Identify the influencing paths of precipitation and soil water storage on runoff: an example from Xinjiang River Basin, Poyang Lake, China

Hongxiang Fan, Ligang Xu, Xiaolong Wang, Yuexia Wu and Jiahu Jiang

ABSTRACT

Runoff generation is a complex meteorological-hydrological process influenced by many factors. We analyzed the effects of changes in precipitation and soil water storage (SWS) on runoff generation using the path-analysis method (PAM) in Xinjiang River Basin (XJRB). By using multiple trend analysis we found that precipitation, SWS and runoff in XJRB fluctuated throughout the past 30 years with no monotonic trends at both annual and seasonal scales. Further analysis demonstrated that runoff is more sensitive to precipitation than to SWS in XJRB. PAM results showed that direct influence of precipitation on runoff was seven times as large as that of SWS. Moreover, the indirect influence of precipitation on runoff through SWS accounts for 11–31% of the total influence of precipitation on runoff. This information will improve the description of precipitation and runoff relationship as well as the planning and management of water resources.

Key words | path analysis, Poyang Lake, precipitation, runoff, soil water storage

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INTRODUCTION

Runoff generation is a complex meteorological-hydrological process influenced by many factors, such as precipitation (Rajurkar *et al.* 2004), temperature (Li *et al.* 2011) and soil water storage (SWS) (Xu *et al.* 2014). Distinction of the direct and indirect influences is important in identifying the contributions of related variables and their interactions with the runoff process. However, a simple statistical method cannot quantitatively differentiate the direct and indirect influences of environmental factors on runoff and their influencing paths. In addition, the model-based approach might be physically sound, but it requires major efforts in model calibration and may lead to distinct results due to the uncertainties in the model structure and parameter estimation. In contrast, the path analysis method (PAM) can identify the important and significant paths and provide estimates of the magnitude and significance of the hypothesized causal connections between sets of variables through decomposing correlations into direct and indirect ones (Wright 1934).

PAM has been applied successfully in genetics (Wright 1983), agriculture (Kozak & Kang 2006), and social science (Deshpande 1982). Only a few studies in water resources, however, have utilized it. For example, Zhang *et al.* (2014) used path analysis with a selection of five factors to examine their influences on the spring snowmelt peak flow in the Kaidu River in Xinjiang, China; Li *et al.* (2011) applied it to analyze the influence of climatic factors on the annual and seasonal runoff depth in the Kaidu River and the Manas River; and Xing *et al.* (2015) applied PAM to determine the runoff components in upper Hailuogou Valley, China. However, all the above-mentioned studies were carried out in glacier-covered alpine catchments and were only focusing on the influencing paths of precipitation and temperature to runoff. The feasibility of PAM and the influencing paths

doi: 10.2166/ws.2017.224

of precipitation and SWS to runoff in inland watersheds are still unclear.

Poyang Lake (Figure 1) is the largest freshwater lake in China, and its hydrological process is complex, providing a good example where hydrological characteristics vary across space and management strategies need to be carefully targeted. Here, we applied PAM in the Xinjiang River Basin (XJRB) to identify the influences of precipitation and SWS on runoff. XJRB (Figure 1) is in the east of Poyang Lake Basin (PYLB), covering 15,535 km^2. The annual mean runoff of Xinjiang River is approximately 1.81×10^{10} m^3. The XJRB belongs to a subtropical wet climate zone with an annual mean precipitation between 1,600 mm and 2,100 mm. The main reason for choosing XJRB as our study site is that it has the fewest human impacts on its waterway, with no major dams on the Xinjiang River compared to the presence of multiple dams in the rivers of the other sub-basins.

