Dynamic response of runoff to soil and water conservation measures and precipitation based on VAR model

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ABSTRACT

The Loess Plateau is one of the most erodible areas in the world, and numerous conservation measures have been implemented to control severe soil erosion. Better understanding of the changes in runoff and their influencing factors is required. A vector autoregression (VAR) model was used to simulate the dynamic relationship between runoff and six factors (precipitation, terraces, afforestation, grassing, check dams' construction, and grazing fencing) based on precipitation, runoff, and controlling measures of the Tuwei River basin in the middle reaches of the Yellow River during 1959–2012. Results showed that response of runoff usually lagged behind precipitation and the implementation of soil and water conservation measures. The annual runoff has no response to the increase of each measure area at the first year, but has varying degrees of response from the second year onward. Moreover, the same measure has different effects on runoff in different periods. The contribution of the factors that affect the annual runoff varied in the order of grazing fencing hillside < grassing < check dams' construction field < afforestation < precipitation < terraces. In the long term, the contribution of soil and water conservation measures would be greater than 70% in the fluctuation of annual runoff.

Key words | precipitation, runoff, soil and water conservation measures, vector autoregression (VAR) model

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INTRODUCTION

The Loess Plateau region, covering an area of 620,000 km^2 in the middle reaches of the Yellow River, is one of the most erodible areas in the world (He *et al.* 2015). To control severe soil erosion, numerous conservation measures have been implemented in the Loess Plateau since the 1950s. The soil conservation measures mainly include constructing dams in the main gullies, planting trees and growing pasturelands on steep slopes (>30%), and building terraces on medium slopes (15% to 30%) (Liu *et al.* 1994). Although these measures have reduced soil erosion, they have also resulted in noticeable reduction in streamflow (Gao *et al.* 2009; Xin *et al.* 2015; Zuo *et al.* 2016). This reduced runoff can cause a severe problem for the environment, rivers, estuary ecosystem, and socioeconomic systems (Miao & Ni 2009; Liu 2014). Water resource managers and planners are looking for simple and easy methods to determine the contribution of the influencing factors on runoff, which supports the sustainable development of natural resources. Better understanding of the changes in runoff and their influencing factors is therefore important for river basin management and soil and water conservation (Wu & Chen 2012; Zhao *et al.* 2014).

Several studies have revealed that the runoff of many rivers presented variations due to climate change and

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human activities (Kahya & Kalaycı 2004; Brown *et al.* 2005; Velpuri & Senay 2013; Lu *et al.* 2014). In the Loess Plateau region, researchers have evaluated the contribution rates of the main influencing factors to runoff changes and revealed that runoff changes involve the superposition of the effects of rainfall and soil conservation measures (Mu 2002). Several methods have been used to assess the impacts of precipitation and soil conservation measures on the hydrological processes. The hydrological model and statistical method are the main methods for the quantitative assessment of the impacts of rainfall and soil and water conservation measures on the runoff at basin scale (Wang *et al.* 2014). However, hydrological models such as the Soil and Water Assessment Tool (Arnold *et al.* 1990) and the Xinanjiang model (Zhao 1992) are always limited due to the time-consuming processes of calibration and validation, and these models also require extensive and complex datasets and have unpredictable output results, model parameters, and structure (Shi 1993; Qi *et al.* 2011). The statistical method is a simple and effective approach to quantifying the impacts of the precipitation and conservation measures on the hydrological process. However, statistical methods such as multi-linear regression (Li *et al.* 2014a, 2014b) and the double mass curve method (Mu *et al.* 2007) use long-term observation data to establish the statistical relation between hydrological variables and their influencing factors, but it is difficult to distinguish the contributions of different driving factors, and the effects of temporal distribution of driving factors cannot be assessed. Therefore, a new statistical method that evaluates the dynamic impact of each soil and water conservation measure and precipitation on runoff change is urgently needed.

The vector autoregression (VAR) model is a widely used econometrics technique for multivariate times series modeling. The VAR model was put forward by Sims (1980) to analyze the mutual influence relationship between macroeconomic variables; it is a generalized reduced form that helps to detect the statistical relationship among the variables in the system. VAR has some very attractive features and has proven to be a valuable tool for analyzing dynamical transmission mechanisms among time series processes (McMillan 1991; Lu 2001). In each equation of the model, endogenous variables will return all the lagged endogenous variable items in order to estimate the dynamic relationship among all the endogenous variables. Although the VAR model was originally developed by analyzing the mutual influence relationship between macroeconomic variables, it makes use of the form of simultaneous multi-equations, which is not based on the economic theory, and has been applied to several other fields. For example, the VAR model was used to analyze and forecast the mutual impacts between variables in the system, and enable the determination of leading and potential factors and quantify their influence (Gao 2006; Kumar *et al.* 2009; Adenomon *et al.* 2013; Li *et al.* 2017; Wu *et al.* 2018).

