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A study on the annual runoff change and its relationship with water and soil conservation practices and climate change in the middle Yellow River basin

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ABSTRACT

Based on the long-term hydrological and meteorological series, DEM, soil database and documents of soil conservation measures of the middle Yellow River, investigations are made on the spatial and temporal changes of runoff and the impact of 11 factors, which include rainfall, temperature, terrain slope, drainage density, gravel, sand, silt, and organic carbon content in soil, water consumption, and soil conservation measures. The results show that the total runoff generated from the middle Yellow River had a decreasing trend in the past 60 years, with two abrupt falls around the years 1971 and 1991. In the spatial dimension, runoff modulus grew from the north to the south and from the west to the east, and the largest gradient of spatial change of runoff modulus happened during the period of 1956–1970 before the first falls of the total runoff. In the period 1954–2009, the average annual rate of temporal change of runoff modulus increased acceleratedly outward from the northwest of the middle Yellow River with a concentric ring pattern. Correlation analysis of runoff modulus with potential influencing factors in the spatial perspective reveals that the spatial distribution of the runoff modulus is principally the results of the regional variation of natural conditions. The results of the correlation analysis of the temporal series of runoff coefficient and influencing factors suggest that climate change, hydraulic engineering and soil conservation measures, were all the major causes of runoff reducing in the second half of the last century in the middle Yellow River. For the whole middle Yellow River, climate change contributed over 40% of the runoff deviations in the 1960s, 1970s and 1990s, while water consumption induced also over 40% runoff reduction in the 1960s, 1970s and 1980s. The runoff reduction due to hydraulic engineering was about 2–3 times of that caused by soil conservation measures, and both of them increased continuously from the 1960s to the 1980s, and kept at a higher level in the 1990s. The contribution of different causes to runoff deviation was variable in different drainage areas. Generally, in the semi-arid areas climate change played a decreasing role in runoff reduction comparing with other causes, while in the semi-humid areas it induced a higher and more variable proportion of runoff deviation according to the decade means.

1. Introduction

In the Yellow River basin, consumption of surface water reached 36 billion m^3 every year, accounting for 75.6% of the natural runoff, of which irrigation water accounted for 76.6% (the average over 2005–2009). In the long term, it is estimated that the water resources of the Yellow River basin is far below the water demand for the water diversion areas inside and outside of this basin (Chen and Zhang, 2001). Therefore, relevant measures of tapping new sources of supply and reducing consumption should be implemented for sustainable utilization of water resources. To determine good alternative measures, nevertheless, it is necessary to find the factors which have impacts on water resources and how they have changed and will change the water resources.

The Yellow River is a sediment laden river. Management of the river is perplexed with interweaved problems of water shortage and sediment surplus (Zhang and Shi, 2001). The main sediment source of the river is the Loess Plateau, which is the main body of the middle Yellow River. Hence, soil conservation measures were put into practice in the 1950s, and enlarged to a large-scale after the 1970s. However, with the progress of soil erosion control practices, runoff in the middle reaches has been reduced continuously. Although the middle reaches is not the primary water source of the basin, the severe water deficiency in the basin requests the middle reaches discharging water as large as possible after satisfying the demands of soil erosion control and water use of local people. For this purpose, the contribution of soil erosion control to runoff reduction should be clarified. This cannot be done by simply relating the measured runoff reduction and indices of the soil erosion control practices because climate change may have also played an important role in the runoff change. Many study results have been reported about runoff variations due to changes in land use

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and climate in the literature (Arnell, 1999; Dai et al., 2010; Ficklin et al., 2009; Gleick, 1987; Kosmas et al., 1997; McCabe and Ayers, 1989; Nash and Gleick, 1991; Němec and Schaake, 1982; Shi et al., 2007; Wang et al., 2000; Xu et al., 2009; Yu et al., 2008). Also, the effect of rainfall variation and human activities (particularly soil conservation measures) on runoff generation and soil erosion in the middle Yellow River has been an academic focus in recent years (Wang and Fan, 2002; Xu, 2005, 2011; Zhang et al., 1998). However, how to reasonably quantify the impacts of relevant factors on variations in runoff generation and to distinguish the contributions of climate change and human activities still remain as an unsolved theoretical and practical issue. Using data of the whole middle Yellow River and by proposing a mechanically based statistical method, the present study makes a further investigation on this issue.

