Thirty-Five Year (1971–2005) Simulation of Daily Soil Moisture Using the Variable Infiltration Capacity Model over China

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ABSTRACT *We use the Variable Infiltration Capacity (VIC) land surface macroscale hydrology model driven by observed maximum and minimum air temperatures and precipitation to map daily soil moisture values over China for the period 1 January 1971 to 31 July 2005. The model is applied over a grid of 10 458 points with a resolution of 30 km × 30 km. The model is first calibrated using observed hydrographs from 35 catchments with drainage areas varying from 190 to 351 530 km^2. The model is then validated over these 35 catchments at different periods, and over an additional eight catchments with drainage areas ranging from 1230 to 10 010 km^2. An estimation procedure to determine model parameters is developed and applied to catchments where hydrographs are not available for the standard calibration process. In situ soil moisture measurements from 28 sites around the country are also used for model validation. VIC performs well over both calibration and validation catchments especially in humid and semi-humid regions. The 35-year soil moisture climatology for the top 1 m from VIC is consistent with known soil moisture conditions in China.*

RÉSUMÉ *[Traduit par la rédaction] Nous utilisons le modèle hydrologique macroscopique de surface à capacité d'infiltration variable (VIC) piloté par les températures maximales et minimales de l'air et les précipitations observées pour cartographier les valeurs quotidiennes d'humidité du sol en Chine durant la période allant du 1er janvier 1971 au 31 juillet 2005. Le modèle est appliqué sur une grille de 10 458 points dont la résolution est de 30 km × 30 km. Le modèle est d'abord étalonné à l'aide d'hydrogrammes observés provenant de 35 bassins hydrologiques dont l'aire de drainage varie entre 190 et 351 530 km^2. Le modèle est ensuite validé à ces 35 bassins hydrologiques pour différentes périodes ainsi qu'à huit autres bassins hydrologiques dont l'aire varie entre 1 230 et 10 010 km^2. Nous définissions une méthode d'estimation permettant de déterminer les paramètres du modèle et nous l'appliquons aux bassins hydrologiques pour lesquels nous ne disposons pas d'hydrogrammes pour le processus d'étalonnage de référence. Nous utilisons aussi des mesures d'humidité du sol faites sur place à 28 sites dans le pays pour la validation du modèle. Le modèle VIC donne de bons résultats tant dans les bassins hydrologiques d'étalonnage que de validation, en particulier dans les régions humides et semi-humides. La climatologie de 35 ans de l'humidité du sol dans le premier mètre fournie par le modèle VIC est compatible avec les conditions connues d'humidité du sol en Chine.*

1 Introduction

The land surface is the interface between the atmosphere and the underlying hydrological regime with the latter being characterized by soil moisture, surface run-off, interflow, baseflow and other hydrological variables (e.g., Lin et al., 2005). Although soil contains only a small fraction of the total available water in the world, the soil moisture condition plays a vital role in global water and energy exchanges. For example, Entekhabi et al. (1999), in their proposed agenda for land surface hydrology research, note that surface soil moisture can be as important a boundary condition for the climate system as sea surface temperature. Koster et al. (2004) in their study, Global Land-Atmosphere Coupling Experiment

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(GLACE)), showed that soil moisture anomalies could have a substantial impact on precipitation in certain regions of the world.

Droughts and floods are two extreme climate events which have posed a great threat to China in the past and continue to do so. The '1949–1995 Chinese Disaster Report' (National Bureau of Statistics of China, 1995) listed droughts and floods as being responsible for 71% of the country's natural disasters in terms of financial cost. In general, a drought is an extended period of abnormally dry weather sufficiently prolonged for the lack of water to cause a serious hydrological imbalance (crop damage, water supply shortage, etc.) in the affected area. However, a precise quantification of drought is still an open question, as there are many different definitions of drought (e.g., meteorological, hydrological and agricultural droughts). A commonly used practice for drought monitoring in China is the use of a soil moisture index based mainly on the soil moisture wetness condition (Zhang and Gao, 2004), which is essentially a measurement of hydrological drought.

It is difficult to obtain soil moisture measurements over a large area (of order 10^6 km^2) through field surveys. Recent advances in the development of land surface hydrological models offer the potential to reconstruct and continually update the spatial and temporal distribution of soil moisture over a large area such as China. The Variable Infiltration Capacity (VIC; Liang et al., 1994, 1996) model is such a land surface macroscale hydrology model. It uses a spatial probability distribution function to represent subgrid-scale variability in soil moisture storage capacity. Such a function is used in the Xinanjiang model (Zhao et al., 1980) for calculating saturation excess run-off, and in the General Runoff Yield model (Wen et al., 1982) for generating infiltration excess run-off. Nijssen et al. (2001) used VIC to generate 14 years (1980–93) of global daily soil moisture at a resolution of 2º × 2º. Su and Xie (2003) studied the effect of climate change on China's run-off using VIC simulations. Andreadis et al. (2005) reconstructed the drought history of the continental United States from 1920 to 2003 based upon VIC soil moisture and run-off at a resolution of 0.5º × 0.5º. Chen et al. (2006) tested the adaptability of VIC over the source region of the Yellow River in China. Li et al. (2005) verified the soil moisture simulated in several reanalysis products over China using in situ measurements.

