), $Q_{i,c}$ is the simulated streamflow (m^3 s^{-1}), and $\overline{Q}_o$ is the mean observed streamflow (m^3 s^{-1}).

Table 4 *A priori* parameter values of the VIC-3L model for the 12 MOPEX French watersheds.

Parameter	Physical meaning	Value
B	Variable infiltration curve parameter	0.3
D_m	Maximum velocity of baseflow (mm day^{-1})	10
D_s	Fraction of D_m where non-linear baseflow begins	0.02
W_s	Fraction of maximum soil moisture where non-linear baseflow occurs	0.8
D_1	Thickness of the first soil layer (m)	0.1
D_2	Thickness of the second soil layer (m)	0.5
D_3	Thickness of the third soil layer (m)	1.5

Model calibration is performed using the following procedures:

(1) Set the estimated value for the depth of the second soil layer (d_2), commonly with a deeper depth for arid regions and a lower depth for humid regions.

Table 5 Calibrated parameter values of the VIC-3L model for the 12 MOPEX French watersheds.

Gauge	B	D_s	D_m (mm day^{-1})	d_2 (m)
J3024010	0.3	0.02	10	1.7
V6035020	0.3	0.02	8	0.48
Y5615030	0.28	0.01	4	0.55
A1522020	0.45	0.035	6	0.45
H2001020	0.25	0.001	20	0.31
H3613020	0.15	0.02	2	10
J2034010	0.3	0.05	2	0.5
J4124420	0.35	0.35	2	2
K0744010	0.38	0.0001	20	0.45
K0753210	0.35	0.0002	20	0.45
Y3514020	0.21	0.01	0.95	0.5
A5723010	0.25	0.01	0.8	1.1

Table 6 Hourly Nash-Sutcliffe efficiency in ungauged and gauged modes.

Gauge	*Priori* (ungauged) Mode (1 Aug. 1995–31 July 2002) (1)	Gauged mode			*Improvement* (2) – (1)
		Calibration period (1 Aug. 1996–31 July 1999)	Validation period (1 Aug. 1999–31 July 2002)	Entire period (1 Aug. 1995–31 July) (2)	
J3024010	0.663	0.528	0.728	0.682	0.019
V6035020	0.424	0.492	0.361	0.423	–0.001
Y5615030	0.774	0.826	0.788	0.788	0.014
A1522020	0.515	0.551	0.519	0.546	0.031
H2001020	0.697	0.761	0.819	0.778	0.081
H3613020	–7.511	0.284	0.317	0.452	7.963
J2034010	–0.107	0.501	0.292	0.389	0.496
J4124420	0.192	0.454	0.556	0.565	0.373
K0744010	0.584	0.722	0.59	0.653	0.069
K0753210	0.634	0.785	0.63	0.691	0.057
Y3514020	0.582	0.762	0.616	0.67	0.088
A5723010	0.136	0.468	0.189	0.342	0.206
Mean	0.463	0.623	0.553	0.593	0.130

Note: The Nash-Sutcliffe efficiency for Gauge H3613020 is excluded from of the mean statistics.

(2) Calibrate the ARNO model parameters (D_m and D_s) to fit the low flow.
(3) Adjust the infiltration parameter B to match the observed flow peaks, with a higher value to increase the peak and a lower value to lower the peak.
(4) Make a fine adjustment to these parameters to get the best simulation results.

The four VIC-3L parameters are calibrated in the first half of the period of record (1 August 1995–31 July 1999) for each of the 12 MOPEX watersheds in France and are used to predict the hourly streamflow for the second half of the period of record (1 August 1999–31 July 2002), which is called gauged simulation mode. The first year is considered as a warm-up period and is not used in the error criteria calculations. Table 5 shows the calibrated parameter values for the 12 French watersheds.

Since the drainage area of the watersheds is not large, ranging from 43.0 to

371.0 km^2, each watershed is treated as a computational unit of the VIC-3L model. The VIC-3L is used to simulate the water balance for the 12 French watersheds for ungauged and gauged modes. In this study, only those vegetation types whose proportions over the computational grid cell are greater than 10% are involved in computing the water and energy balances, and we use the parameter values of the soil type with the highest proportion over the watershed as the parameters for the whole watershed.