To date, no research has addressed the question as to whether the VAR model can be used to quantitatively analyze the relationship between precipitation, soil and water conservation measures, and runoff. The objectives of the present study therefore are: (1) to apply the VAR model in analyzing the response of runoff variation to annual precipitation and soil and water conservation measures; and (2) to reveal the long-term effects of soil conservation measures on runoff change using the Tuwei River basin as an example. The study will strengthen the understanding of the effects of soil and water conservation measures on hydrological regime shifts.

MATERIAL AND METHODS

Study area

The Tuwei River basin is located in northwest China at latitude 38°10′–39°10′N and longitude 109°45′–110°35′ E with a total catchment area of 3,294 km^2 (Figure 1). This river is a secondary branch of the Yellow River and flows from the northwest to the southeast. The main stream length is 139.6 km, and the altitude ranges from 297 m in the southeast to 1,886 m in the northwest. The basin belongs to a semi-arid climate zone, which has a mean temperature of 8.5 °C and an annual precipitation of 380 mm, of which more than 60% occurs from June to September. The landscape patterns of aeolian processes of the basin are deep, especially a sandy grass shoal region and loess hilly-gully region in the upper and middle reaches of the basin. The terrain is high in the northwest and low in the southeast. Loess soil is the dominant soil type in the entire basin.

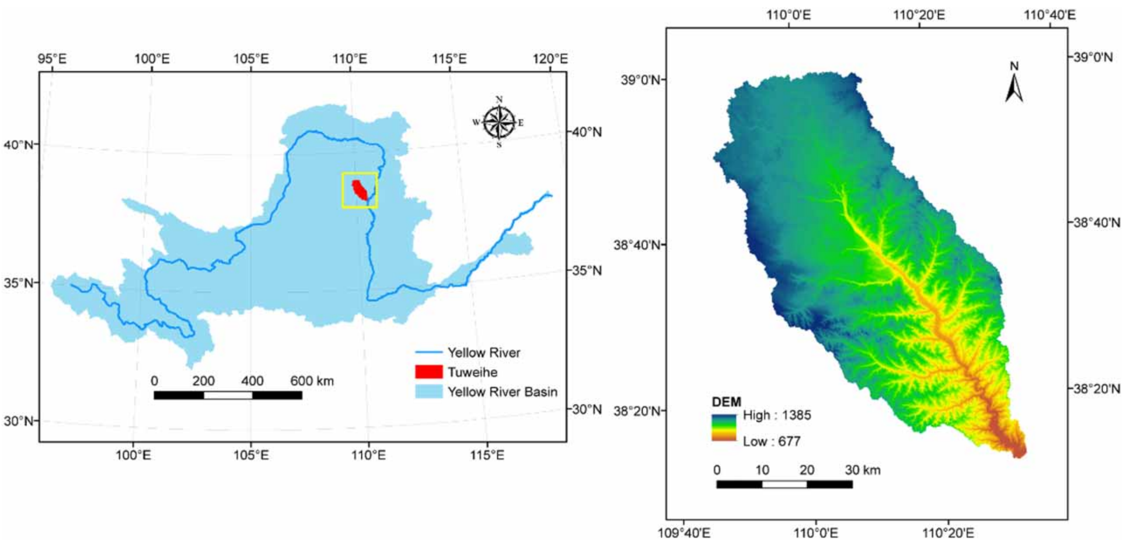

Figure 1 | Location of the study area.

Loess is an aeolian sediment formed by the accumulation of wind-blown silt, typically in the 20–50 μm size range, 20% or less clay and the balance of equal parts sand and silt that are loosely cemented by calcium carbonate.

A series of conservation measures to control soil erosion was conducted in the Tuwei River basin from 1950. From the 1950s to the 1980s, small-scale conservation measures were implemented gradually, and the total affected area was very limited. After the 1980s, the conservation measures were accelerated and intensified, and by 2012, the total area affected was over 35% of the total basin area. The conservation measures included building terraces and check dams' construction and changing land cover by planting trees and improving pastures.

Data collection

Annual precipitation data during the period of 1959–2012 for the Tuwei River basin were obtained from the China Meteorological Data Sharing Service System (http://data.cma.gov.cn/). The precipitation data within the Tuwei River basin were collected from ten rainfall gauging stations, and the average precipitation was interpolated by the method of Thiessen polygons.

Annual runoff data of the Tuwei River from 1959 to 2012 were collected from the Gaojiachuan hydrological station, which is located at the outlet of the river, with a controlled area of 3,253 km^2 accounting for 98.76% of the basin area. All the runoff data were obtained from the Hydrological Year Book of the Yellow River.

