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Analysing the influence of human activity on runoff in the Weihe River basin

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Abstract Changing runoff patterns can have profound effects on the economic development of river basins. To assess the impact of human activity on runoff in the Weihe River basin, principal component analysis (PCA) was applied to a set of 17 widely used indicators of economic development to construct general combined indicators reflecting different types of human activity. Grey relational analysis suggested that the combined indicator associated with agricultural activity was most likely to have influenced the changes in runoff observed within the river basin during 1994–2011. Curve fitting was then performed to characterize the relationship between the general agricultural indicator and the measured runoff, revealing a reasonably high correlation (R^2 = 0.393) and an exponential relationship. Finally, a sensitivity analysis was performed to assess the influence of the 17 individual indicators on the measured runoff, confirming that indicators associated with agricultural activity had profound effects whereas those associated with urbanization had relatively little impact.

Key words Weihe River basin; principal component analysis; grey relational analysis; sensitivity analysis method; social and economic activities

1 INTRODUCTION

Runoff volumes are sensitive to both climate change and changing land use patterns (He *et al*. 2012). Consequently, there is great interest in determining how global warming interacts with other environmental changes and human activities to influence runoff behaviour and the water cycle (Hou *et al*. 2011). The measured runoff volumes in China's six largest river basins have declined significantly over the last 50 years; a particularly pronounced decline has occurred in the middle and lower reaches of the Yellow River, especially in the basins of the Jinghe and Weihe rivers (Zhang *et al*. 2007, 2009). The Weihe River basin is located in the eastern part of the fragile ecological environment of Northwest China, which is prone to natural disasters and is heavily affected by human activity, especially in the vicinity of Guanzhong. Because alterations in the region's runoff patterns could adversely affect regional development and hinder attempts to mitigate climate change, we investigated the relationship between runoff in the Weihe River basin and changes in socio-economic activity within the basin over time.

The Weihe River flows over China's Loess Plateau, originating north of Niaoshu mountain in Weiyuan county of Gansu Province, and emptying into the Yellow River in Tongguan county of Shaanxi Province. It has a drainage area of 135 000 km^2, is 818 km long, and flows in an eastward direction through 84 counties and three provinces across the Guanzhong basin (Zhang *et al*. 2009). The Weihe River basin spans longitude and latitude ranges of 103.5°–110.5°E and 5°–37.5°N, respectively. Its two main tributaries are the rivers Jinghe and Beiluohe (Jiang *et al*. 2013). The southeastern part of the Weihe River basin is located in the continental monsoon zone, while the northwest is in the transitional zone between arid and humid regions, which experiences droughts in spring and alternating periods of rainy heat and drought in summer due to the west Pacific Subtropical High. The region is dry and cold in the autumn and winter due to the Mongolia High (Zhang 2002). Around 65% of the basin's annual precipitation occurs between July and October (Wang and Wang 2000). The region's average temperature is –1 to –3°C in the coldest month (January) and 23–26°C in the warmest (July) (He and Xu 2006).

2 DATA SOURCES AND METHODOLOGY

2.1 Data sources

Socio-economic data for the Guanzhong region were obtained from the statistical yearbook of Shaanxi province (1995–2012). Measured and unimpaired runoff volumes were obtained from

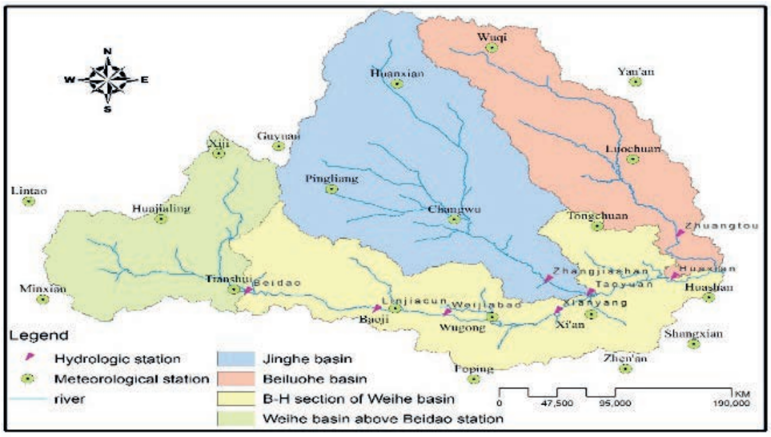

Fig. 1 The Weihe River basin

measurements made at Huaxian Station (1994−2011) and were kindly provided by the Yellow River Conservancy Commission.