We use VIC driven by observed maximum and minimum air temperatures and precipitation to reconstruct 35 years (1971–2005) of daily soil moisture values for China at a resolution of 30 km × 30 km. Our study is different from earlier works as actual observations and not reanalysis products are used to drive VIC, and the spatial resolution of the model is higher. There are two objectives for this study. The first is to use VIC to generate a high resolution soil moisture data bank for China. However, it is difficult to obtain soil moisture measurements over a large area as already mentioned. The second is to apply a model calibration and validation methodology using hydrographs and in situ soil moisture measurements. This methodology includes an estimation procedure using regression to determine model parameters from catchment and climate characteristics and a test of the transferability of the procedure to catchments where hydrographs are not available for calibration. We show details of the calibration and validation methodology so that interested readers may have sufficient information to use this methodology for their own study.

We calibrate and validate the model with observed daily hydrographs from 43 catchments, and also validate the model with observed soil moisture anomalies from 28 sites. We compare qualitatively the simulated 35-year average of the soil moisture in the top 1 m with an official chart of dry and wet zones in China. VIC soil moisture is now used operationally by the Chinese Ministry of Water Resources (CMWR) to calculate a soil moisture index, and nationwide maps of the index are published daily for drought monitoring.

2 Methodology

Version 4.04 of VIC is used in this study to reconstruct daily soil moisture from 1 January 1971 to 31 July 2005. This version was the latest release at the time of our study and includes some of the new features that are described in Liang et al. (1999) and Cherkauer and Lettenmaier (1999). Figure 1 shows the model grid for the calculation of surface water balance. The energy balance is not considered because observations of shortwave radiation are not available. VIC has four types of user-defined parameters: soil, vegetation, hydrology, and 'catchment definition'. By the latter, we mean basin characteristics (latitude, longitude, elevation) and climate parameters (time-averaged near-surface air temperature and precipitation). Soil, vegetation and catchment definition parameters are physically based and calibration procedures are not needed to define them. For each grid point, we use the global 10 km soil profile dataset (Reynolds et al., 2000) and the global 1 km land cover classification dataset (Hansen et al., 2000) to define the model soil and vegetation parameters. The catchment definition parameters are determined using the Global 30 Arc-Second Elevation Data Set from the U.S. Geological Survey and observed time-averaged near-surface air temperatures and precipitation from the CMWR. Values from 624 meteorological stations in China (Fig. 1) provide the meteorological forcing to VIC. This continually updated dataset has been available since 1 January 1971 and is quality controlled. The daily maximum and minimum station air temperatures and precipitation are estimated on a 30 km × 30 km grid using the inverse distance weighted method. This is one of the best methods for interpolation of these Chinese data. Meteorological values and observed daily hydrographs are obtained from the CMWR. The hydrographs are not corrected for the operation of reservoirs and irrigation as we are unable to obtain such information; some calibration cases could be affected by such operations.

VIC has seven user calibrated hydrological parameters, shown in Table 1. We use basin observed hydrographs to calibrate the model because they reflect the integrated basin

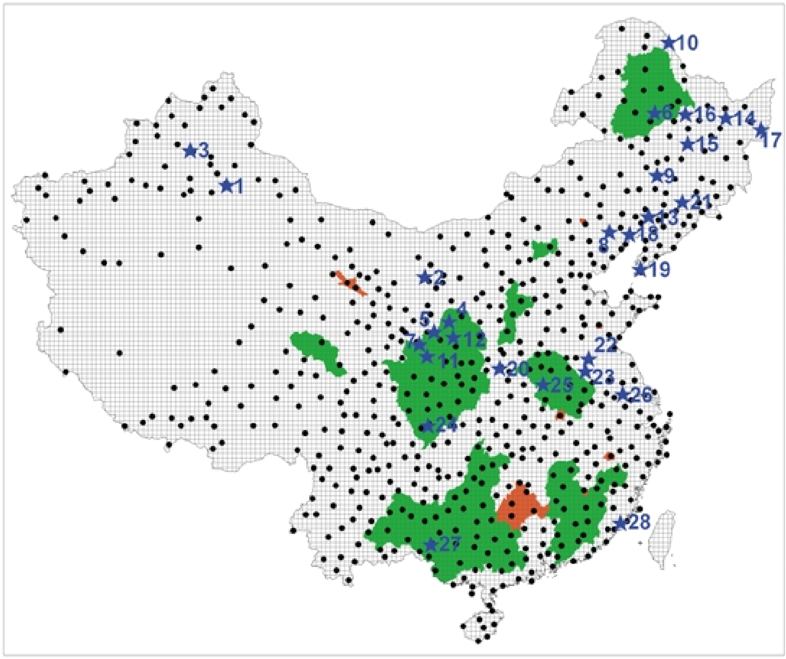


Fig. 1 The grid shown above is the VIC model grid over China with 10 458 grid points, at a resolution of 30 km × 30 km. The dots represent the 624 meteorological stations used in this study, and the stars (numerically ordered) show the 28 sites where in situ soil moisture measurements are available. The 35 calibration and 8 validation catchments are coloured green and red respectively.