To this end, the main objectives of this study are to: (1) evaluate the temporal pattern of hydro-climatic variables (i.e., precipitation, SWS and runoff) in XJRB; (2) evaluate the relationship among the three hydro-climatic variables in XJRB; and (3) differentiate the direct along with indirect influence of the environmental factors on runoff quantitatively by analyzing the influencing paths of precipitation and SWS to runoff generation. The research findings can lay an important theoretical basis and have essential scientific significance for understanding the runoff process in PYLB.

DATA PREPARATION

The observed data were obtained from the Guixi meteorological station, which provided the daily precipitation of XJRB from 1978 to 2007. Daily runoff data were provided by the

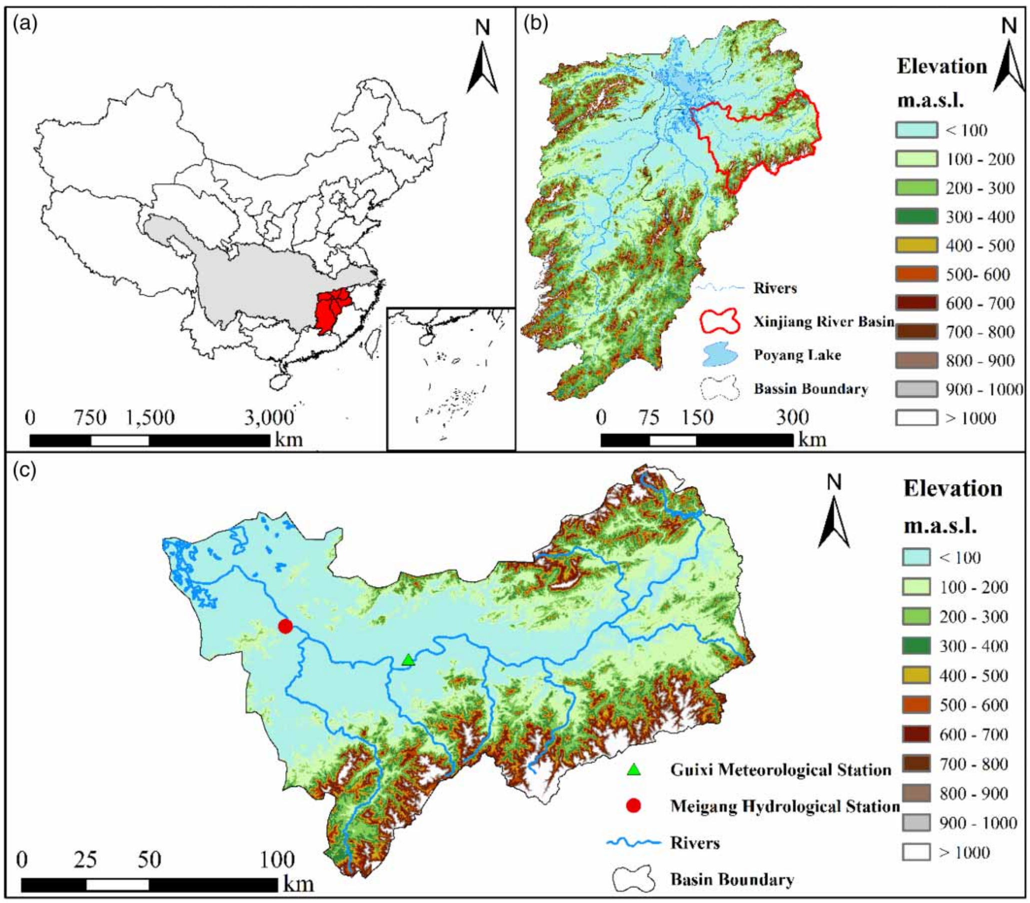

Figure 1 | (a) Location of Poyang Lake Basin; topography and river networks of (b) Poyang Lake Basin, (c) Xinjiang River Basin.

Meigang gauging station. The data had gone through a standard quality control process before delivery with no missing data in each variable. Monthly mean SWS data were simulated by the system dynamic model (Xu *et al.* 2014). The model was calibrated using monthly data for a period from 1978 to 1997 with a Nash–Sutcliffe model efficiency coefficient (NSE) larger than 0.9. All variables were converted to the unit of millimeter (mm) for uniformity.