2. Study area

The middle Yellow River is the reaches between the Toudaoguai and Huayuankou hydrological stations (Fig. 1), with a drainage area of about 344,000 km^2. It is bounded by the Taihang Mountains in the east, the Qin Mountains in the south, and the Mu Us desert in the northwest. On the west side of the Yellow River is the famous Loess Plateau, and on the east side is the Luliang Mountains. The middle Yellow River has a semi-humid and semi-arid temperate and warm temperate monsoon climate with the mean annual precipitation changing from 300 mm to 700 mm southeastward and the mean annual temperature from about 6 °C to 11 °C southward.

3. Data and methods

Data used in this study include the annual runoff of 216 hydrological stations, mean daily precipitation and mean daily temperature of 129 meteorological stations within and surrounding the study area, digital elevation models (DEM) with a spatial resolution of 90 m (http://srtm.csi.cgiar.org/), grain composition and organic carbon content in one-meter surface soil with a one-kilometer grid (extracted from Harmonized World Soil Database, http://www.iiasa.ac.at/), the areas of soil and water conservation measures in several periods (1982, 1989 and 1999). The runoff data come from the Hydrological Data of the Yellow River Basin issued yearly by the Yellow River Conservancy Commission. According to Yan (1984), the procedures used for the hydrological survey at hydrometric stations in China follow the national standards issued by the Chinese Ministry of Water Resources and are basically the same as those used internationally. A few of the 216 stations had been observably relocated in the study period, and the longest series of annual runoff recorded at a location of each of these stations was kept. The data of precipitation and temperature are downloaded from China Meteorological Data Sharing Service System. The 129 meteorological stations are among the 756 basic national meteorological stations which have been managed by the China Meteorological Administration and measurement of precipitation and temperature has been carried out following the national criteria (China Meteorological Administration, 2003). The data of soil and water conservation measures contain the areas of terrace, check dam, forestation, grass sowing, farmland irrigation and reservoir capacity. They are among the basic data of soil and water conservation in the Yellow River basin collected from the local governments on the Loess Plateau by the Bureau of Middle Yellow River Management of the Yellow River Conservancy Commission.

The boundary, average slope and drainage density of catchments upstream of 216 stations are calculated from DEM using hydrological analysis tools in the ArcGIS. In the calculation of drainage density, the effects of soil characteristics and slope on the threshold of flow accumulation for generating the river nets from DEM are considered in order to obtain a more reasonable result. The monthly and yearly mean rainfall and temperature for each catchment are computed using the ordinary Kriging method in the ArcGIS. With the boundary of basins and soil database and soil conservation data, calculations are done on the average contents of gravel, sand, silt, clay and organic carbon, and mean areas of terrace, check dam, forestation, grass sowing and irrigation for each basin. The runoff of each watershed is obtained from the discharge input from the upstream hydrological stations and the output at the downmost hydrological station