Table 1. The seven VIC user calibrated hydrological parameters.

Parameter	*Description*
b _infilt	variable infiltration curve
Dsmax	maximum velocity of baseflow
Ds	fraction of *Dsmax* where non-linear baseflow begins
Ws	fraction of maximum soil moisture where non-linear baseflow occurs
*d*1	thickness of first soil moisture layer
*d*2	thickness of second soil moisture layer
*d*3	thickness of third soil moisture layer

hydrological response. We keep the thickness of the first soil moisture layer constant ($d1 = 0.1$ m), and use observed daily hydrographs from 35 catchments (Fig. 1) with drainage areas varying from 190 to 351 530 km^2 to calibrate the remaining six parameters. In version 4.04 of VIC, the upper layer depth is taken as the sum of the depths of the first and second soil moisture layers, and the surface run-off is assumed to be generated from the upper layer. Therefore, our choice of using a constant $d1$ is justifiable because VIC treats the first and second soil moisture layers as one entity when calculating the surface run-off.

We first discuss the calibration and validation processes of the six parameters mentioned earlier using observed hydrographs. We start with best estimates for each model grid point of the 35 calibration catchments. We then apply VIC forced by gridded daily maximum and minimum air temperatures and precipitation for each catchment over periods of 5–6 years, depending on the availability of observed hydrographs, with a model time step of 24 hours. We use an auto-optimization procedure based on Rosenbrock (1960) for calibration. The optimization procedure uses two objective functions:

$$E_r = \left(\overline{Q_c} - \overline{Q_o}\right) / \overline{Q_o}$$

$$E_c = 1 - \sum_i \left(Q_{i,c} - Q_{i,o}\right)^2 / \sum_i \left(Q_{i,o} - \overline{Q_o}\right)^2$$

where, $\overline{Q_c}$ and $\overline{Q_o}$ are the time-averaged simulated and observed discharges respectively; E_r is the relative error; $Q_{i,c}$ and $Q_{i,o}$ are the simulated and observed discharge at time step (i) respectively; and E_c is the Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970). We have also used another auto-optimization procedure (Duan et al., 1992) and found the optimized parameters to be generally similar using either procedure. We will refer to this calibration process, using hydrographs, as standard calibration.

We now turn to parameter determination for catchments where hydrographs are not available for calibration. This is important as not all catchments are gauged, and hydrographs may not always be available even for gauged catchments. We refer to such catchments for the purpose of this discussion as ungauged. We use an estimation procedure based on regression to determine parameter values in this case. In particular, we regress the six VIC hydrological parameters (Table 1) with 17 catchment and climate characteristics over the 35 calibration catchments. These 17 characteristics are shown in Table 2. The regression relations are then used for parameter estimation on ungauged catchments. The determination of the

TABLE 2. The 17 catchment and climate characteristics used for regression in the estimation procedure of model parameters.

Parameter	Description
Ksat	saturated hydrologic conductivity (mm d^{-1})
EXPT	the parameter describing the variation of *Ksat* with soil moisture
BUBBLE	bubbling pressure of soil (cm)
QUARZ	quartz content of soil
SAT	saturated soil moisture
WcrFT	fractional soil moisture content at the critical point
WpFT	fractional soil moisture content at the wilting point
RESM	soil moisture layer residual moisture
Weff	effective soil moisture
T	average temperature (°F)
P	mean annual precipitation (mm)
Em	mean annual measured evaporation (mm)
Dry	mean annual drought index (= *Em* / *P*)
CV_T	coefficient of variation of mean monthly temperature
CV_P	coefficient of variation of mean monthly precipitation
CV_E	coefficient of variation of mean monthly measured evaporation
CV_Dry	coefficient of variation of mean monthly drought index

regression relations is similar to the study of Abdulla and Lettenmaier (1997). A stepwise process generates regression coefficients, and retains only those that are statistically significant. We show below the six regression relations that relate the user calibrated hydrological parameters (Table 1) to the catchment and climate characteristics (Table 2). The statistically significant independent variables that are retained in our study are consistent with those obtained by Abdulla and Lettenmaier (1997).

$$
\begin{aligned}
b\_infilt &= (-5.3262 + 1.4628\sqrt{CV\_Dry} + 9.8681\sqrt{SAT} \\
&\quad -3.9723\sqrt{WpFT} + 3.7661\sqrt{RESM} \\
&\quad +0.6554\sqrt{CV\_T} - 1.4943\sqrt{CV\_P})^2 \\
Ds &= (-1.2819 - 0.7718\sqrt{Dry} + 0.8036\sqrt{CV\_P} \\
&\quad +0.0280\sqrt{Em} + 0.7640\sqrt{CV\_T} \\
&\quad +0.3529\sqrt{CV\_E} + 0.2330\sqrt{CV\_Dry})^2 \\
Dsmax &= (283.20 + 267.52\sqrt{WpFT} + 0.1143\sqrt{P} \\
&\quad +1.2008\sqrt{BUBBLE} - 103.03\sqrt{QUARZ} \\
&\quad -569.58\sqrt{WcrFT} + 6.0872\sqrt{CV\_T})^2 \\
Ws &= -6.6682 - 0.3302CV\_P + 7.8802QUARZ \\
&\quad -0.1629EXPT - 0.0014Ksat + 18.63WcrFT \\
&\quad -0.3262CV\_Dry \\
d2 &= (8.0807 - 1.0168\sqrt{CV\_Dry} - 0.2240\sqrt{T} \\
&\quad +1.0026\sqrt{EXPT} - 15.341\sqrt{SAT} \\
&\quad +8.1252\sqrt{Weff} - 1.6263\sqrt{CV\_E})^2 \\
d3 &= 3.3291 - 2.4999CV\_E - 0.0708T + 0.1882EXPT \\
&\quad -4.9105WpFT + 0.0011Em - 1.4516CV\_P
\end{aligned}
$$