METHODOLOGY

The trend analysis was done for multiple periods for different start and end years with at least 10 years in length using Sen's slope estimator and the Mann-Kendall test. Besides, the sensitivity analysis of runoff was performed follow the same procedure proposed by Kundzewicz *et al.* (2014). Following that, the PAM was used to evaluate the causal structure of the data. All the statistical analysis in this study was performed with the R statistical software 3.3.3 ×64 version (R Core Team 2017).

Mann-Kendall test

The Mann-Kendall test statistics S (Mann 1945; Kendall 1975) is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

where n is the length of the time serial, x_i and x_j are the values in time series i and j $(j > i)$, respectively, and $\text{sgn}(x_j - x_i)$ is the sign function defined as:

$$\text{sgn}(\theta) = \begin{cases} 1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{2}$$

Statistics S distributes normally when $n > 10$. The variance is:

$$\text{var}(s) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

When sample size $n > 10$, the standard normal test statistics Z_{MK} is computed according to Equation (4).

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{var(S)}} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \dfrac{S+1}{\sqrt{var(S)}} \text{ if } S < 0 \end{cases} \tag{4}$$

Positive values of Z_{MK} demonstrate an increasing trend whereas negative Z_{MK} values indicate a decreasing trend. In this study, the trend was tested at 5% significance level.

Sen's slope estimator

The Sen's slope estimator (Sen 1968) is presented as:

$$\beta = \text{Median}\left(\frac{x_j - x_k}{j-k}\right), \forall j > k \tag{5}$$

where β stands for the slope of trend, x_j and x_k are numerical values at times j and k $(j > k)$, respectively.

Sensitivity analysis

A climate sensitivity study was conducted in XJRB based on the relative changes of precipitation, SWS and runoff depth. For each season, the relative change rate is calculated for the three variables. The relative change rate of runoff depth is then plotted on a precipitation-SWS plane, and interpolated to a regular grid with ordinary kriging method (Kundzewicz *et al.* 2014).

Path-analysis

Path analysis is an extension of the regression model, which can partition correlations into direct and indirect effects (Wright 1934). If the correlation relationship between the exogenous variables (x_1, x_2) and the exogenous variable (y) exists, then the following equations are established:

$$r_{10} = p_{01} + r_{12}p_{02} \tag{6}$$

$$r_{20} = p_{02} + r_{12}p_{01} \tag{7}$$

where r_{10} is the correlation coefficient between x_1 and y, whereas r_{20} is the correlation coefficient between x_2 and y; r_{12} is the correlation coefficient between x_1 and x_2; p_{01} and p_{02} are the path coefficients indicating the direct effect of x_1 and x_2 on y, respectively; $r_{12}p_{02}$ indicates the indirect effect of x_1 through x_2 on y, and $r_{12}p_{01}$ indicates the indirect effect of x_2 through x_1 on y.

RESULTS

Characteristics of precipitation, SWS and runoff

Characteristics of precipitation

Results of multiple trend analysis for precipitation are presented in Figure 2. As shown in Figure 2, at annual scale, two statistically significant positive trends were detected in precipitation for the periods of 1978–2000 and 1985–2000 with a rate of 35.27 mm/yr and 58.36 mm/yr, respectively. In addition, a significant decreasing trend was found during the period from 1995 to 2005, with a rate of −5.0 mm/yr.

For the seasonal scale, a significant upward trend in precipitation was found in spring from 1985 to 1995 with a rate of 35 mm/yr. In addition, significant positive trends (30 mm/yr) in precipitation were also detected in summer from 1985 to 2000, followed by a significant downward trend (−50 mm/yr) from 1995 to 2005. Autumn precipitation in XJRB significantly decreased with a rate of −15 mm/yr from 1980 to 1995. No significant trend in precipitation was found in winter throughout the whole study period.