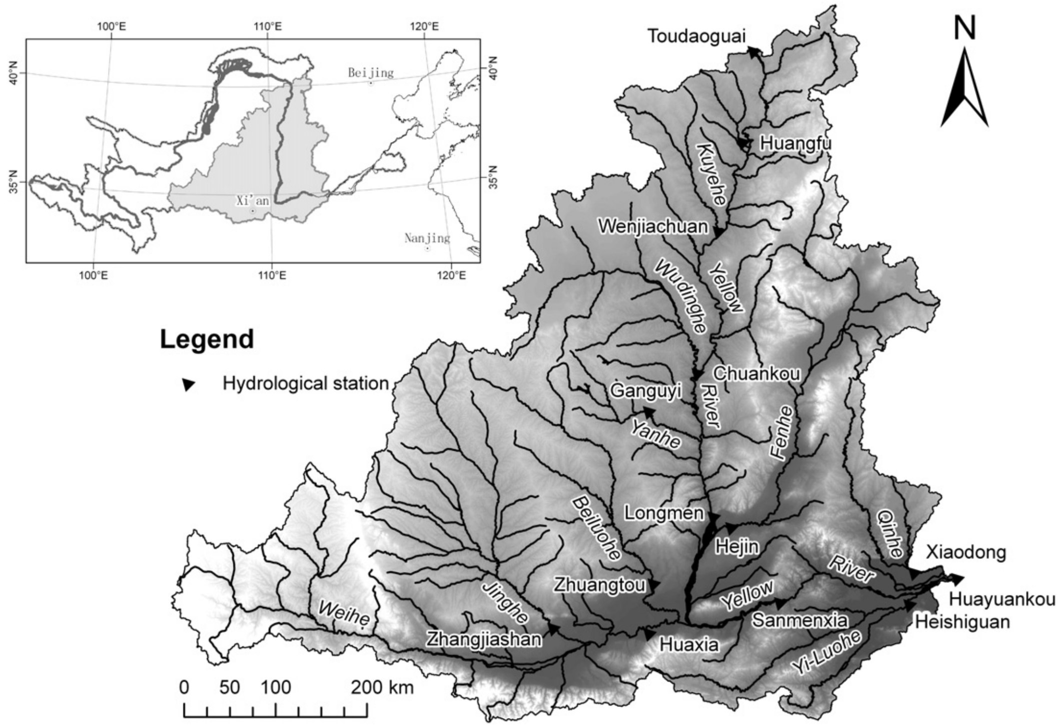

Fig. 1. The middle Yellow River.

according to the river network. The missing runoff records for some years at some stations are interpolated using the hydrological data of the neighboring upstream and/or downstream stations.

Linear regression is used to test the trend in a runoff series. Sequential Cluster test is used to diagnose the abrupt changes in runoff series, and rank-sum to determine the significance. The relationship of runoff with influencing factors is constructed through principal component analysis and regression analysis.

4. Results and discussions

4.1. Temporal and spatial variations of runoff

4.1.1. Temporal variations of runoff

The difference of annual runoff between Toudaoguai and Huayuankou, the entrance and outlet of the middle Yellow River, is shown in Fig. 2. It represents the runoff generated from the middle reaches.

A clear decreasing trend of runoff can be seen in Fig. 2, with a reduction gradient of 322 million m^3 per year. Moreover, the curve of the 10-year moving average of runoff displays a decline in an obvious staircase form. Sequential Cluster and rank-sum test (Ding, 1986) detected a primary abrupt change around the year 1971 and a secondary around the year 1991 (Fig. 3). Runoff reduced by about 46.9% after 1970 than before, and by about 44.1% after 1991 than in the period of 1971–1990. Since 2000, the annual runoff had declined to only 8.48 billion m^3 per year, which was about one-third of that in the 1950s (24.01 billion m^3 per year). The causes for the occurrence of the two abrupt changes will be discussed later after the impacts of influencing factors on runoff being investigated.

4.1.2. Spatial variation of runoff modulus

Rainfall is the primary source of runoff in the middle Yellow River, so following with the spatial distribution pattern of rainfall, runoff increases from north to south and from west to east as shown in Fig. 4. Fig. 4a shows the average of annual runoff modulus in the period of 1956–1970 before the first abrupt fall of runoff generated from the middle Yellow River. In the main, runoff modulus was between 25 mm and 100 mm, and the horizontal gradient was bigger in the south and southeast. The average annual runoff modulus in the period of 1971–1990 was drawn in Fig. 4b, showing a spatial distribution pattern similar to the period of 1956–1970, but the value of runoff modulus declined obviously. In the recent two decades, runoff modulus reduced further and so did its horizontal gradient, especially in the south and southeast of the middle Yellow River (Fig. 4c). The average change rate of runoff modulus and the horizontal gradient of runoff changes increased gradually outward from the northwest of the middle Yellow River with a concentric ring form (Fig. 4d), revealing that the reduction of runoff was higher at areas with a higher runoff modulus.

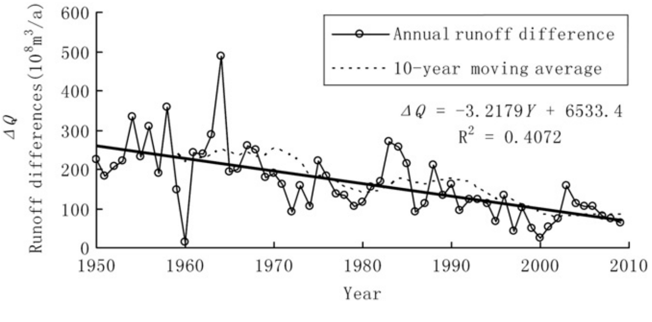

Fig. 2. The annual runoff difference between Huayuankou and Toudaoguai stations in the period of 1950–2009.