TABLE 3. The significance of the six regression relations for the model parameters. RMSE, R^2 and F are the root-mean-square error, percentage of variance explained and the F-test value for statistical significance. The results are all significant at the 95% level.

Parameter	RMSE	R^2	F
b_infilt	0.100	0.65	8.6
Ds	0.080	0.78	16.7
Dsmax	1.024	0.51	4.9
Ws	0.121	0.62	7.6
*d*2	0.141	0.56	6.0
*d*3	0.241	0.70	10.7

We have conducted a significance test of the above six regression relations and the results are given in Table 3; they are all significant at the 5% level as determined by the F-test, as used in Abdulla and Lettenmaier (1997).

For model validation, we use observed hydrographs from the same 35 calibration catchments taken over different periods than for the calibration, and from eight additional catchments with drainage areas varying from 1230 to 10 010 km^2 (Fig. 1). Thus, a total of 43 catchments is used for calibration and validation; they are selected to reflect China's diversified climate conditions and for consistency in catchment characteristics. Table 4 provides a summary of these characteristics; additional information in the last four columns for calibration and validation will be discussed in Section 3. The catchments numbered 1 to 35 are used for both calibration and validation, whereas those numbered from 36 to 43 are treated as ungauged with model parameters estimated using the six regression relations. The calibration and validation periods for the first 35 catchments are, on average, 5–6 and 2 years respectively.

We also obtained in situ soil moisture measurements from 28 sites (Robock et al., 2000; Fig. 1) for model validation. The measurements were taken at 11 vertical levels starting from the surface down to a depth of 1 m and were made three times per month (8, 18, and 28) from 1981 to 1999. The ranges of annual average precipitation and soil moisture content are from 13 mm to 1316 mm and 67 mm to 381 mm over the 28 sites, covering dry and wet catchments. As soil properties are highly heterogeneous, point soil moisture observations are typically inconsistent with model results which represent grid box averages. Therefore, comparison of simulated soil moisture with in situ observations is problematic and is an issue of active debate. Nevertheless, we use in situ soil moisture anomalies for model validation; the high resolution model simulation would also help in this respect. Our study, with a resolution of 30 km, is the highest resolution model used to date in China.

3 Results

We show the calibration and validation results in the last four columns of Table 4, using the relative error (E_r) and Nash-Sutcliffe model efficiency coefficient (E_c) for the first 35 catchments. The validation period is different from the calibration period for these catchments as described in the table.

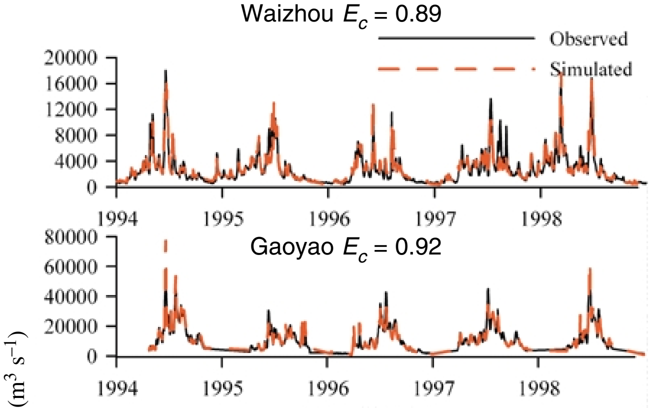
TABLE 4. Description of the 43 calibration and validation catchment characteristics, and results of the calibration and validation (last four columns). E_r and E_c are the relative error and the Nash-Sutcliffe model efficiency coefficient respectively. For the column labeled "period", the period of the entire record is given first, followed by the validation period in brackets. For example, 94–97(97) indicates that the record length is 1994–97 with 1997 used for validation; thus 1994–96 is used for calibration.

