Spatio-temporal variation of surface soil moisture over the Yellow River basin during 1961–2012

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Abstract Soil moisture plays a significant role in agricultural and ecosystem development. However, in the real world soil moisture data are very limited due to many factors. VIC-3L model, as a semi-distribution hydrological model, can potentially provide valuable information regarding soil moisture. In this study, daily soil moisture contents in the surface soil layer (0–10 cm) of 1500 grids at 0.25 × 0.25 degree were simulated by the VIC-3L model. The Mann-Kendall trend test and Morlet wavelet analysis methods were used for the analysis of annual and monthly average surface soil moisture series. Results showed that the trend of surface soil moisture was not obvious on the basin scale, but it varied with spatial and temporal conditions. Different fluctuation amplitudes and periods of surface soil moisture were also discovered on the Yellow River basin during 1961 to 2012.

Key words surface soil moisture; VIC-3L; variation; Mann-Kendall test; Morlet wavelet analysis

INTRODUCTION

Soil moisture plays a significant role in climatic circulation and hydrological cycle as it governs the mass and energy balance between the land surface and atmosphere. It is a key variable in hydrological processes, effecting evaporation, transpiration, runoff and precipitation directly or indirectly, and has an impact on plant growth and carbon fluxes (Dirmeyer *et al.*, 1999; Entekhabi *et al.*, 1999). The Yellow River basin, as the second largest drainage basin of China, is one of the regions facing agricultural and ecological issues; accommodates 114 million (2010) people and suffers from serious water loss and soil erosion. Taking the variation of soil moisture into account will benefit the water management and ecosystem construction of the Yellow River basin. However, its application is difficult as due to the difficulties of *in situ* or remotely sensed measurements, the soil moisture data are always unavailable or limited in their spatial and temporal resolution (Nied *et al.*, 2013). A macroscale hydrologic model, the Variable Infiltration Capacity (VIC-3L) was used to simulate the hydrologic processes in the Yellow River basin from 1961 to 2012. And daily soil water contents in three layers with depths of 0–10, 10–50 and 50–200 cm were simulated as outputs. The Mann-Kendall trend test and Morlet wavelet analysis were chosen to do research on the varying trends and oscillation features of soil moisture in the Yellow River basin.

Yellow River basin

The Yellow River (Fig. 1) originates in the Tibet Plateau, crosses the Loess Plateau and the North China Plain and reaches the Yellow Sea after 5464 km. The area of the whole basin is 7.95 × 10^5 km^2 and contains all the four types of climatic zone (arid/semi-arid and humid/semi-humid zones). Mean annual precipitation decreases from the southeast to northwest and the 400 mm precipitation isoline crosses the basin from northeast to southwest. Because of the complexity of the terrain and climate conditions, the air temperature varies from –4° to 12°C depending on spatial location.

VIC-3L Model

The VIC-3L model is now widely and successfully used for hydrological modelling in many regions all around the world. Because of the physical exchange mechanism between the atmosphere, vegetation and soil is considered in this model, the variation of water–energy conditions and water–energy transfer is reflected. Additionally, VIC-3L represents the effects of multiple vegetation types.

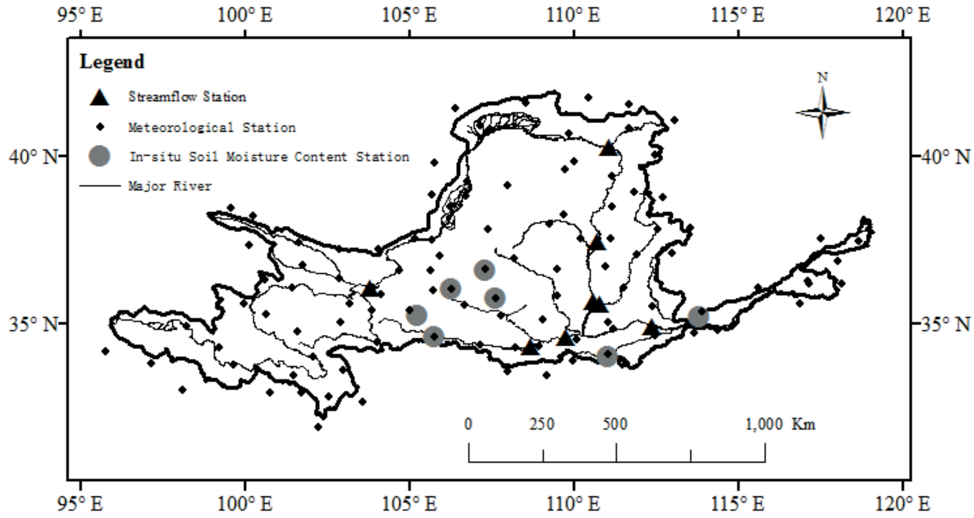


Fig. 1 The Yellow River basin and the geographical distribution of the stations used in this study.