Soil and water conservation data ranging from 1959 to 2012 were obtained from compilation of the soil and water conservation data of each country in the Tuwei River basin. The dataset covers some general characteristics of the Tuwei River basin, as well as terraced-field, afforestation, grassing, check dams' construction, and grazing fencing.

In order to eliminate the heteroscedasticity of variables, the data are standardized due to different dimensions of variables and large differences in values; the z-score standardization method is as follows:

$$V_i' = \frac{(V_i - \overline{V_i})}{\sigma} \tag{1}$$

$$\sigma = \sqrt{\frac{1}{16}\sum_{i=1}^{16}(V_i - \overline{V_i})^2} \tag{2}$$

$$\overline{V_i} = \frac{1}{17}\sum_{i=1}^{17} V_i \tag{3}$$

where V_i' is a time without dimensions, i is time, V_i is time series of original observations of annual runoff, annual precipitation, or area value of soil and water conservation measures.

Methods

VAR is a multiple time series modeling approach that constructs a model for a vector of time series instead of constructing models for individual time series. VAR is basically meant for stationary time series of all the variables under consideration. VAR model equations, apart from forecasting, are also used to simulate the effect of sudden change (impulse) in one variable on other variables. This technique, known as impulse response function (*IRF*), enables us to estimate the timescale over which the effect of change in precipitation and soil conservation measures leads to variations in runoff. Another application of the VAR model is variance decomposition that deals with forecast error variance. Variance decomposition gives an account of how much (in terms of percentage) of a forecast error variance can be attributed to each individual variable used in the model.

If x_t represents an $(n \times 1)$ vector of n variables, p *is* the lagged values of VAR, denoted as VAR(p), and the mathematical representations of VAR can be expressed as follows:

$$x_t = c + \alpha_1 x_{t-1} + \alpha_2 x_{t-2} + \ldots + \alpha_p x_{t-p} + \rho_t \quad (4)$$

where c is a $(n \times 1)$ vector of constants; α_j is a $(n \times n)$ matrix of autoregressive coefficient for the lag order; and ρ_t is a $(n \times 1)$ vector generalization of white noise: $E(\rho_t) = 0$.

Selection of lag length for VAR model

Most VAR models are estimated using symmetric lags, i.e., the same lag length is used for all variables in all equations of the model. The lag length is frequently selected using criteria such as the Akaike information criterion (AIC). These information criteria are statistical model fit measures (Gao 2006). They quantify the relative goodness of fit of various previously derived statistical models, given a sample of data.

Impulse response functions (IRF)

As the VAR model is a non-theoretical model, the relationships among the variables in a VAR model are difficult to determine directly from the parameter matrices, but can be obtained by analyzing the dynamic impact on the system when an error term changes or when the model is shocked. Therefore, impulse response functions have been proposed as tools for interpreting VAR models. The impulse technique of response analysis is a descriptive device representing the reaction of each variable to a shock in each equation of the system. The *IRF* can be used to reflect the impact on the current value and future value of the endogenous variables from a random distribution term, which can characterize the dynamic response on random disturbances from the endogenous variables, reflecting how any random disturbance influences other variables through the model and the dynamic process of feedback to itself. The *IRF*, with a strong time characteristic, can show the degree of response on any new information generated by any system variables from a variable. A VAR can be modeled as a triangular moving average process, which can be written in vector form as Equation (5). Thus,

$$\frac{\partial x_{t+s}}{\partial \rho_{1t}} = \varphi_s \quad (5)$$

where the row i column j element of φ_s identifies the consequences of a one-unit increase in the jth variable's innovation at time $t(\varepsilon_{ij})$ for the value of the ith variable at time $t + s$ $(x_{i,t+s})$, holding all other innovations at all times constant. It is common to draw bootstrapped confidence intervals around *IRF*.

Variance decomposition

If the innovation that actually drives the system can be identified, a further tool used to interpret the VAR model is variance decomposition. To examine the short-run dynamic interactions between the variables, variance decomposition is used. Variance decomposition is a term used to describe a relativity effect, and it gives an account of how much of a forecast error variance can be attributed to each impact factor on the VAR system.

Therefore, it is necessary to analyze the variance decomposition to trace these shocks. The variance decomposition provides information about the relative importance of each random innovation in affecting the variables in the VAR.

Test of stationarity

In order to avoid spurious regression in the regression analysis and stationarity of the model, the augmented Dickey–Fuller (ADF) test (Xia 2005) and the Phillips–Perrron (PP) test (Phillips & Perron 1986) for testing stationarity of the variables were used. If there is no unit root, the sequence is stable; otherwise, it may cause pseudo-regression. The Johansen cointegration test (Johansen 2015) was used to test the cointegration relationship between each variable. After the unit root test and cointegration test, regression was performed, and their quantitative relation was worked out. Moreover, the autoregression (AR) root estimate method was used to test the stationarity of the VAR model. If the inverse of all the root modules is less than the radius of the unit circle, which is equal to 1, the VAR model is stable, otherwise (i.e., there are scattered points outside the unit circle) the model is unstable.