2.2 Methodology

Principal component analysis (PCA) was used to extract principal components from a set of indicators of social and economic activity in the Guanzhong area of the Weihe River basin. Grey relational analysis was then used to determine the correlation between these principal components and the runoff data. The curve estimation feature of SPSS was used to obtain establish a regression equation relating the principal components to the measured runoff values. Finally, a sensitivity analysis was performed to determine the influence of each individual socio-economic activity indicator on the runoff volumes of the Weihe River basin.

2.2.1 Principal component analysis PCA was introduced by Pearson in 1901 and extended to random vectors in 1933 by Hotelling (Yu and Fu 2005). It is mainly used to reduce the dimensionality of large datasets by converting many observations of correlated variables into a set of values of linearly uncorrelated principal components, thereby simplifying subsequent data handling and interpretation (Liu and Zhang 2011). PCA was performed using SPSS as described by Lin and Zhang (2005) to construct generalized indicators reflecting different types of social and economic activity within the basin.

2.2.2 Grey relational analysis Grey relational analysis (GRA) is a component of the grey system theory developed by Prof. Deng. It aims to quantitatively describe the evolution of a studied system in comparative terms. Essentially, it is used to determine the extent to which a given sequence of observations resembles a reference sequence and to determine the correlation between the two (Zhou and Li 2007).There are two kinds of GRA, absolute and relative. Relative GRA is used to characterize the dynamic similarity of the investigated sequences and only provides information of the rate of change of the values in the sequence. However, it avoids some problems that have been identified with absolute GRA (Chen 2007). In this work, a relative GRA was performed to assess the similarity of the trends observed in the runoff data to the variation observed in the generalized socio-economic activity indicators obtained from the principal component analysis.

2.2.3 Sensitivity analysis Sensitivity analysis is used to determine how sensitive the output of a model or system is to uncertainty in its various inputs. In this work, sensitivity analysis was performed on a model relating the runoff due to human activity within the Weihe River basin to variation in one of the generalized socio-economic activity indicators derived by principal component analysis. The sensitivity analysis was performed to determine how changes in the individual socio-economic activity indicators that contribute to the generalized indicator influence the expected runoff.

3 RESULTS AND ANALYSIS

3.1 Principal component analysis of social and economic activities

Seventeen indicators of socio-economic activity in the Weihe River basin were subjected to principal component analysis to create generalized measures of socio-economic activity in the region (Table 2).

The proportion of the total variation in the indicator data set explained by each individual principal component is shown in Table 1, along with the cumulative variation explained by each successive component. The first principal component (PC_1) explained 83% of the variation in annual precipitation, and the first two components (which both had eigenvalues of >1) together explained 92% of the variation. Thus, the first two PCs together describe the variation in the socio-economic indicators for the Guanzhong area of the Weihe River basin quite well. The coefficients of each indicator in these two principal components are shown in Table 2.

Table 1 Principal component analysis of the seventeen socioeconomic activity indicators.

Component	Initial Eigenvalues			Extraction sums of squared loadings		
	Eigenvalues λi	Proportion of variation (%)	Cumulative proportion of variation (%)	Eigenvalues λi	Proportion of variation (%)	Cumulative proportion of variation (%)
1	13.311	83.193	83.193	13.311	83.193	83.193
2	1.442	9.014	92.208	1.442	9.014	92.208
3	0.748	4.674	96.881			
	:	:	:			
17	2.083E-7	1.302E-6	100.000			

Table 2 Coefficients of the 17 socio-economic indicators in the first two principal components.

Indicators	Principal components	
	PC_1	PC_2
X_1 Total population at year-end (10 000 persons)	A_1: 0.888	B_1: –0.249
X_2 Area of Cultivated Land (1000 ha)	A_2: –0.799	B_2: 0.514
X_3 Total sown area (1000 ha)	A_3: –0.370	B_3: 0.702
X_4 Total crop area (1000 ha)	A_4: –0.765	B_4: 0.584
X_5 Livestock inventory (head)	A_5: 0.578	B_5: –0.503
X_6 Primary industry GDP (10 000 yuan)	A_6: 0.979	B_6: 0.175
X_7 Secondary industry GDP (10 000 yuan)	A_7: 0.986	B_7: 0.154
X_8 Total power of agricultural machinery (10^4 kw)	A_8: 0.986	B_8: –0.078
X_9 Housing construction area (10^4 $m^{2)}$	A_9: 0.898	B_9: 0.294
X_{10} Fixed investments (100 million yuan)	A_{10}: 0.964	B_{10}: 0.231
X_{11} Total retail sales of consumer goods (100 million yuan)	A_{11}: 0.989	B_{11}: 0.141
X_{12} Per capita annual disposable income of urban households (yuan)	A_{12}: 0.989	B_{12}: 0.076
X_{13} Per capita net income of rural residents (yuan)	A_{13}: 0.973	B_{13}: 0.162
X_{14} Industrial energy consumption (million kw/h)	A_{14}: 0.989	B_{14}: 0.023
X_{15} Residents' energy consumption (million kw/h)	A_{15}: 0.994	B_{15}: 0.081
X_{16} Gross agricultural output (100 million yuan)	A_{16}: 0.971	B_{16}: 0.204
X_{17} Gross industrial output (100 million yuan)	A_{17}: 0.969	B_{17}: 0.229