Characteristics of SWS

Figure 3 presents the results of multiple trend analysis for SWS. For annual scale, significant upwards trends were found in the 1980s and 1985–2000, whereas a decreasing trend was detected in 1995–2005, with a rate of −25 mm/yr.

For seasonal scale, SWS in XJRB decreased in spring for almost the whole study period and significant negative trends were found during the 1990s and 2000s. In addition,

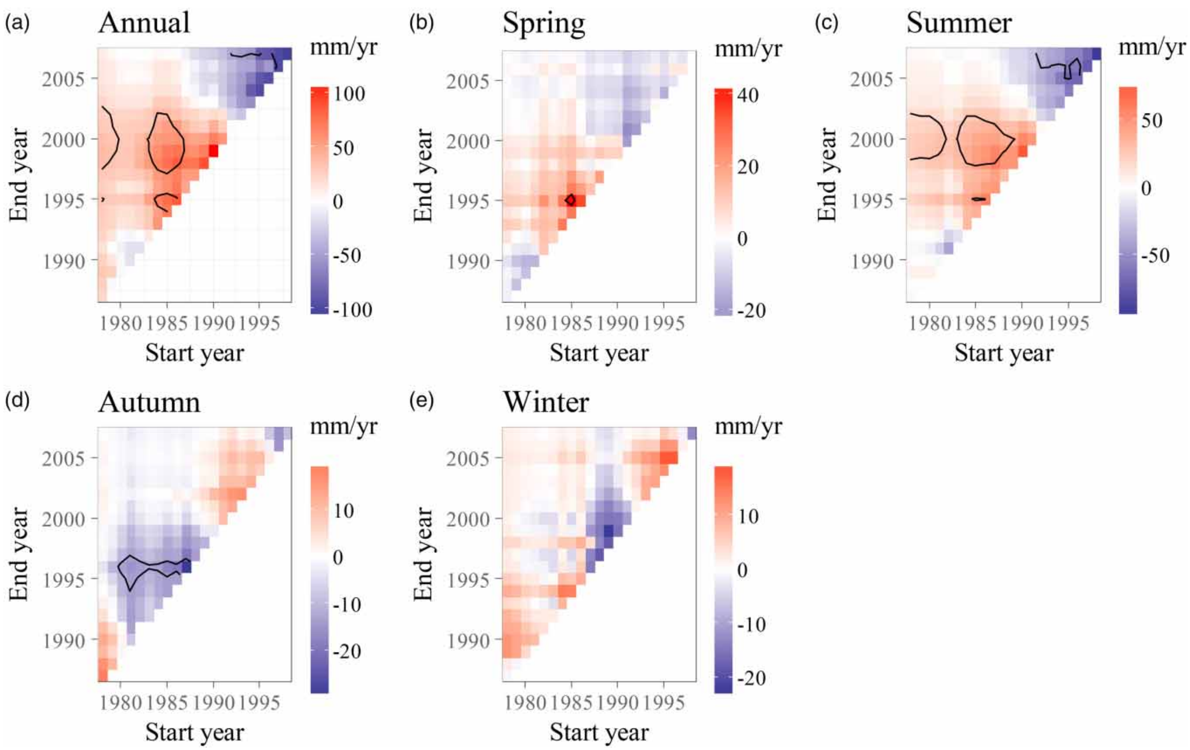

Figure 2 | Multiple trend analyses for seasonal precipitation in XJRB. Black contours delineate areas of significant trends at 5% significance level.