RESULTS AND ANALYSIS

Temporal trend of annual runoff, precipitation, and soil and water conservation

Figure 2 shows the temporal variation of observed annual runoff and precipitation during 1959–2012 in the Tuwei River basin. It can be seen from Figure 2 that annual runoff showed a significant decreasing trend ($P < 0.01$). The maximum value of annual runoff was 5.3938×10^8 m^3 in 1967, while the minimum was 1.832×10^8 m^3 in 2010. From six order fitting curves of the annual runoff, it can be found that annual runoff slightly decreased in the 1960s and significantly reduced in the early 1970s, with a stable state from the mid-1980s to the late 1990s; for the 21st century, at the beginning it is decreasing and then increasing.

The average annual precipitation shows weak fluctuating changes in the basin in the period of 1959–2012. The maximum precipitation was 652.7 mm in 1967, while the minimum value was 223.6 mm in 2013. The annual precipitation showed a slightly decreasing trend ($P > 0.05$) overall, which was inconsistent with annual runoff.

Figure 3 displays the changing characteristics of the percentage between the area of annual runoff, the soil and water conservation measures and the total basin area. It was found that the soil conservation measures' area only accounted for 0.78% of the total basin area in 1959. During the period of the 1950s to the 1980s, small-scale conservation measures were implemented gradually, and the total area affected was very limited. After the 1980s, soil and water conservation measures significantly increased (e.g., afforestation, check dams' construction and grazing fencing), especially for the afforestation, which was 19% higher during 1980–2012 than it was before 1980.

VAR results

VAR modeling was carried out for the time series of the annual runoff (TW*ZRUNOFF*), the annual precipitation (TW*ZP*), and the area of soil conservation measures including terraces (TW*ZTF*), afforestation (TW*ZFL*), grassing

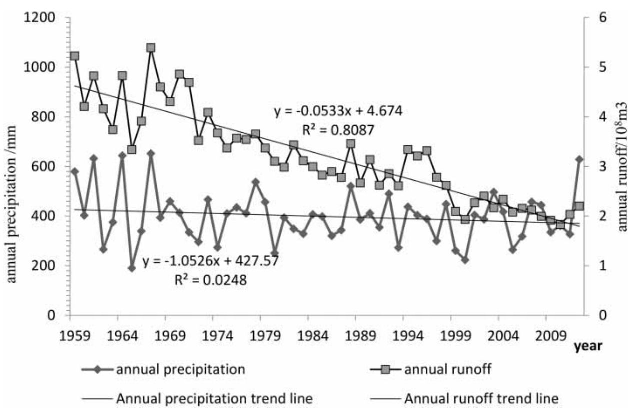

Figure 2 | Temporal change of annual runoff and precipitation during 1959–2012.

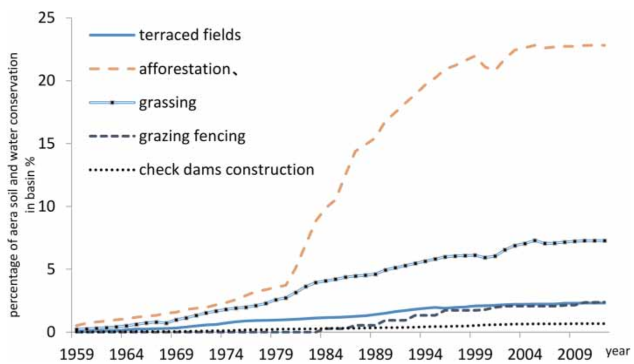

Figure 3 | The percentage of soil and water conservations in the Tuwei River basin during 1959–2012.

Table 1 | Stationarity test results of each variable

Sequence	ADF-Statistic	PP-Statistic	Conclusion
TWZRUNOFF	−1.0897	−2.4480	Unstable
D(TWZRUNOFF)	−11.8958***	−12.4808***	Stable
TWZP	−5.8189***	−8.6698***	Stable
TWZTF	−1.3152	−1.0223	Unstable
D(TWZTF)	−4.7846***	−4.7846***	Stable
TWZFL	−1.1503	−0.4036	Unstable
D(TWZFL)	−1.7828	−3.0063	Unstable
D2(TWZFL)	−9.2414***	−11.0902***	Stable
TWZGL	−0.8425	−0.5970	Unstable
D(TWZGL)	−4.5551***	−4.5855***	Stable
TWZDF	−0.1292	0.3123	Unstable
D(TWZDF)	−4.5069***	−4.4346***	Stable
TWZPL	0.0828	0.7408	Unstable
D(TWZPL)	−2.1207	−7.9633***	Unstable
D2(TWZPL)	−18.0037***	−23.8568***	Stable

Note: D refers to the first order difference; D^2 refers to the second order difference. The asterisks ***, **, and * represent the statistical significance at 1%, 5%, and 10% levels, respectively.