Table 6 shows the hourly Nash-Sutcliffe efficiency in ungauged and gauged modes for the 12 French watersheds. Figure 1 shows the comparison of the observed daily streamflow with the simulated in the ungauged and gauged modes at Gauge Station Y5615030. For the ungauged mode, the VIC-3L model with the *a priori* parameters can basically simulate the hourly runoff for the French watersheds. Among the 12 watersheds, the hourly Nash-Sutcliffe efficiency for eight watersheds is larger than 0.40, and the mean value for eleven watersheds (except H2001020) is 0.463. For gauged mode, the VIC-3L model with the calibrated parameters simulates better than that with the *a priori* parameters. For the calibration period (1 August 1996–31 July 1999), the hourly Nash-Sutcliffe efficiency for most of watersheds is larger than 0.50, and the mean value of hourly Nash-Sutcliffe efficiency for the 12 watersheds is 0.623. The mean value of hourly Nash-Sutcliffe efficiency for the 12 watersheds for the validation period is 0.553.

The hourly Nash-Sutcliffe efficiency cumulative distribution and the simulated annual runoff with the observed from 1998 to 2002, are shown in Figs 2 and 3 respectively, which imply that the gauged mode is superior in simulating streamflow for the 12 French watersheds.

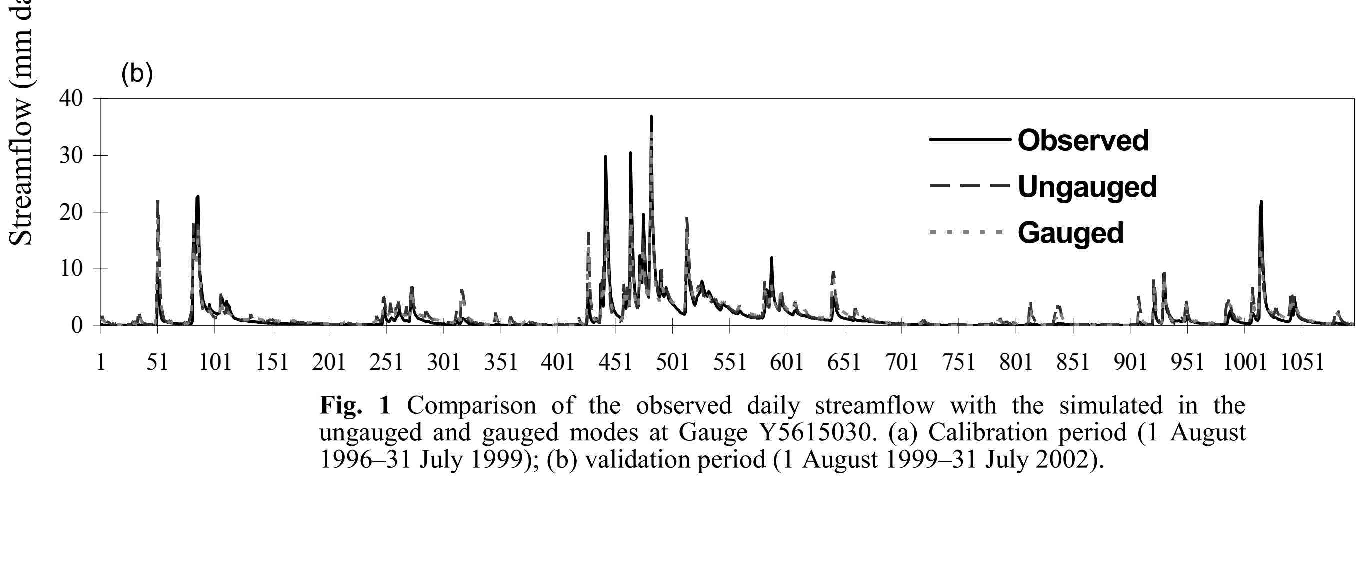

Fig. 1 Comparison of the observed daily streamflow with the simulated in the ungauged and gauged modes at Gauge Y5615030. (a) Calibration period (1 August 1996–31 July 1999); (b) validation period (1 August 1999–31 July 2002).