VIC-3L covers water and energy budgets, which can drive both the energy and water balance (Xie *et al.*, 2007). It uses the variable infiltration curve to account for the spatial heterogeneity of runoff generation and assumes that the surface runoff from the upper two soil layers is generated by those areas for which precipitation, when added to soil moisture storage at the end of the previous time step, exceeds the storage capacity of the soil. In addition, soil water diffusion between the three soil layers is also considered in the VIC-3L model as well.

DATA

Meteorological data from 109 weather stations inside and close to the Yellow River basin were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). The dataset, including daily precipitation, maximum temperature, minimum temperature and wind speed from 1961 to 2012, comprised the forcing datasets. Digital elevation data with 1-km resolution were obtained from the National Oceanic and Atmospheric Administration (NOAA). Vegetation-related parameters were calculated from the Global Land Cover Facility dataset produced by Maryland University. Soil characteristics were derived from a 5-min Food and Agriculture Organization (FAO) dataset. The datasets above were interpolated into the 1500 grids by the method of inverse distance square; the influence of elevation on the air temperature was specifically considered.

Daily streamflow data from 10 streamflow stations were used for adjusting parameters in the calibration and validation of the model. Periods 1961–1990 and 1991–2012 were selected as the calibration and validation periods. The precision of the model in both the calibration and validation periods was able to pass the required accuracy using the targets of the Nash-Sutcliffe coefficient (NSCE) (Nash and Sutcliffe, 1970) and the relative error (BIAS).

Measured soil water content datasets of seven stations, obtained from the China Meteorological Administration (CMA), in the Yellow River basin from 1981 to 1999 were compared with the model simulated soil moisture content data. This dataset was limited in time scale (about 10 days), sometimes was not continuous and was interrupted in winter. The results show a good correspondence between the two different approaches of soil moisture in the top layer (0–10 cm), but the soil moisture data are no good in the other two layers. Pearson correlation coefficients for the comparison varied from 0.24 to 0.71 and averaged 0.55. Table 1 reveals the correlation coefficients between the simulated soil moisture and soil moisture from the seven *in situ* stations.

The inspected surface soil moisture data generated by VIC model were used to analysis the spatial and temporal variation in the Yellow River basin.

Table 1 Correlation coefficients between the simulated and *in situ* soil moisture data.

Station	Latitude (N)	Longitude (E)	P
Huanxian	36°34′	107°18′	0.66
Guyuan	36°00′	106°16′	0.69
Xifengzh	35°44′	107°38′	0.59
Tongwei	35°13′	105°14′	0.71
Tianshui	34°35′	105°45′	0.57
Lushi	34°00′	111°01′	0.42
Xinxian	35°10′	113°49′	0.24

P, Pearson correlation index

METHODOLOGY

Mann-Kendall trend test

Non-parametric tests are more suitable for analysing non-normally distributed data and censored data hydro-meteorological time series (Li *et al.*, 2012). The Mann-Kendall trend test is an example of a non-parametric test that is appropriate for detection of trend in hydrological series (Mojtaba, 2012).

The variation trend can be estimated from the test statistic UF:

$$UF = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}}, k = 1,2,\cdots,n \quad (1)$$

where $S_k = \sum_{i=1}^{k}\sum_{j=1}^{i-1} a_{ij}$, $a_{ij} = \begin{cases} 1, & x_i > x_j \\ 0, & x_i < x_j \end{cases} (1 \leq j \leq i)$ and $E(S_k) = \frac{k(k-1)}{4}$, $Var(S_k) = \frac{1}{72}k(k-1)(2k+5)$, where *n* is the length of the time series, *x* is the value of data.

If the UF < 0 (>0), it indicates a decrease (increase) trend in the series. The hypothesis is rejected (no trend) if $|UF| < z_{1-\alpha}$ where z is from standard normal distribution and α is the significance level. In this study, α = 95% (z = 1.96) is selected as the significance level.

Wavelet analysis

As a method developed for signal analysis, image compression, audio encoder, pattern recognition, etc., wavelet analysis is widely used in analysis of hydrologic time series, and is powerful for describing multi-scale and non-stationary processes. While traditional Fourier spectral analysis is limited for non-stationary data, continuous wavelet transforms (CWTs) can be effectively applied for historical hydrological time series analysis and providing a time-scale representation of the signal (Nakken, 1999; Krikup *et al.*, 2001; Beecham and Chowdhury, 2010).