				Area	Elevation	Annual precip.	Lat.	Calibration		Validation	
	Catchment	River	Period	(km^2)	(m)	(mm)	(°N)	E_r (%)	E_c	E_r (%)	E_c
1	Hejin	Fenhe	94-97 (97)	38,720	1119	480	35.570	7.3	0.665	55.6	0.695
2	Jimai	Yellow river	94–97 (97)	45,010	4452	409	33.770	–2.6	0.576	22.3	0.682
3	Xiangshui	Yongdinghe	94–96 (96)	14,500	1257	372	40.520	9.8	0.629	–1.2	0.111
4	Weijiabao	Weihe	80–90 (89–90)	38,230	1860	511	34.300	–2.5	0.757	5.5	0.519
5	Zhangjiash	Weihe	80–90 (89–90)	43,740	1462	475	34.633	–1.6	0.668	5.0	0.544
6	Huaxian	Weihe	80–90 (89–90)	106,500	946	611	34.583	0.9	0.794	–0.6	0.623
7	Zhuangtou	Weihe	80–90 (89–90)	25,840	1276	512	35.033	0.3	0.512	5.3	0.431
8	Xixian	Huaihe	91–97 (96–97)	10,190	142	1053	32.330	–11.6	0.717	7.8	0.689
9	Wangjiaba	Huaihe	91–95 (95)	30,630	95	1031	32.430	5.9	0.879	42.8	0.718
10	Runheji	Huaihe	92–97 (97)	40,360	155	1158	32.520	6.6	0.858	29.5	0.260
11	Rutaizi	Huaihe	91–97 (96–97)	88,630	181	850	32.566	–7.5	0.750	1.9	0.767
12	Benbu	Huaihe	91–97 (96–97)	121,330	41	817	32.933	–14.8	0.670	–3.9	0.709
13	Tongmen	Songhuajiang	94–98 (98)	108,020	500	499	48.070	8.8	0.649	–18.7	0.823
14	Jiangqiao	Songhuajiang	94–98 (98)	162,570	478	465	46.783	18.7	0.342	–4.3	0.882
15	Waizhou	Ganjiang	94–00 (99–00)	80,940	285	1572	28.630	–0.7	0.871	8.3	0.823
16	Taoyuan	Yuanjiang	94–00 (99–00)	85,220	653	1325	28.900	–1.6	0.611	6.2	0.707
17	Baihe	Hanjiang	94–00 (98)	59,110	1176	847	32.820	1.8	0.863	2.8	0.941
18	Beipei	Jialingjiang	94–00 (99–00)	156,140	1340	849	29.850	2.8	0.831	–1.1	0.850
19	Gaoyao	Xijiang	94–00 (99–00)	351,530	771	1401	23.050	–0.4	0.909	10.1	0.900
20	Xindou	Xijiang	94–00 (99–00)	6,380	387	1597	24.000	–14.0	0.748	1.7	0.774
21	Yangkou	Minjiang	94–99 (98–99)	12,670	427	1737	26.800	9.2	0.719	3.6	0.837
22	Qilijie	Minjiang	94–99 (98–99)	14,790	563	1712	27.017	5.4	0.799	–7.6	0.904
23	Shaxian	Minjiang	94–99 (98–99)	9,920	527	1638	26.383	–5.8	0.702	–0.9	0.819
24	Caoan	Hanjiang	94–00 (99–00)	29,080	365	1622	23.667	–0.8	0.823	–0.9	0.835
25	Hengshan	Hanjiang	94–00 (99–00)	12,620	294	1640	24.467	–3.0	0.839	–2.6	0.851
26	Xikou	Hanjiang	94–00 (99–00)	9,230	498	1629	24.533	–6.2	0.672	–9.2	0.722
27	Yongding	Hanjiang	94–00 (99–00)	840	533	1596	24.733	–3.0	0.675	–7.0	0.736
28	Shanghang	Hanjiang	94–00 (99–00)	5,890	529	1649	25.050	–8.5	0.720	–8.4	0.759
29	Guanyinqi	Hanjiang	94–00 (99–00)	380	470	1683	25.850	3.2	0.769	3.4	0.749
30	Yangjiafan	Hanjiang	94–00 (99–00)	740	682	1641	25.383	–13.8	0.671	–16.8	0.630
31	Zhangping	Jiulongjiang	94–00 (99–00)	4,940	647	1603	25.283	–0.5	0.618	2.1	0.629
32	Maiyuan	Jiulongjiang	94–00 (99–00)	640	643	1615	25.600	–8.4	0.669	2.3	0.699
33	Longmen	Jiulongjiang	94–00 (99–00)	190	751	1629	25.100	–8.3	0.520	–21.1	0.666
34	Boluo	Dongjiang	94–00 (99–00)	25,330	260	1778	23.167	–5.2	0.757	–3.7	0.747
35	Qilinzui	Dongjiang	94–00 (99–00)	2,870	209	1937	23.350	–9.9	0.719	–3.9	0.646
36	Shaziling	Fuhe	94–98	1,230	321	1729	26.883				
37	Shangrao	Xinjiang	94–98	2,740	235	1802	28.450				
38	Shuangfeng	Xiangjiang	94–98	1,460	159	1129	27.399				
39	Hengyang	Xiangjiang	94–00	52,150	390	1475	26.950				
40	Luizixiang	Yangtse River	80–85	3,000	163	1267	30.933				
41	Donglidian	Yijiang	94–98	1,180	403	675	36.222				
42	Weichang	Ruanghe	94–98	1,280	1129	421	42.112				
43	Yinluoxia	Heihe	94–00	10,010	3614	326	38.800				