(TWZ*GL*), check dams' construction (TWZ*DF*), and grazing fencing (TWZ*PL*) at the end of each year.

Test of stationarity

The first step in VAR modeling is to examine whether the time series under consideration are stationary. Table 1 summarizes the results of a unit root test applied on the time series. All the other time series are under the significance level of 1% except precipitation, so they cannot reject unit root process and are all non-stationary time series. However, the second-order difference sequence can be obtained from the unit root process. Therefore, the VAR model can be used to describe the effect among the variables.

Table 2 presents the results of the Johansen cointegration test. The trace test indicated four cointegrating equations at the 0.05 level, and the max-eigenvalue test indicates four cointegrating equations at the 0.05 level, according to Table 2. From the results, it can be concluded that there are four stable long-term equilibrium relationships among the series of annual runoff, annual precipitation and the areas of soil and water conservation at the 0.05 level.

Selection of lag length for VAR

An important issue of the VAR model is the determination of lag length. If the lag length is too short, it cannot fully reflect the dynamic relationship between variables, while a too long lag length can reduce the degree of freedom and affect the validity of the model parameters estimated. Table 3 shows the results of different information criteria, *LR*, *FPE*, *AIC*, *SC*, and *HQ*, applied to VAR models of all the time series. It can be found that the optimal lag value is 3 in the case of *LR*, *FPE*, and *AIC*, while the optimal lag is phase 1 in the case of *SC* and *HQ* at 5% significance level. Considering the *AIC* criterion tends to choose large lag values (Paulsen 1984), it is therefore evident that the maximum lag among the recommended lag values by the information criterion is 3.

Table 2 | Results of Johansen cointegration test

Trace-test				Max-eigenvalue test			
H0: rank = r	Trace statistic	0.05 critical value	Prob.	H0: rank = r	Max-eigen statistic	0.05 critical value	Prob.
r = 0*	238.24	125.62	0	r = 0*	89.42	46.23	0
r ≤ 1*	148.82	95.75	0	r ≤ 1*	55.26	40.08	0.0005
r ≤ 2*	93.56	69.82	0.0002	r ≤ 2*	38.66	33.88	0.0124
r ≤ 3*	54.90	47.86	0.0095	r ≤ 3*	27.93	27.58	0.0452
r ≤ 4	26.97	29.80	0.1023	r ≤ 4	14.24	21.13	0.3458
r ≤ 5	12.73	15.49	0.1249	r ≤ 5	8.91	14.26	0.2939
r ≤ 6	3.82	3.84	0.0504	r ≤ 6	3.83	3.84	0.0504

Note: The asterisks represent the statistical significance at 5% levels, respectively.

Table 3 | Lag order selection

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−73.1482	NA	5.47×10^{-8}	3.1431	3.4082	3.2444
1	354.8432	721.711	1.95×10^{-14}	−11.7193	−9.5981*	−10.9088*
2	396.6008	58.95020	2.89×10^{-14}	−11.4353	−7.4580	−9.9155
3	471.5579	85.2453*	1.41×10^{-14}*	−12.4533*	−6.6199	−10.2242

Note: The asterisks represent the statistical significance at 5% levels, respectively.

VAR estimation

As an illustration, the VAR model equation for runoff obtained through the E-views software can be written as:

$$\begin{aligned}[\mathrm{ZR}]_t = {} & 0.1677[\mathrm{ZR}]_{t-1} + 0.1523[\mathrm{ZR}]_{t-2} - 0.2647[\mathrm{ZR}]_{t-3} \\ & - 0.0805[ZP]_{t-1} - 0.1931[ZP]_{t-2} + 0.1493[ZP]_{t-3} \\ & - 1.0856[ZTF]_{t-1} + 1.0491[ZTF]_{t-2} + 0.4656[ZTF]_{t-3} \\ & - 0.1678[ZFL]_{t-1} + 1.3704[ZFL]_{t-2} - 0.5843[ZFL]_{t-3} \\ & + 0.7898[ZGL]_{t-1} - 1.8471[ZGL]_{t-2} - 0.2089[ZGL]_{t-3} \\ & + 0.1903[ZPL]_{t-1} - 0.2416[ZPL]_{t-2} + 0.2022[ZPL]_{t-3} \\ & - 1.2936[ZDF]_{t-1} - 0.1017[ZDF]_{t-2} \\ & + 0.6476[ZDF]_{t-3} + 0.0122 \end{aligned} \quad (6)$$

In this equation, only those coefficients have been retained for which t-statistics were found to be significant at the 0.05 level of significance.