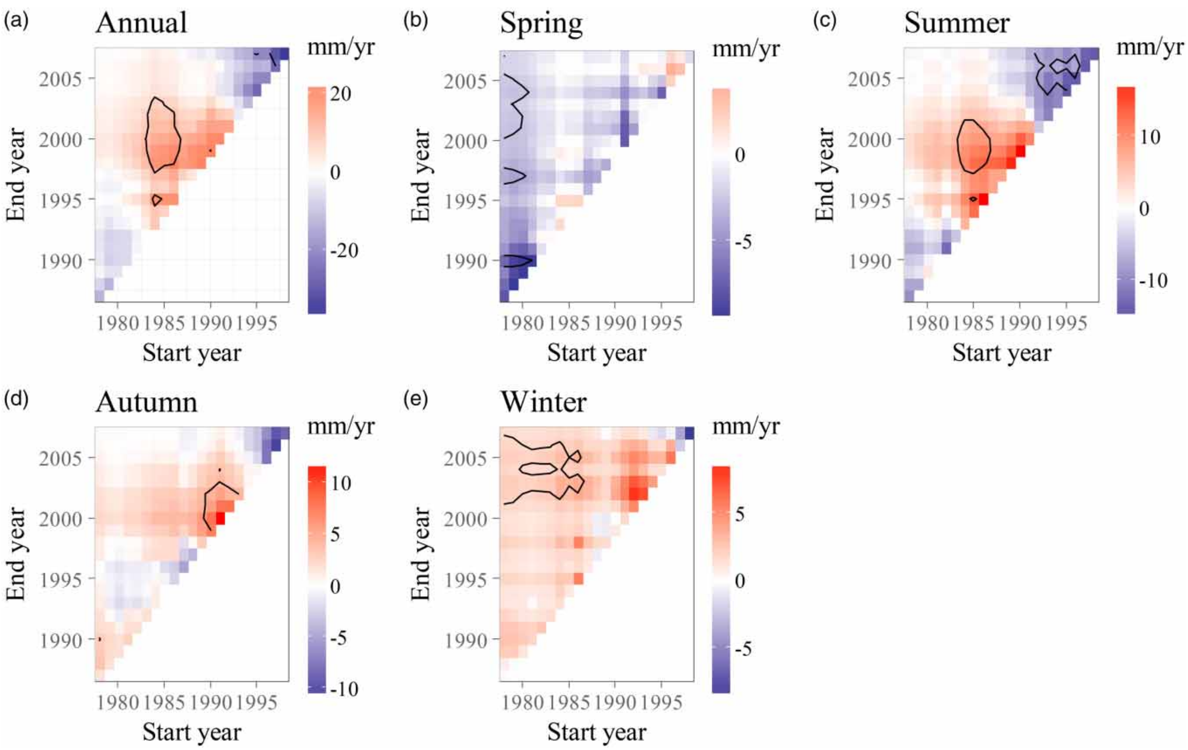

Figure 3 | Multiple trend analyses for seasonal SWS in XJRB. Black contours delineates areas of significant trends at 5% significance level.

summer SWS in XJRB increased significantly from 1985 to 2000, followed by a significant decreasing trend from 1995 to 2005. Moreover, there also existed a significant upward trend in autumn SWS from 1990 to 2000 with a rate of 10 mm/yr. Winter SWS significantly increased throughout the whole study period.

Characteristics of runoff

Figure 4 presents results of the multiple trend analysis for runoff depth in XJRB. Results shows that a significant positive trend of runoff depth was found for the time periods ending in the beginning of the 2000s, with a rate of approximately 30.26 mm/yr, while a decreasing trend was detected in the period of the 1990s to 2000s.

At seasonal scale, a significant increasing trend was found in spring during the 1980s with a rate of 25 mm/yr. For the summer period, runoff depth in XJRB was increasing for the period from 1980 to 2000s, with a rate of about 30 mm/yr, whereas a significant downward trend was found from 1995 to 2005, with a rate of 25 mm/yr. In addition, autumn runoff depth in XJRB was found to increase significantly during the 1990s, with a rate of 10 mm/yr. No significant trend in runoff depth was found in winter.