Most of the indicators with positive coefficients in PC_1 are measures of economic development, such as residential and industrial energy consumption or total retail sales of consumer goods. Conversely, most of the indicators with negative coefficients in PC_1 are measures of agricultural development such as the region's total sown and total crop areas, and total area of cultivated land. We can thus identify PC_1 as a combined economic development indicator. Similarly, the second principal component (PC_2) can be described as a combined agricultural development indicator. PC_1 and PC_2 were defined as follows:

$$PC_1 = A_1 \times X_1 + A_2 \times X_2 + \cdots + A_{17} \times X_{17} \quad (1)$$

$$PC_2 = B_1 \times X_1 + B_2 \times X_2 + \cdots + B_{17} \times X_{17} \quad (2)$$

3.2 Grey relational analysis of PCs and runoff

To assess the impact of human activity on runoff in the Weihe River basin, we examined runoff measurements made at the Huaxian monitoring station. The difference between the unimpaired runoff $Q_{H,T}$ and the measured runoff $Q_{H,S}$ was computed to determine the runoff due to human activity, $Q_{H,R}$, in the years 1994–2011, and equations (1) and (2) were used to compute values for PC_1 and PC_2 over the same period. GRA was then used to assess the relationship between $Q_{H,R}$ and the two principal components. The γ values for PC_1 and PC_2 were $\gamma_1 = 0.50$ and $\gamma_2 = 0.889$, respectively, indicating that the variation in $Q_{H,R}$ most closely resembles that of PC_2.

3.3 Curve fitting

The curve estimation module of the SPSS software package was used to analyse the relationship between $Q_{H,R}$ and PC_2. The best fit was achieved with an exponential relationship (Table 3). The regression analysis yielded the following relationship:

$$Q_{H,R} = 16.287 \times e^{0.083 \times PC_2} \quad (3)$$

Figure 2 depicts an increasing function, suggesting that as the agricultural development of the Weihe River basin proceeds, human activity will cause progressively more pronounced changes in the basin's runoff.

Table 3 Results of the curve fitting analysis.

Formula	R^2	F	df_1	df_2	Sig.	Constant	b_1
Exponential	0.393	9.706	1	15	0.007	16.287	0.083

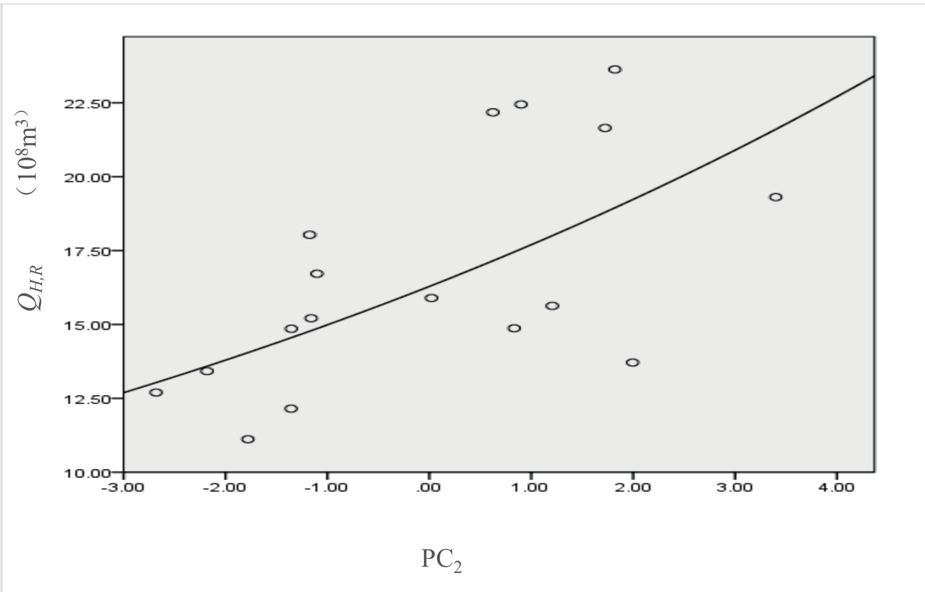

Fig. 2 The relationship between PC_2 and $Q_{H,R}$. The solid line shows the fitted curve.