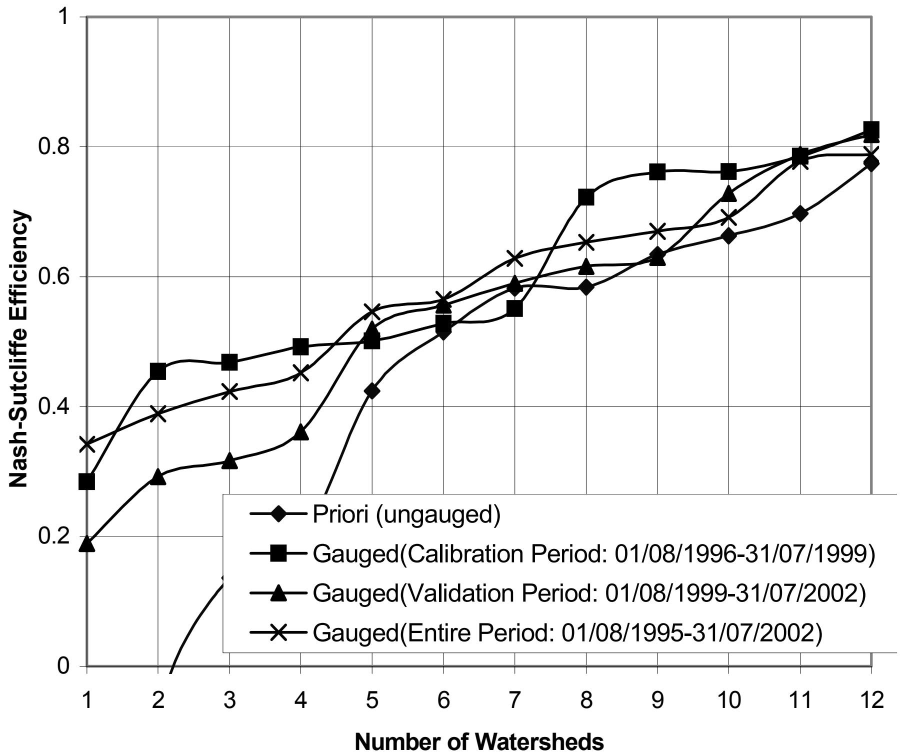

Fig. 2 Hourly Nash-Sutcliffe efficiency cumulative distribution.

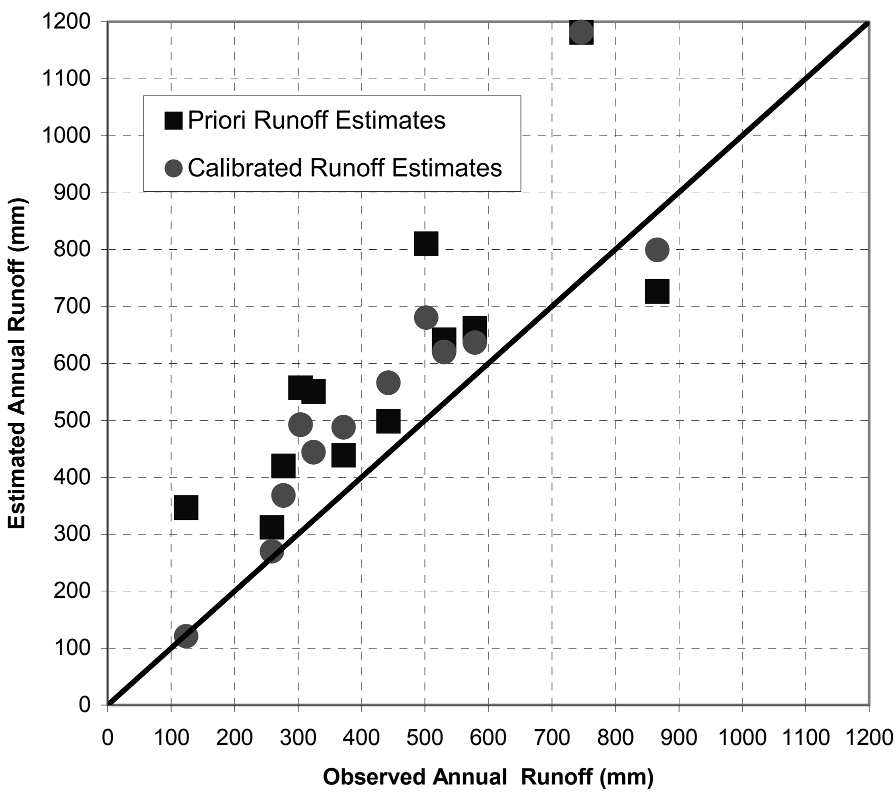

Fig. 3 Comparison of the simulated annual runoff with the observed during 1998–2002.

PARAMETER SENSITIVITY

A sensitivity analysis on the four parameters mentioned above is presented by varying each parameter value around its best estimate by ±10% and ±25% and comparing the Nash-Sutcliffe model efficiency coefficient and runoff for the different parameters. The sensitivities of the Nash-Sutcliffe efficiency coefficient and runoff to the four parameters for calibration are presented in Figs 4 and 5, respectively, which show that B and d_2 are more sensitive than the other two parameters (D_m and D_s). When B is altered by +25%, +10%, –10% and –25%, the mean variation of the Nash-Sutcliffe coefficient is 0.018, 0.007, 0.009 and 0.029, and the mean variation of runoff volume