Effect of soil and water conservation measures and precipitation on runoff change

Figure 4 shows how the shock of one standard deviation (hereafter, SD) to precipitation and each variable of the soil and water conservation measures leads to responses on runoff in lag of 15 years. Using a Monte Carlo simulation with 10,000 repetitions, the *IRF* with its standard error was estimated and is shown in Figure 4. The response of runoff to all variables showed a significant effect at 5% level within 15 lag years.

Figure 4(a) displays the response of annual runoff to annual precipitation. Impulse response of runoff to precipitation in the first year is 0, indicating the influence of annual precipitation on annual runoff is hysteretic. The impacts of precipitation started in the second year with the impulse effect fluctuating up and down at zero value. It can be concluded from the results that the annual runoff will be rapidly increased initially with the increase of annual rainfall, whereas the accumulative total effect of precipitation on runoff decreases is negative in 15 years (i.e., increased runoff). Hence, the reduction of runoff could be attributed to the vegetation construction.

Figure 4(b) shows the responses of runoff to terraces. When the impulse of terraces is given, annual runoff started decreasing rapidly and attained a minimum value after a period of about two years. Thereafter, annual runoff slowly increased. The results indicated that the runoff would be reduced with the construction of terraces in the basin. This is due to the fact that implementing the terraces' measure can effectively increase rainfall infiltration and reduce the surface runoff, thereby increasing interflow and base flow.

Figure 4(c) depicts the response of runoff to shocks in afforestation. It can be seen from Figure 4(c) that the effect of increasing the afforestation area was not obvious regarding the runoff in the first two years, whereas the annual runoff slowly increased after the fourth year.

The response of runoff to shocks in grassing is shown in Figure 4(d). The increase of grassing in the current year has a negative effect on annual runoff which was first slightly increased, then decreased, and finally approached zero. The total effect of grassing on annual runoff was gradually decreased.

Figure 4(e) presents the response of runoff to shocks in grazing fencing. It can be seen that the total effect of enclosed land on annual runoff is slightly increased for nine years, and finally became zero. The results indicated that enclosed land can promote the increase of annual runoff in the preliminary stage of enclosed land, thereby achieving the aim of increasing annual runoff.