3.4 Sensitivity analysis of social and economic activities and runoff

Sensitivity analysis was performed to assess the influence of changes in specific social and economic activity indicators on PC_2 and $Q_{H,R}$. Because equation (3) is nonlinear, the selection of the reference year influenced the results of the sensitivity analysis for $Q_{H,R}$. Arbitrarily, 2011 was selected as the reference year in the analysis. A tornado diagram showing the relative impact of a 1% increase in each of the 17 socioeconomic activity indicators on $Q_{H,R}$ is shown in Fig. 3.

Most of the individual indicators (with the exception of X_1, X_5, and X_8) caused $Q_{H,R}$ to increase when their value was increased by 1%, The most influential indicators were X_3, X_4 and X_2, which caused $Q_{H,R}$ to rise by 0.23%, 0.16% and 0.12%, respectively, when increased by 1%. The most

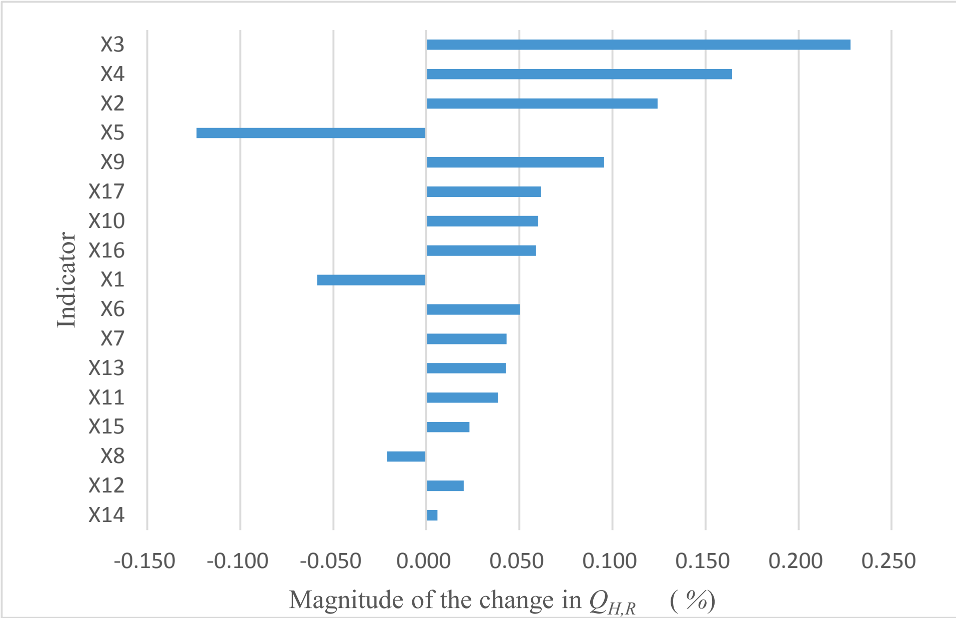

Fig. 3 Tornado diagram showing the sensitivity of $Q_{H,R}$ to a 1% increase in each of the 17 individual socioeconomic activity indicators considered in this work.

influential factor with a negative impact on $Q_{H,R}$ was X_5. Six indicators (X_9, X_{17}, X_{10}, X_{16}, X_1) had modest impacts, causing $Q_{H,R}$ to change by 0.05–0.1%. The other indicators all changed $Q_{H,R}$ by less than 0.05%. The indicators associated with the most pronounced changes in $Q_{H,R}$ were all linked to agricultural activity, demonstrating that agriculture continues to account for most of the water use in the Weihe River basin and has profound effects on the basin's runoff as well as the demand for water resources. Indicators associated with urbanization have relatively little impact on runoff.

4 CONCLUSIONS

Principal component analysis (PCA) has been used to construct combined indicators of human social and economic activity in the vicinity of Guangzhong in the Weihe River basin from a set of 17 individual indicators. Relative GRA was then used to determine which of these combined indicators had the greatest effect on the runoff due to human activity ($Q_{H,R}$). Finally, curve fitting and sensitivity analysis were used to determine which of the original 17 indicators had the greatest impact on the impact of these combined indicators on $Q_{H,R}$. It was found that most of the variation in the 17 socio-economic activity indicators could be summarized using only two principal components: PC_1, which was interpreted as a general economic development indicator, and the general agricultural development indicator PC_2. Relative GRA revealed that the variation in $Q_{H,R}$ resembled that of PC_2 (γ_2 = 0.889) more closely than that of PC_1. Curve fitting using SPSS was used to derive an exponential expression relating $Q_{H,R}$ and PC_2, and sensitivity analysis was then performed to identify the individual socio-economic activity indicators with the greatest effect on $Q_{H,R}$. Overall, our results indicate that agriculture has profound effects on runoff in the Weihe River basin, but the impact of urbanization on runoff is less clear.

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