Sensitivity analysis of runoff

Figure 5 illustrates the relative change in runoff as a function of relative changes in precipitation and SWS. As shown in Figure 5, patterns of runoff sensitivities differ among four seasons. Although the general pattern of the runoff sensitivity contour plot appears to be similar, it can be stated that runoff is more sensitive to precipitation and SWS in summer and autumn than in spring and winter. In addition, runoff in XJRB is more sensitive to precipitation than to SWS.

Influencing paths of precipitation and SWS to runoff

Table 1 shows the direct and indirect effects of environmental variables on runoff depth. Annually, the direct effect of monthly precipitation (MP) on monthly runoff

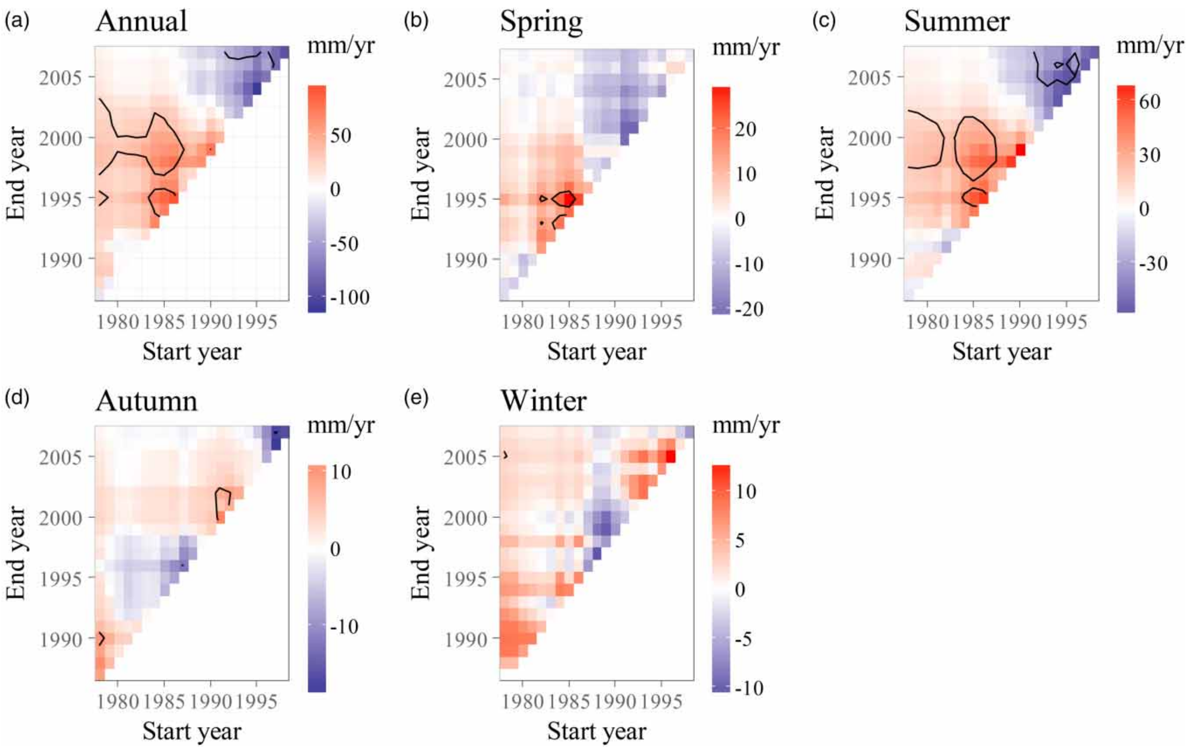

Figure 4 | Multiple trend analyses for seasonal runoff depth in XJRB. Black contours delineate areas of significant trends at 5% significance level.

depth (MRD) was 0.85, almost seven times as large as the indirect effect, which was only 0.12. The direct effect of monthly soil water storage (MSWS) on runoff depth, however, was only 0.17.