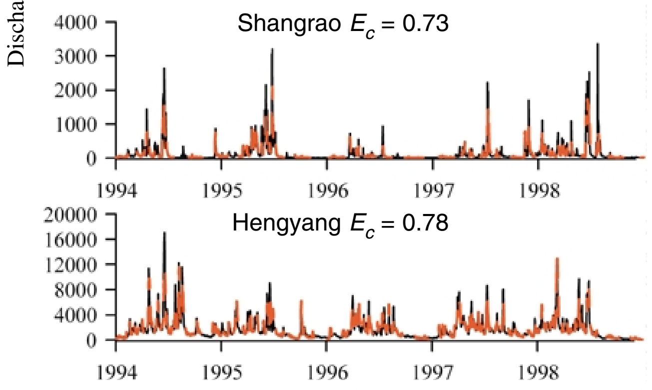
The values of E_r and E_c over the calibration period vary respectively from –14.8% to 18.7% and 0.34 to 0.91, and the average values over these catchments are -1.4% and 0.71 respectively, indicating a satisfactory calibration. According to Boone et al. (2004), a deterministic hydrological simulation is considered good if $E_c \geq 0.7$. Figure 2a shows examples of hydrographs for two such catchments in the Yangtze River and Pearl River basins. The calibrated hydrographs compare well with observations. In general, VIC performs well in the east, south-east, central, south and south-central regions of China, which are semi-humid and humid. The calibration results from the arid west and north-west regions are not as satisfactory. It is known that hydrological models do not work well in arid conditions. The network of meteorological stations is also much denser in the humid and semi-humid areas compared to the arid areas, partly due to the denser population distribution and more advanced economic development.

We now turn to the validation results. We first validate the simulated hydrographs with observations over the same 35 calibration catchments, but for different periods than for the calibration. Table 4 shows that the values of E_r and E_c vary respectively over the validation period from –21.1% to 55.6% and 0.11 to 0.94 for the 35 calibration catchments, with average values of 3.0% and 0.71 respectively. These are compatible with the calibration results. The ranges of values are larger over the validation period.

We next examine results from the eight additional validation catchments, numbered 36 to 43 in Table 4. These catchments are first treated as ungauged, with no hydrographs available to determine model parameters through the standard calibration process. Instead we use the regression relations



(a) Calibration



(b) Validation

Fig. 2 Comparison of the simulated (red dashed) and observed (black solid) hydrographs over 2 calibration and 2 validation catchments. The Nash and Sutcliffe coefficient (E_c) is given in the figure.

described earlier that relate the six VIC hydrological parameters to the catchment and climate characteristics to estimate parameter values. We are thus testing the transferability of the regression relations, which were determined over the 35 calibration catchments. The eight catchments are actually gauged, but we apply the regression relations, treating them as ungauged. In Table 5 we show E_r and E_c from this estimation procedure. We also show in this table the values obtained using the standard calibration process using hydrographs. The values of E_r and E_c vary from –63.5% to 50.5 % and 0.15 to 0.78 respectively over the eight catchments, treating them as ungauged, with an average of –12.2% and 0.53. If the catchments were treated as gauged, standard calibration would give a significant improvement; the average E_r and E_c become –1.2% and 0.74 respectively, with a corresponding range of –9.3% to 11.2% and 0.52 to 0.85 (Table 5). This improvement is expected, showing the value of hydrographs in parameter determination. Figure 2b shows the simulated and observed hydrographs for two of these eight catchments in the Yangtze River Basin, treating them as ungauged. As with the previous results, VIC performs less well in arid areas.

TABLE 5. Results of VIC validation over the additional eight catchments. "Estimated parameters" refers to using the six regression relations linking model parameters to catchment and climate characteristics to estimate parameter values, treating the catchment as ungauged. "Calibrated parameters" refers to using the standard calibration process with hydrographs instead.

			Estimated parameters		Calibrated parameters	
	Catchment	Period	E_r (%)	E_c	E_r (%)	E_c
36	Shaziling	1994–1998	–2.4	0.731	–0.8	0.806
37	Shangrao	1994–1998	5.6	0.733	–9.0	0.792
38	Shuangfeng	1994–1998	50.6	0.578	10.6	0.712
39	Hengyang	1994–2000	15.4	0.780	1.9	0.853
40	Luizixiang	1980–1985	–11.1	0.635	–9.3	0.852
41	Donglidian	1994–1998	–37.8	0.363	11.2	0.632
42	Weichang	1994–1998	–55.0	0.289	–7.6	0.521
43	Yinluoxia	1994–2000	–63.5	0.147	–6.8	0.773

We note, from the generally lower E_r and E_c scores for catchments with significant snow, that VIC does not simulate the timing of ground snowmelt well. For example, the values for the north-east catchment, Jiangqiao, are 18.7% and 0.34 respectively. Over this catchment, we have set 0.5°C as the maximum threshold temperature for snow and –0.5°C as the minimum threshold for rain. These thresholds could have strong localized characteristics, and their particular values could affect snowmelt simulation. The snowmelt problem in VIC was also found in the North American Land Data Assimilation System (NLDAS) project (e.g., Fig. 12 in Lohmann et al. (2004)). This difficulty might be partly caused by the scale problem of estimating grid precipitation and temperature from point gauges as discussed in Pan et al. (2003). Another reason might be the way VIC is used in this study where we only calculate the surface water balance and not the energy balance: we do this because observations of shortwave radiation are not available. Further study is needed on the snowmelt issue.