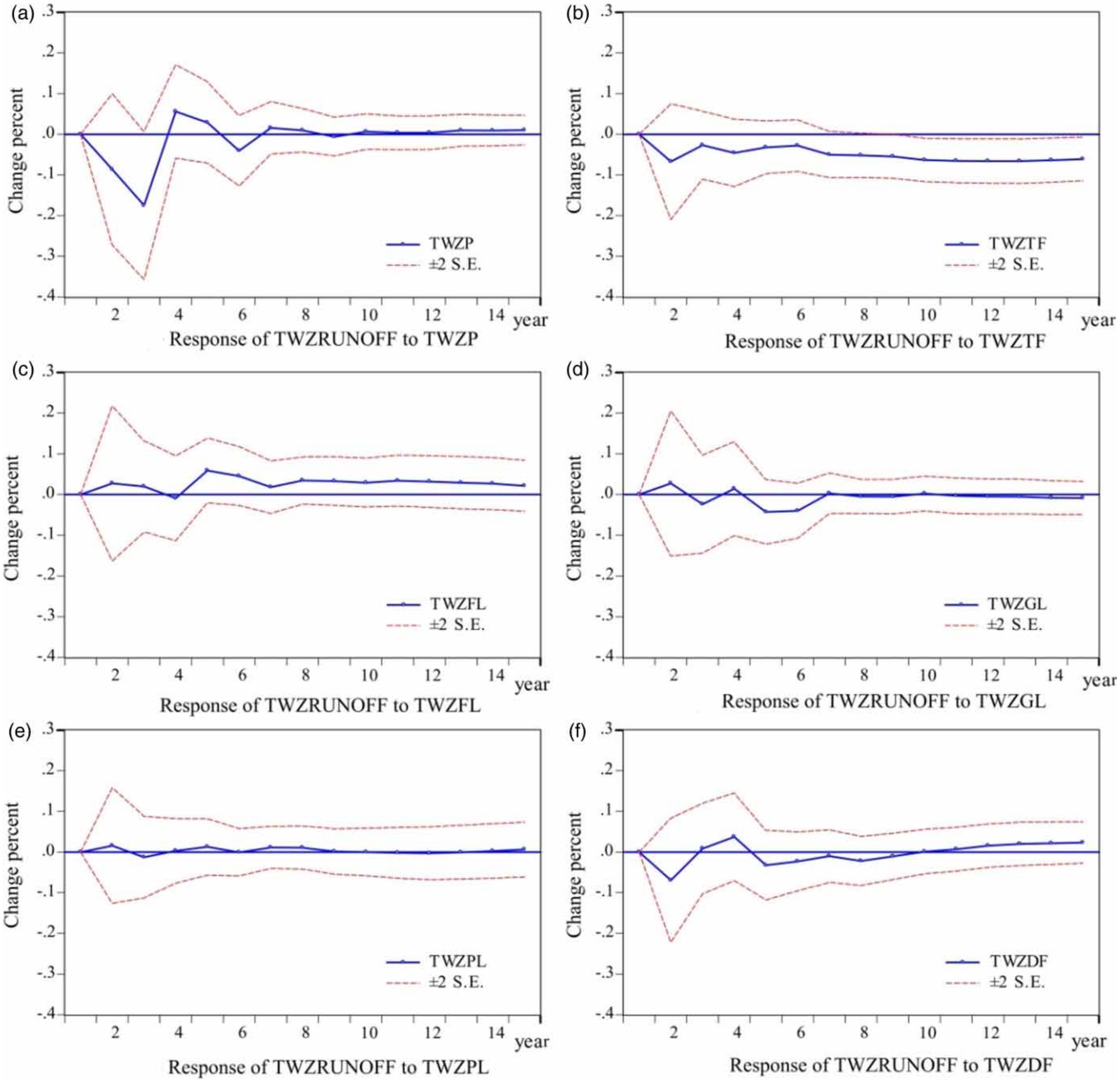

Figure 4 | Response of TWZRUNOFF to relative factors.

The response of annual runoff to shocks in check dams' construction is shown in Figure 4(f). The increase of check dams' construction in the current year has a fluctuant effect on future annual runoff which was first decreased and then increased.

Variance decomposition

The variance decomposition of annual runoff is shown in Table 4. The response of annual runoff on runoff, terrace, afforestation, grassing, check dams' construction, and grazing fencing is observed. The runoff seemed to be less exogenous in the system which explained more than 70% of its variance after two years (12 periods). In addition, approximately 30% of the variance decomposition was explained by soil and water conservation in the variation of annual runoff.

In addition to annual runoff itself, the effects of other variables such as precipitation, terraces, afforestation, grassing, check dams' construction, and grazing fencing on

Table 4 | Results of TWZRUNOFF's variance decomposition

			Soil and water conservation						Relative contribution (%)	
Lags	**TWZRUNOFF**	**TWZP**	**TWZTF**	**TWZFL**	**TWZGL**	**TWZDF**	**TWZPL**	**Subtotal**	**Precipitation variability**	**Soil and water conservation**
1	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	90.38	2.42	3.73	1.49	0.11	1.68	0.20	9.62	25.12	74.88
3	82.46	10.48	3.69	1.36	0.20	1.55	0.26	17.54	59.76	40.24
4	81.68	10.71	3.89	1.31	0.24	1.92	0.25	18.32	58.43	41.57
5	79.67	10.58	4.91	1.71	0.62	2.19	0.33	20.33	52.01	47.99
6	78.27	10.81	5.56	1.81	0.92	2.31	0.33	21.73	49.77	50.23
7	77.24	10.65	6.57	1.97	0.90	2.30	0.37	22.76	46.78	53.22
8	75.65	10.42	7.85	2.38	0.89	2.38	0.42	24.35	42.80	57.20
9	74.43	10.25	8.96	2.68	0.88	2.37	0.42	25.57	40.10	59.90
10	73.22	10.05	10.15	2.98	0.86	2.33	0.41	26.78	37.54	62.46
12	70.90	9.71	12.36	3.47	0.84	2.32	0.40	29.10	33.38	66.62
13	69.89	9.56	13.33	3.61	0.83	2.39	0.40	30.11	31.76	68.24
14	68.99	9.43	14.21	3.68	0.82	2.47	0.39	31.01	30.42	69.58
15	68.21	9.32	14.97	3.70	0.82	2.58	0.39	31.79	29.32	70.68

annual runoff began in the second year, and then fluctuated slightly in the later periods. As the implementation of soil and water conservation measures increased, annual runoff rapidly increased in the second year and after attaining a minimum in the third year, it again started increasing gradually. After a period of ten years, the effect of the annual precipitation on annual runoff was about 40%, while influence of soil and water conservation measures accounts for about 60%. In the long run, regardless of the contribution of annual runoff itself, the contribution of soil and water conservation measures to annual runoff can reach more than 70%, which indicated that the annual precipitation and soil and water conservation measures in different periods have different impacts on the annual runoff, and the influence of annual precipitation on annual runoff was gradually decreased.

DISCUSSION

Lagging response of runoff to soil and water conservation measures

Overall, the impulse response curves are smooth, indicating that the influence process of annual precipitation and soil conservation measures on annual runoff is slow and lengthy. The annual runoff does not respond to the implementation of the measures in the first year, but shows varying degrees of response from the second year. The hydrological effect, that the soil and water conservation measures delay or reduce surface runoff, has been gradually recognized (Saghafian *et al.* 2008; Amini *et al.* 2011).