In spring and summer, the direct effects of MP on MRD were 0.83 and 0.86, respectively, much higher than those of MSWS, which were only 0.23 and 0.17. The direct effect of MSWS on MRD increased in autumn and winter, reaching 0.46 and 0.43.

DISCUSSION

This study took XJRB as a case study for demonstrating the applicability of the path analysis approach. Previous studies have well evaluated the feasibility of PAM in analyzing the hydrological process in glacier-covered alpine catchments such as the Kaidu River Basin (Li *et al.* 2011) and upper Hailuogou Valley (Xing *et al.* 2015). Their results demonstrated the importance of temperature on runoff generation, that temperature could influence runoff indirectly by determining the soil frozen state in arid or semi-arid zones. However, it is not the case in inland basins such as XJRB. According to our results, we found that precipitation is a key factor directly influencing runoff in XJRB, and SWS has a strong indirect influence especially in autumn and winter.

Previous studies have also demonstrated that evapotranspiration is a significant water loss that should influence the runoff generation process; however, the relationship between evapotranspiration and runoff in XJRB is not significant. In addition, although there existed significant trends in air temperature in XJRB in the past decades, the influence of temperature on runoff is not significant (Guo *et al.* 2007). Consequently, the simplified conceptual model of 'precipitation-SWS-runoff' is applied in XJRB. However, the error terms in the four seasons were 0.24, 0.21, 0.40 and 0.18, respectively. The amount of error terms was as much as the effect of SWS, indicating that caution is needed in interpreting these results because the uncertainty could affect the final results. In addition, other factors such as topography, land cover and consumptive water use should be evaluated in future studies.