Soil moisture measurements from the 28 sites are also used for validating the model. Figure 3 shows the simulated and observed soil moisture anomalies for Xifengzhen (site 12 in Fig. 1) located in a semi-humid region. The correlation coefficient of simulated and observed soil moisture anomalies (r) is also given in the figure. We calculated r for each of the 28 sites, and the overall average values are r = 0.60, 0.50 and 0.52 for depths of 0–20, 20–100 and 0–100 cm respectively, indicating satisfactory model performance. We next examine the model performance under different precipitation regimes. To this end, we ordered the 28 sites according to their annual precipitation, with the geographical ordering of the stations shown in Fig. 1. For example, site 1 in the north-west (Turpan) has an annual precipitation of only 13 mm, the least of all the sites. The site with the highest precipitation (Baise in the south-east) is numbered 28, with 1316 mm. Figure 4 shows there is a clearly increasing trend of r values from arid to wet regions for the 0–20 cm depth, showing that soil moisture values are better simulated under humid conditions. However, such a trend is not found for the 20–100 cm depth. We would expect the top layer (0–20 cm) to be more influenced by precipitation. This has been confirmed by our F-test. The correlation coefficient for the trend in Fig. 4 is significant

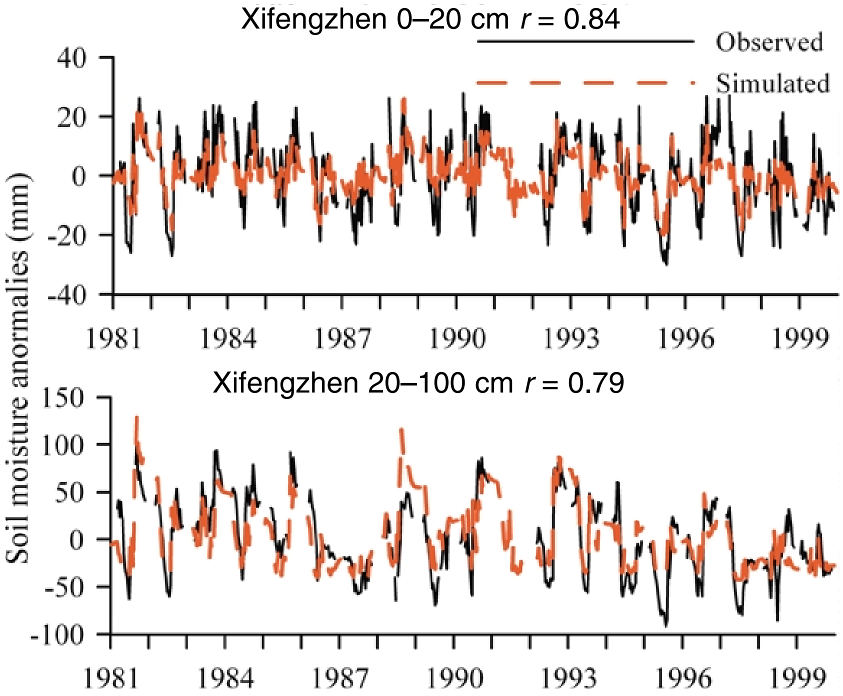


Fig. 3 Comparison of simulated (red dashed) and observed (black solid) soil moisture anomalies (mm) for depths of 0–20 and 20–100 cm at one site. The correlation coefficient (r) is given in the figure.