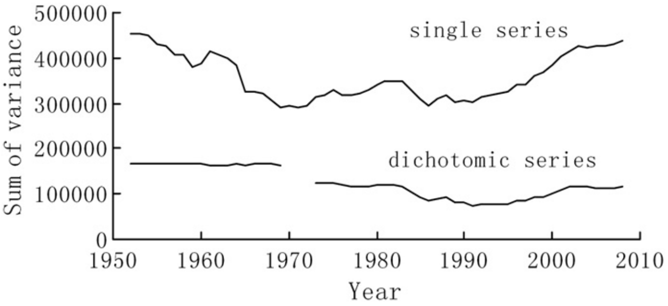

Fig. 3. The abrupt changes detected by the Sequential Cluster test in the series of annual runoff difference between Huayuankou and Toudaoguai stations in the period of 1950–2009.

4.1.3. Spatial variation of runoff coefficient

Fig. 5 shows that the runoff coefficient has a similar pattern of the spatial distribution as the runoff modulus discussed above. It was smaller in the midwest of the Loess Plateau and increased southward and eastward with a growing gradient in the period between 1956 and 1970. The horizontal gradient reduced in the period of 1971–1990. After 1991, the depression of runoff coefficient appeared in the southeast of the middle Yellow River, where the lower reaches of the Fenhe River, Weihe River and Qinhe River are located. From 1956 to 2009, runoff coefficient reduced evidently, especially in the south of the middle Yellow River. The rate of runoff coefficient decrease was less than -0.001/a in the midwest of the Loess Plateau, and a local increase of runoff coefficient even appeared there.

4.2. Influencing factors for spatial variation of runoff coefficient

The middle Yellow River has a long history of human activity, and its intensity enhanced in recent several decades for soil erosion control and utilization of water resources. Thus, the human activities may be another cause for the spatial variation in runoff coefficient besides the nature factors. To test this speculation, an investigation is done on the correlation of runoff coefficient with climate, terrain, soil factors and water and soil conservation measures.

According to the mechanism of runoff generation, a simple model is constructed to express the relationship of runoff coefficient with influencing factors, which is as follow:

$$Q/P = a + b_\mathrm{i}X_\mathrm{i} \tag{1}$$

where Q is the runoff modulus, mm; P is the rainfall, mm; X_i is each of the influencing factors, including rainfall (mm), temperature (°C), drainage density (km/km^2), the mean slope (°), contents of gravel, sand, silt and organic carbon in the 1-meter top soil (%), reservoir capacity per square kilometer (10^4 m^3/km^2), the ratio of irrigation area to the total area of a watershed, the ratio of weighted area of check dam, forestation and grass sowing to the total area of a watershed (detailed explanation is given below). a and b_i are coefficients.

The reason for using a weighted area than the area of each soil and water conservation measure is that the areas of all the measures had been increased through time, so they are highly correlated with each other and their real contributions to runoff cannot be revealed in the regression analysis. For determining the weighted area, the weight of each measure is estimated in light of its capacity of retaining runoff. According to Zhang et al. (1994), the capacity of runoff interception of terrace, sediment check dam, forest and grass on the Loess Plateau is 700.5 m^3/ha, 4500 m^3/ha, 199.5 m^3/ha and 150 m^3/ha, respectively. Thus, assuming a weight of 1 for terrace, the weights of check dam, forestation and grass sowing would be 4500/700.5, 199.5/700.5 and 150/700.5, respectively. With these weights for all measures, the runoff-detaining-efficiency weighted area of soil conservation measures can be calculated.