Mathematically a CWT can be expressed as:

$$C(a,b) = \frac{1}{\sqrt{a}}\int s(t)\Psi^*\left(\frac{t-b}{a}\right)dt \quad (2)$$

where C is the wavelet coefficient, *a* and *b* are the temporal scale and the time position functions, $s(t)$ is the signal, Ψ^* is the complex conjugate of the mother wavelet Ψ. The wavelet coefficients (C) are the results of the CWT of signal $s(t)$.

In the CWT process, the Morlet wavelet in equation (2) is commonly used:

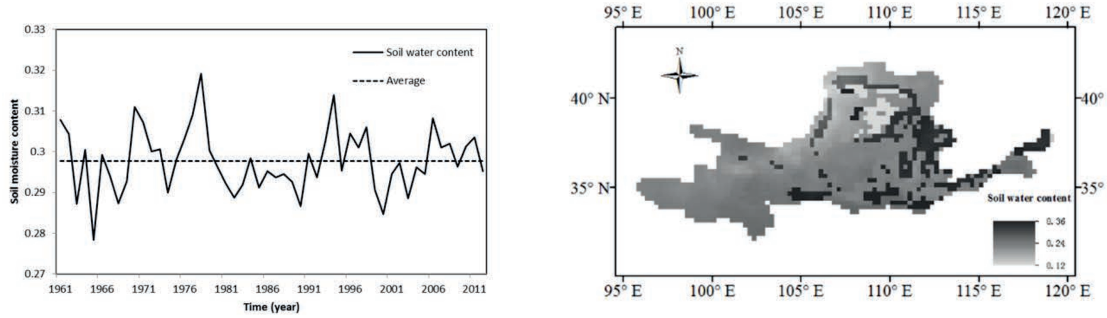
$$\Psi(t) = e^{iw_0 t}e^{-t^2/2} \quad (3)$$

where i is the imaginary part, and w_0 is the nondimensional frequency (Sang *et al.*, 2011).

RESULTS

With the help of statistical methods, Fig. 2 shows the variation of mean surface soil water content within the Yellow River basin and the spatial distribution of average surface soil water content during the 52 years. The average surface soil water content varied from 0.279 to 0.320, with a mean value of 0.298. The relatively high water content appeared in some places including besides the

Yellow River in the Ningxia and Inner Mongolia irrigation area, Weihe River basin, Fenhe River basin and the downstream drainage basin. Drier surface soil moisture conditions occurred in the Wudinghe River basin.



(a) (b)

Fig. 2 (a) Variation of mean surface soil water content for the Yellow River basin, and (b) spatial distribution of average surface soil water content during 52 years

Trend analysis

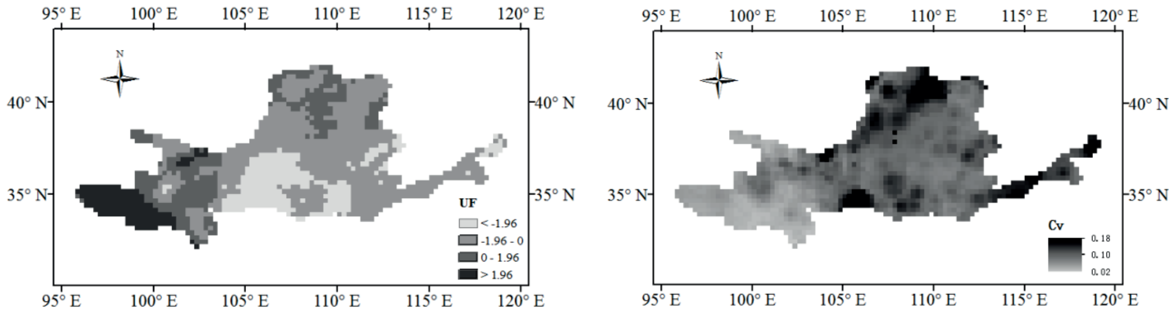
Application of the Mann-Kendall test to time series of the annual surface soil moisture content over the whole basin showed no significant trend (UF = 0.34, Cv = 0.026). Time series of 1500 grids were also used to drive the Mann-Kendall test. Figure 3(a) shows the spatial distribution of UF value from the Mann-Kendall test; 9.1% grids, mostly in the source region of the Yellow River (East Tibet Plateau), showed significantly increasing trends. The most obvious increasing trend occurred in the grid of 33.625N–98.625E, with a UF value 4.54 (0.0004/10a, passing the 99% significance level). In 17% of grids, mostly in the middle of the basin (Weihe River basin and Fenhe River basin), significantly decreasing trends were found. The most obvious decreasing trend appeared in the grid of 34.375N–110.125E, with a UF value –3.54 (–0.0033/10a, passing the 99% significance level). The average linear increasing (decreasing) tendency of surface soil moisture content in the significant increasing (decreasing) area was 0.0003/10a (–0.0022/10a).