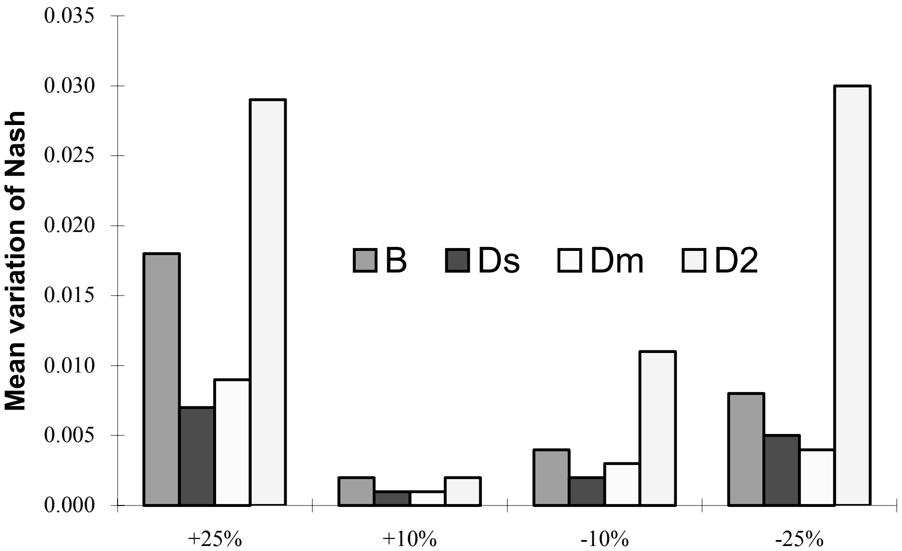

Fig. 4 Sensitivities of the Nash-Sutcliffe efficiency coefficient to the four model parameters for calibration.

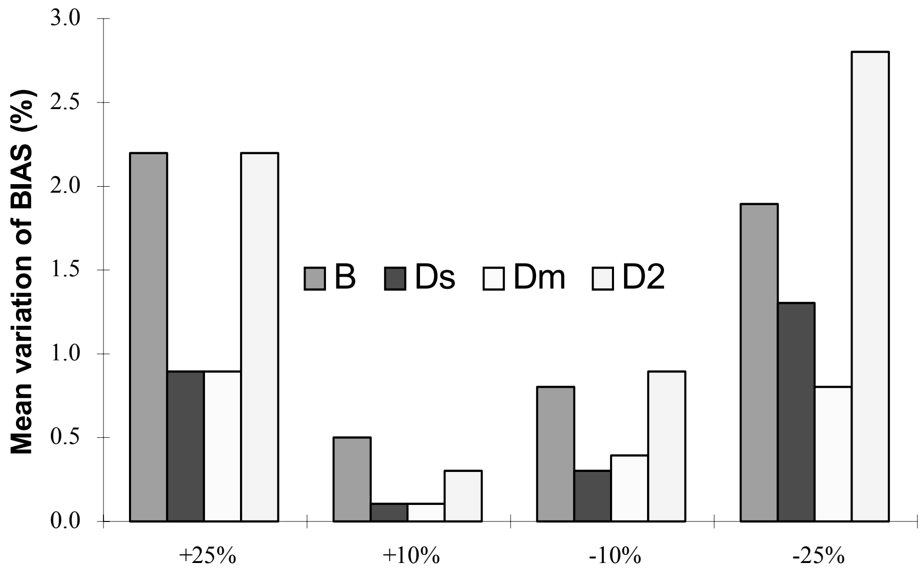

Fig. 5 Sensitivities of runoff to the four model parameters for calibration.

is 2.2%, 0.9%, 0.9% and 2.2%, respectively. By altering d_2 in the same way, the mean variation of the Nash-Sutcliffe coefficient is 0.008, 0.005, 0.004 and 0.030, and the mean variation of runoff volume is 1.9%, 1.3%, 0.8% and 2.8%, respectively. However, the same alteration of d_m and d_s produces much smaller variation in the Nash-Sutcliffe coefficient and runoff volume.

CONCLUSIONS

In this study, a parameter estimation scheme for the VIC-3L land surface model is discussed and applied to the 12 MOPEX watersheds in France, in which four VIC-3L parameters, i.e. the variable infiltration curve parameter (B), the baseflow parameters (D_m and D_s) and the depth of the second soil layer (d_2) are chosen for calibration. The VIC-3L with the calibrated parameters, when evaluated against the *a priori* parameter estimates, is able to reduce the model bias and increase the Nash-Sutcliffe efficiency coefficient of the streamflow simulation. Also, a sensitivity analysis on the calibrated parameters shows that the variable infiltration curve parameter (B) and the depth of the second soil layer (d_2) are most sensitive among the model parameters for calibration. Therefore, suitable calibration for the parameters of the land surface model VIC-3L, especially for the variable infiltration curve parameter (B) and the depth of the second soil layer (d_2) is very important for simulating land surface behaviour in a specific region.

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