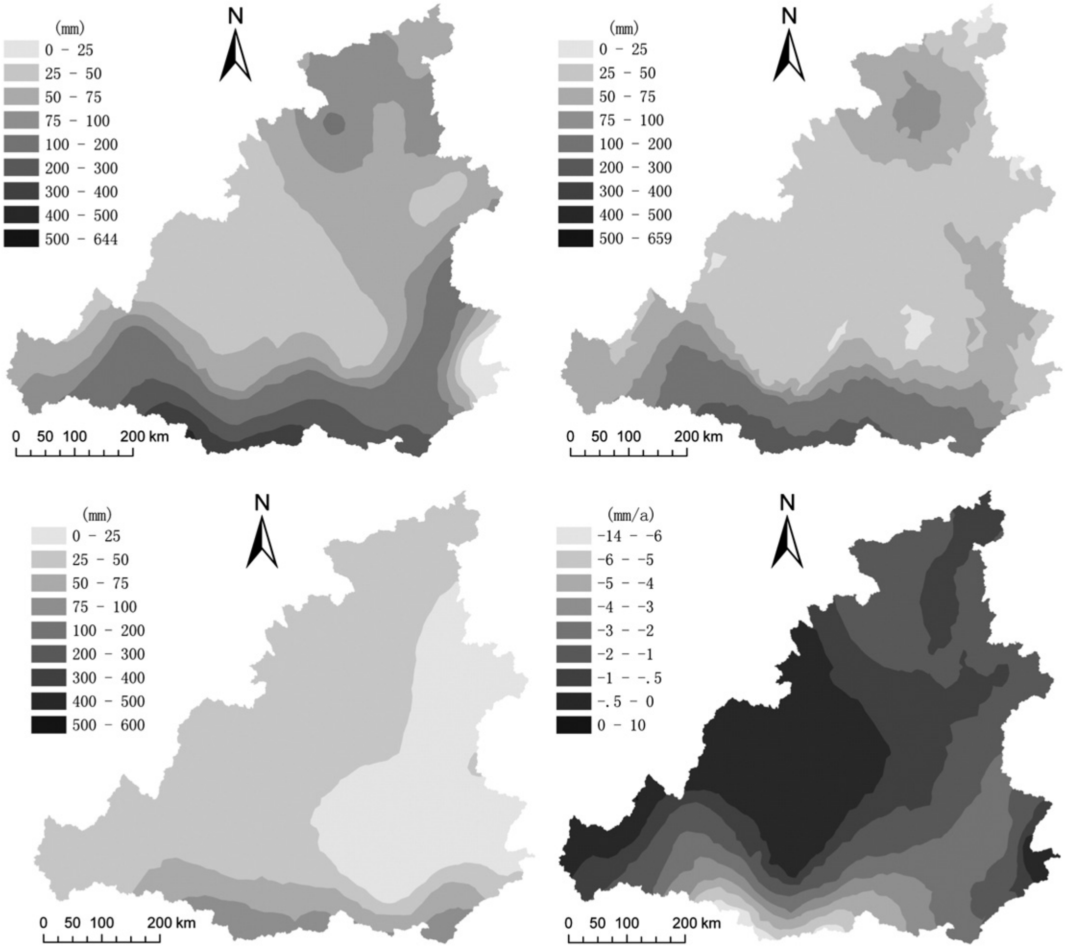

Fig. 4. Distribution of runoff modulus in the middle Yellow River in different periods (up left, 1956–1970; up right, 1971–1990; bottom left, 1990–2009; bottom right, the rate of change over 1956–2009).

The relationship of the average annual runoff coefficient with all influencing factors is analyzed by stepwise and backward regressions for each of the periods of 1956–1970, 1971–1990 and 1991–2009. The significance levels of 0.05 and 0.1 are set as the criteria, respectively, for the entry and removal of a factor from the regression model. Because the data of soil conservation measures in the last decade is not available, the data in the year 1999, which is just in the middle of this period, is used as the average of the period of 1991–2009. Results are given in Tables 1a, 1b, 1c. For the period of 1956–1970 (Table 1a), 4 of 12 factors are retained in the equation. According to the absolute values of standardized coefficients of all variables, the contributions to runoff coefficient decrease successively from rainfall, silt content, temperature to slope. In other words, the spatial distributive feature of runoff coefficient is mainly affected by the variations of natural conditions. Even though in the periods of 1971–1990 and 1991–2009 with intensive human activities, the natural factors had still a higher impact on the spatial distribution of runoff coefficient than human activities (Tables 1b, 1c). For the period of 1991–2009, the irrigation area enters the model of backward regression. However, runoff coefficient is usually negatively related with the irrigation area, that is to say, with the increase of irrigation area, water diversion grows, and in turn the runoff decreases. Here, the positive correlation of irrigation area with runoff coefficient may reflect a fact that the areas with more runoff are in favor of agricultural irrigation, so irrigation diversion augments in these areas. In other words, the positive correlation between irrigation area and runoff coefficient is the indirect reflection of natural conditions. Therefore, the spatial distribution of runoff modulus has been decided mainly by natural conditions up to now.