Fluctuation characters analysis

Figure 3(b) is the spatial distribution of the deviation coefficients for the surface soil moisture variation, which shows the variation. It illustrates the fluctuation range of the variation. Some areas in the Inner Mongolia irrigation area, upstream of the Weihe River basin and downstream of the Yellow River basin show relatively greater volatility during the 52 years. Areas in the upstream of the Yellow River basin, mostly in the Tibet Plateau, showed low amplitude.

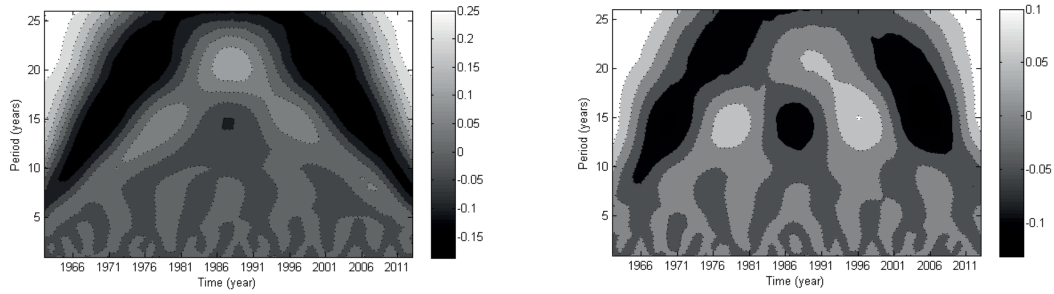
Analysing the time series with the Morlet wavelet, power features within a range of frequencies (or periods) may appear dominant in the time-series power spectrum at some times of the series (Nicolas *et al*., 2004). The power spectrum trends vary congruously with the fluctuation of the signal and the coefficients reflect the oscillation intensity. Positive coefficients indicate relatively high soil moisture and negative values the opposite.

Figure 4(a) shows the power spectrums for annual surface soil moisture content of the whole basin, and exhibit obvious oscillating periods of 20 years and 14 years. There are two distinct dry periods and one wet period during the 20 years period, varying from increase via decrease to increase for the surface soil moisture. The spectrum for the 14 years period, contains five significant fluctuation times, showing relatively less soil moisture in 1966–1970, 1981–1995 and 2002–2006.



(a) (b)

Fig. 3 (a) Spatial distribution of UF value in Mann-Kendall test, and (b) spatial distribution of deviation coefficients (Cv).



(a) (b)

Fig. 4 (a) Morlet wavelet power spectrum for annual, and (b) Morlet wavelet power spectrum for January surface soil moisture series.

Morlet wavelet analysis was also applied to surface soil moisture series of January, April, July and October. Wavelet power spectrums in April, July and October were similar to the spectrum for annual surface soil moisture, but differed from that for January. Figure 4(b) shows the power spectrums for January surface soil moisture content over the whole basin. The obvious oscillating period was 14 years, and there were the three drier temporal centres (1970, 1988 and 2006) and two wetter temporal centres (1978 and 1996); the 20 years period was not distinct.

The wavelet analysis suggested that there were cycles of fluctuation in surface soil moisture every 20 and 14 years. A short-term vibration of about 3 years was also clear on the spectrums.

CONCLUSION

The main findings can be summarized as follows:

(a) Annual average surface soil water content varies from 0.279 to 0.320 without a significant variation.
(b) Surface soil moisture in the source region of the Yellow River shows a significant increasing trend.
(c) Surface soil moisture in Weihe and Fenhe basins displays a significant decreasing trend.
(d) The amplitude of the surface soil moisture series over areas revealed to have a downward trend was greater than that with an upward trend.
(e) The deviation coefficients of surface soil moisture vary from 0.02 to 0.18. Some areas in the Inner Mongolia irrigation area, upstream of the Weihe River basin and downstream of the Yellow River basin show relatively larger oscillation during 52 years, and some places in the Tibet Plateau showed low amplitude.
(f) Oscillations with 20- and 14-year periods were found on the annual and seasonal (except winter) surface soil moisture series, while only the 14-year period occurred for series in winter.

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