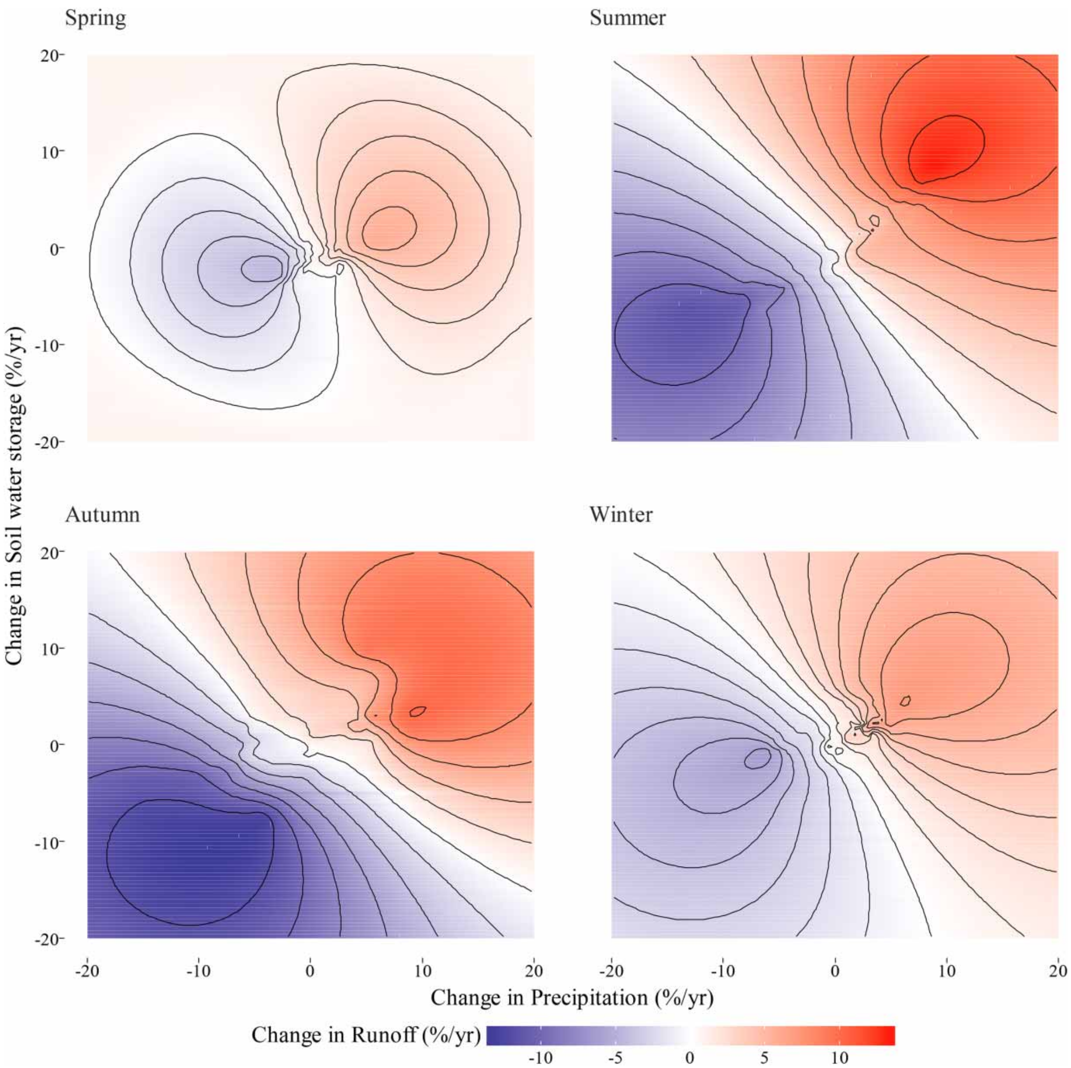

Figure 5 | Seasonal runoff sensitivities to precipitation and SWS in XJRB.

Table 1 | Analyses of direct and indirect effects of monthly precipitation (MP) and monthly soil water storage (MSWS) on monthly runoff depth (MRD) in XJRB

Variables	Correlation coefficient	Direct effect	Indirect effect By MSWS	Error source	R^2
MP (annual)	0.97	0.85	0.12	0.22	0.95
MSWS (annual)	0.80	0.17	/		
MP (spring)	0.95	0.83	0.12	0.24	0.95
MSWS (spring)	0.67	0.23	/		
MP (summer)	0.97	0.86	0.11	0.21	0.95
MSWS (summer)	0.75	0.17	/		
MP (autumn)	0.82	0.60	0.22	0.40	0.84
MSWS (autumn)	0.75	0.46	/		
MP (winter)	0.93	0.64	0.29	0.18	0.97
MSWS (winter)	0.86	0.43	/		

CONCLUSIONS

In this study, we applied PAM to differentiate the direct and indirect contributions of environmental factors on runoff in XJRB. From the results obtained, the following conclusions can be made:

(1) Changes in hydro-climatic variables were found using multiple trend analysis with different start and end years at different time scales. Precipitation, SWS and runoff in XJRB fluctuated throughout the past 30 years with no monotonic trends at both annual and seasonal scales.
(2) In XJRB, positive correlations among precipitation, SWS and runoff depth were significant at both annual and seasonal scale. Moreover, runoff is more sensitive to precipitation than to SWS, and higher runoff elasticity was found in summer and autumn.
(3) The PAM presented in this study is relatively simple, but it is a feasible method for differentiating the influencing paths of environmental factors to runoff. In XJRB, the direct influence of MP on MRD was seven times as large as that of MSWS. Moreover, the indirect influence of MP on MRD through MSWS accounts for 11–31% of the total influence of MP on MRD.

ACKNOWLEDGEMENTS

The research was supported by National Science Foundation of China (41371121, 41771235), Key Research and Development Pan of Jiangxi Province (20171BBH80015) and National Science & Technology Pillar Program during the Twelfth Five-year Plan Period (2014BAC09B02).

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First received 14 August 2017; accepted in revised form 31 October 2017. Available online 13 November 2017