The above analysis of the relationship between runoff coefficient and influencing factors in the spatial dimension has excluded the impacts of water and soil conservation measures on runoff. Nevertheless, some message of the impacts of water and soil conservation measures on runoff can still be detected from the regression models for different periods. First, the correlation coefficients (r^2) of the models decrease from 0.595 (215 samples) for the period of 1956–1970, to 0.503 (stepwise regression) and 0.512 (backward regression) (215 samples) for the period of 1971–1990, and further to 0.254 (stepwise regression) and 0.258 (backward regression) (217 samples) for the period of 1991–2009, suggesting a growing disturbance to the spatial distribution of natural runoff modulus by gradually intensified human activities in the middle Yellow River. Secondly, if we substitute the precipitation and temperature over the period of 1956–1970 for those of the later two periods, the average runoff modulus calculated from the stepwise regression models in Tables 1a, 1b, 1c will be 81.1 mm, 69.8 mm and 42.7 mm for the periods of 1956–1970, 1971–1990 and 1991–2009, respectively. The decrease of runoff modulus from the early to the later periods under a same climate condition declares that impacts of water and soil conservation measures on runoff has been growing.

4.3. Relation of temporal variation in runoff coefficient with climate change and water and soil conservation measures

As the relationship between runoff coefficient and influencing factors from the spatial perspective is unable to quantify the connection of runoff modulus with the soil conservation measures, we turn to an

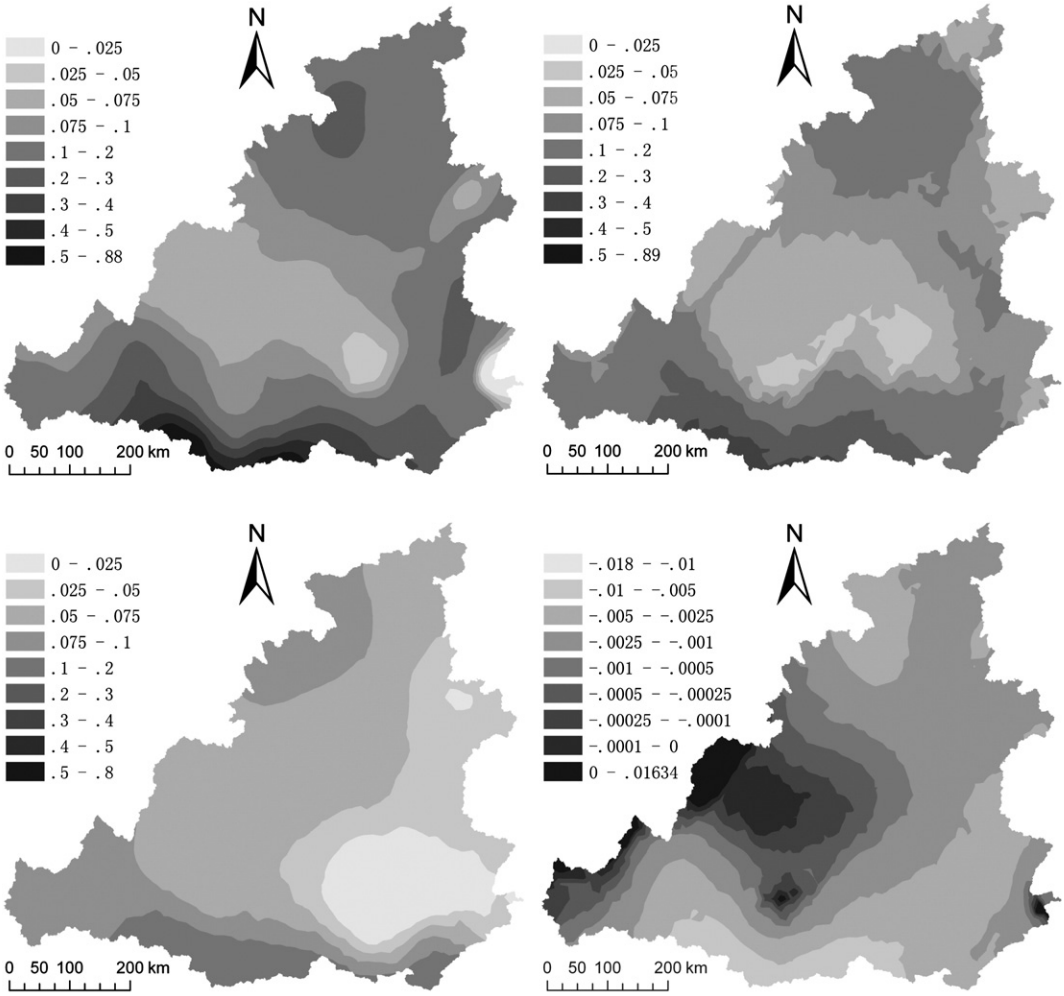

Fig. 5. Distribution of runoff coefficient in the middle Yellow River in different periods (up left, 1956–1970; up right, 1971–1990; bottom left, 1990–2009; bottom right, the average annual rate of change over 1956–2009).