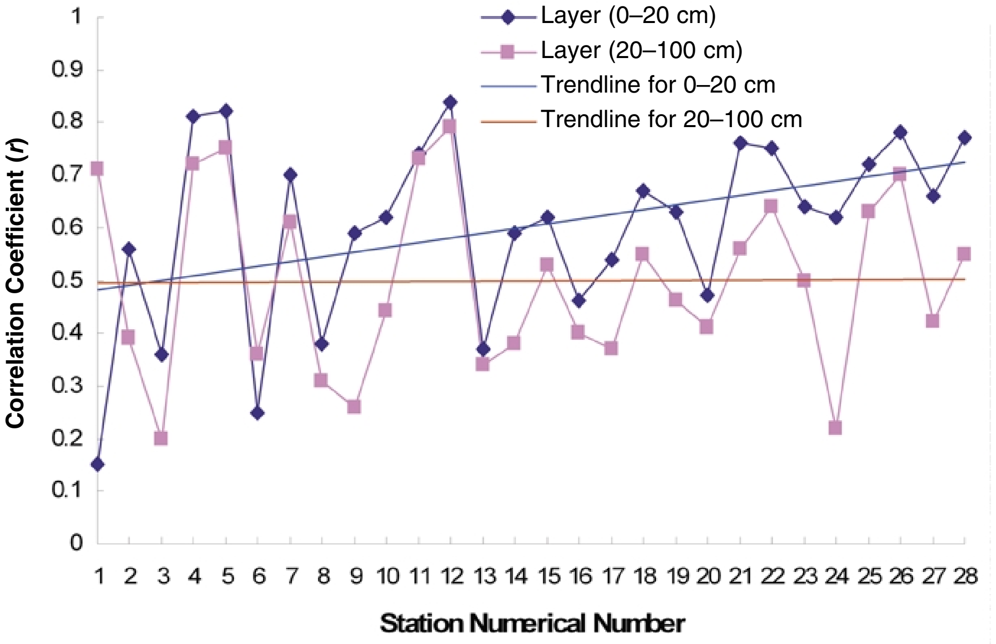


Fig. 4 The geographic variation of the correlation coefficient of simulated and observed soil moisture anomalies (r) with annual precipitation for the 28 sites, for depths of 0–20 and 20–100 cm. The geographical ordering of the sites is shown in Fig. 1, with annual precipitation increasing with station number.

for only the top layer (0.51) and not for the second layer (0.07). The threshold for significance at the 95% level is 0.37. We note that three of the highest correlations, exceeding 0.8, in Fig. 4 are found in the so-called “moisture rich” Yellow River irrigation area in the southern part of Ningxia Hui Autonomous Region and eastern Gansu Province. It is well known in China that irrigation in this area gives a semi-humid local climate, which may partly explain the high correlation.

Figure 5 presents the 35-year (1971–2005) average of the soil moisture in the top 1 m along with the 180 mm soil moisture contour, showing humid regions in the south and arid regions to the north. The calibrated VIC wilting point varies

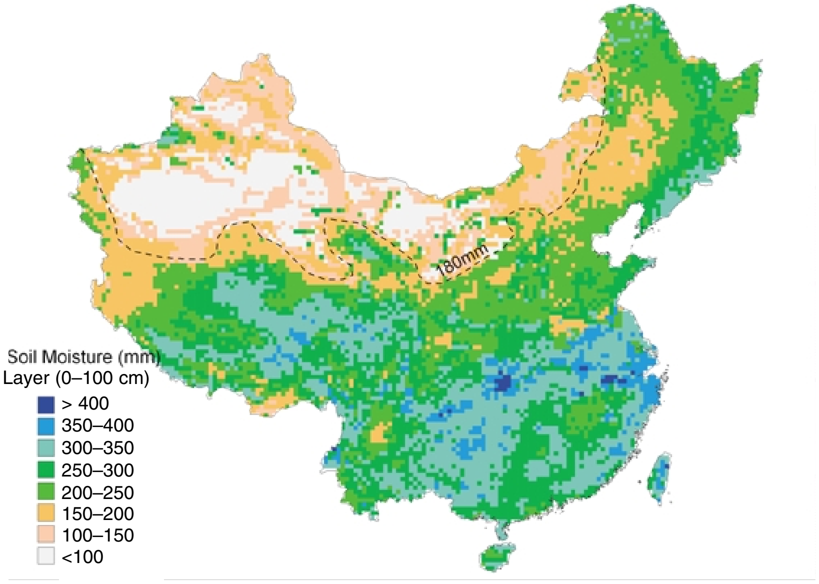


Fig. 5 The 35-year simulated soil moisture climatology for the top 1 m over China for the period 1971–2005. The 180 mm contour is shown; see text for discussion.

from 43 to 331 mm, with an average value of 173 mm, close to our 180 mm threshold. The soil moisture distribution compares well qualitatively with an official chart of dry and wet zones in China, published by the CMWR (1997). Our simulated 180 mm soil moisture contour is in close agreement with the dry and wet zone division of the chart (results not shown). We are in the process of examining reports of China's drought history from 1949–90 contained in CMWR (1977). Preliminary results indicate that our simulated daily soil moisture correlates well in both time and space with the recent drought history of 1971–90. These results will be reported in a future publication.

4 Conclusion

We have used the VIC land surface macroscale hydrology model driven by observed maximum and minimum air temperatures and precipitation to map daily soil moisture values over China from 1 January 1971 to 31 July 2005, at a resolution of 30 km. The model is first calibrated and validated using observed daily hydrographs over 43 catchments. The simulated soil moisture anomalies agree well with in situ observations from 28 sites, especially in humid and semi-humid regions. The 35-year soil moisture climatology for the top 1 m layer agrees well with known soil conditions in China. The soil moisture dataset generated in this study represents the first effort at using a hydrological model to estimate soil moisture at such a high resolution over the entire country. An estimation procedure to determine model hydrological parameters based on regression relations between these parameters and catchment and climate characteristics has been developed. The relations have been applied over catchments where hydrographs are not available for standard model calibration.

As a result of our study, the CMWR has adopted VIC operationally for drought monitoring. More specifically, VIC soil moisture is used in the calculation of a soil moisture index by the CMWR, and nationwide maps of the index are published daily for drought monitoring. The drought monitoring maps are provided to the Office of State Flood Control and Drought Relief Headquarters in China for use in decision making. This soil moisture dataset can be used to understand trends and variability relevant to drought and climate.

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