Difference in hydrological effects of different soil and water conservation measures

As shown in Figure 4, in the long term, the terrace and grazing fencing showed first increased runoff, and then decreased runoff; thereafter, approximately ten years later, runoff change tended to be stable. However, as Figure 4(c)–4(e) show, the existence of afforestation, grassing, and check dams' construction restrained runoff increase in the early stage, and then promoted the increase of runoff; thereafter, approximately ten years later, runoff change tended to be stable. The hydrological effects of soil and water conservation measures have different impacts on runoff within ten years of implementation (Zhao *et al.* 2017).

The hydrological effect of the same water conservation measures is inconsistent in the long term and has long-term heterogeneity. The effect of terraces on runoff is shown as a continuous negative effect to reduce runoff. It is indicated that the increase in terraces leads to the reduction of runoff in the basin. This conclusion is consistent with the findings of Shao (2013). The response of the runoff to the afforestation indicates that the annual runoff volume is slightly increased as the area of afforestation increases. Other authors have also drawn similar conclusions (Liu & Zhong 1978; Li *et al.* 2018). The response of annual runoff to grassing showed that the annual runoff first decreased and then increased, which fluctuated for about ten years with the increase of grassing area, and the general trend of runoff was to decrease. This phenomenon, that the conversion of farmland to forest can reduce runoff, has been verified by many previous studies.

The response of annual runoff to the enclosed land demonstrated that the annual runoff decreased after the increase, and then slightly increased with the increase in grazing fencing. The results indicate that enclosed land can promote the increase in annual runoff in the preliminary stage of enclosed land, thereby achieving the aim of increasing annual runoff. Moreover, although there was a slight decrease in the intermediate stage, the cumulative effects of the grazing fencing on runoff were positive in the long run.

The response of annual runoff to check dams' construction revealed that the annual runoff first decreased and then increased with the peak in the second year, and the positive response level was higher than that of other influencing factors. It is suggested that the check dams' construction has a significant effect on runoff in the short term, and the cumulative effect of the check dams' construction on the annual runoff is positive during a lag period of 15 years.

Contributions of precipitation and soil and water conservation measures on runoff

It can be found from variance decomposition results that the influence of soil and water conservation measures on annual runoff increased gradually, and became stable after ten years. The relative contribution of the variables that affect the annual runoff were varied in the order of grazing fencing < grassing < check dams' construction < afforestation < precipitation < terrace field. Regardless of the contribution of the annual runoff itself, the contribution of soil and water conservation measures to annual runoff is more than 70% of total contribution of the influencing factors, while the contribution of precipitation is close to 30%. The decrease in runoff during the study period is related to the large-scale implementation of soil and water conservation measures. Other authors have also drawn similar conclusions (Zheng *et al.* 2009; Zhao *et al.* 2014; Li *et al.* 2014a, 2014b).

It can be seen that the variation of annual runoff is the result of multiple factors, and the contribution of each influencing factor to the runoff is different. In general, soil and water conservation measures are the main factors of the variation of the runoff. Moreover, the contributions of terraces, afforestation, grassing, check dams' construction, and enclosed land are different, and the effect on runoff in a period after implementation is variable.

CONCLUSIONS

In this study, the response of runoff to precipitation and soil and water conservation measures (terraces, afforestation, grassing, check dams' construction and grazing fencing) in the Tuwei River basin was investigated by the VAR model. The time series from 1959 to 2012 of annual runoff, rainfall, and soil and water conservation measures in the Tuwei River basin were standardized, and the first-order difference of the data sequence proved to be stable by the stability test. It is suggested that there is a long-term stable relationship between annual runoff, precipitation, and soil and water conservation measures by the Johansen cointegration test, indicating that the VAR model can be developed and applied.

The response of annual runoff to annual precipitation and soil and water conservation measures is hysteretic. The annual runoff has no response to the increase in each measure area in the first year, but has different degrees of response from the second year. The effects of soil and water conservation measures on annual runoff are different and long term. Moreover, the same measure has different effects on runoff in different periods. During the 15-year lag period, runoff sometimes increases and sometimes decreases, and the influence of the measures on runoff decreases gradually with time.

The grassing and grazing fencing hillside have a relatively weaker effect on annual runoff as compared with the precipitation, and the measures of terraces and afforestation. The contribution of the factors that affect the annual runoff were varied in the order of grazing fencing < grassing < check dams' construction < afforestation < precipitation < terraces. In the long term, the contribution of soil and water conservation measures would be greater than 70% in the fluctuation of annual runoff.

The VAR model describes the long-term effect of soil and water conservation measures on runoff. It can reflect different impacts of different soil conservation measures and different stages of the same measures on runoff. This means that the planning of soil and water conservation measures is not entirely dependent on the current benefit of the measures, and the spatial heterogeneity of the long-term effects of the measures should be fully considered.

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