investigation on it from the temporal perspective. Here, Formula (1) is still used, but only factors representing climate and water and soil conservation measures are taken into account. They are rainfall, temperature, reservoir capacity per square kilometer, the ratio of irrigation area to the total area of a watershed, and the ratio of weighted area of terrace, check dam, forestation and grass sowing to the total. The other six factors including drainage density, slope, and contents of gravel, sand, silt, and organic carbon in 1-meter top soil are not considered because they can be regarded as invariant in several decades in the study area.

The relationships between the runoff and the influence factors are constructed through stepwise regression for 217 watersheds using the time series of data over the period of 1956–1990. An unreasonable phenomenon is found that influence factors cannot enter into the regression formulae simultaneously in most cases due to the existence of a strong correlation between the factors. For this reason, we apply principal component analysis to the time series of the factors and select two principal components which have the first and second largest percentage of variance and the sum of the two percentages is close to or greater than 80%. Then, the runoff coefficient is related with the two principal components through regression analysis. Finally, the coefficient of each of factors and constant term

Table 1a
Regression relationship of the average annual runoff coefficient with factors of climate, terrain, and water and soil conservation measures for the period of 1956–1970.

Stepwise/backward regression	Coefficient	Standardized coefficient	T	Significance level
Constant	−0.0523		−1.13	0.26
Precipitation	0.000894	0.556	7.05	0.000687
Temperature	−0.0177	−0.297	−3.99	2.5E−11
Slope	0.00816	0.254	3.45	2.55E−17
Silt content of soil	−0.00740	−0.411	−9.26	9.19E−05

Table 1b
Regression relationship of the average annual runoff coefficient with factors of climate, terrain, and water and soil conservation measures for the period of 1971–1990.

	Coefficient	Standardized coefficient	T	Significance level
Stepwise regression				
Constant	0.00943		0.206	0.837
Precipitation	0.000631	0.447	5.37	2.03E−07
Temperature	−0.0171	−0.296	−3.65	0.000335
Slope	0.00906	0.297	3.78	0.000201
Silt content of soil	−0.00578	−0.327	−6.61	3.13E−10
Backward regression				
Constant	−0.0376		−0.732	0.465
Precipitation	0.000563	0.399	4.63	6.54E−06
Temperature	−0.0153	−0.265	−3.23	0.00144
Slope	0.00997	0.327	4.11	5.6E−05
Silt content of soil	−0.00755	−0.427	−6.01	8.29E−09
Organic carbon content of soil	0.288	0.139	1.95	0.0527

Table 1c
Regression relationship of the average annual runoff coefficient with factors of climate, terrain, and water and soil conservation measures for the period of 1991–2009.

	Coefficient	Standardized coefficient	T	Significance level
Stepwise regression				
Constant	0.0717		2.62	0.00930
Precipitation	0.000148	0.229	2.25	0.0256
Temperature	−0.00912	−0.384	−3.90	0.000129
Drainage density	−0.114	−0.457	−4.68	5.19E−06
Slope	0.00407	0.332	2.72	0.00709
Organic carbon content of soil	0.185	0.221	3.02	0.00284
Backward regression				
Constant	−0.0277		−0.909	0.364
Precipitation	0.000149	0.231	2.86	0.00461
Temperature	−0.00935	−0.394	−5.40	1.83E−07
Irrigation area	0.354	0.149	2.36	0.0194
Gravel content of soil	0.00394	0.165	2.23	0.0268
Sand content of soil	0.00115	0.224	3.54	0.000497

are worked out through reverting the principal components to the influencing factors. Through making a batch program in SPSS software, the principal component analysis of the influence factors and the regression analysis of the relationship between runoff coefficient and the two principal components are completed. Since the time series of runoff of some watersheds are too short to yield reasonable results, each of the watersheds with a record of annual runoff shorter than 18 years, half of the period from 1956 to 1990, is merged with a proximate downstream watershed which has a runoff record long enough. Moreover, watersheds with obviously unreasonable results are also merged with its proximate downstream watersheds. At last, data of 110 stations are reserved for analyzing the relationships between the runoff and the influence factors.

Fig. 6 shows the spatial distribution of coefficient of each factor and constant term of the relationships between the runoff and the influence factors for the 110 stations. The constant term is computed by using the average rainfall and temperature over the period of 1956–1990, so the runoff coefficient may also be regarded as the natural one because it represents that under the condition of average climate condition and without the impacts of water and soil conservation measures. It can be seen that the spatial distribution of runoff coefficient in Fig. 6 is similar to that in Fig. 5 for the period of 1956–1970.

Fig. 6a indicates that runoff coefficient is generally between 0.05 and 0.5 without the influence of human activities. The depression of the natural runoff coefficient is located in the middle and midwest of the middle Yellow River, and the high values appear in the south. It can be seen that each factor of climate and water and soil conservation measures has impacts on the runoff coefficient (Fig. 6b–f). In most areas, the runoff coefficient increases with rainfall, and the increment of runoff coefficient per increment of rainfall augments southward and eastward from the lowest in the north of the Loess Plateau and desert area. With the increase of temperature, runoff coefficient reduces over the whole middle Yellow River, but the reduction of runoff coefficient per unit temperature increase is smaller in the north of the Loess Plateau and desert area, and bigger in the east and south of the middle Yellow River. Reservoirs, irrigation and soil conservation measures reduce the runoff coefficient in most areas with low absolute values of the factor's coefficients occurring in the upper reaches of the Jinghe and Luohe rivers and a general southward and eastward increasing trend, but the spatial distribution of factor's coefficients is relatively irregular.

4.4. Rationality analysis

Using the data of water and soil conservation measures in 1999, rainfall and temperature in the period of 1991–1999, the annual runoff of each of the main tributaries and of the drainage areas between Toudaoguai and other hydrological stations on the main stream of the middle Yellow River is calculated by the models of the 110 watersheds for the period of 1991–1999. There is a good match between the calculated and measured runoff, as shown in Fig. 7, which displays the results of three tributaries and three reaches between Toudaoguai and three hydrological stations on the main stream of the Yellow River. Also, the Nash–Sutcliffe efficiency coefficients for ten main tributaries and the three reaches are computed and listed in Table 2.

Except for the Qinhe River and the Yi-Luohe River, all the other efficiency coefficients are in the range of 0.24–0.8, indicating that the models can give good predictions on the mean runoff at least and on the yearly runoff for some cases. Comparing with the measured runoff, the maximum relatively error of computed average annual runoff for the period of 1991–1999 is 18%, and it is 14% at Huayuankou station, which is the minimum. In view of insufficient data of water and soil conservation measures, regulation of reservoirs, and others, the accuracy of predictions is acceptable. As for the bad predictions of runoff for the Qinhe River and Yi-Luohe River, the conceivable causes are runoff regulation by large reservoirs and exploitation of underground water. According to Qiao and Zhang (2007), the average volume of underground water exploitation in the Qinhe River was 0.1 billion m^3 per year before 1990, and increased significantly to 0.474 billion m^3 per year then after. Meanwhile, runoff supply from spring declined by 81 million m^3 per year. If the annual increment of underground water exploitation is added to and the annual decrease of spring is deducted from the annual runoff of the Qinhe River, the efficiency coefficient for this river will be 0.73. There are two large reservoirs built in the Yi-Luohe River basin. They are among the top 20 largest reservoirs in the Yellow River basin and the biggest reservoirs in all the tributaries of the river. The two large reservoirs have great effects on the runoff of the Yi-Luohe River. The Luhun Dam was built on the Yihe River in 1965 with a storage capacity of 1.29 billion m^3. The Guxian Dam has a storage capacity of 1.175 billion m^3 and was built on the Luohe River in 1991. Besides, there are 10 medium reservoirs on the Yi-Luohe River with a total storage capacity of about 2.65 billion m^3, and they control a drainage area of 9798 km^2, which accounts for 52% of the Yi-Luohe River watershed. Unfortunately, only the impoundment variation of the Guxian reservoir is available. If the measured annual runoff of the river is adjusted only by the impoundment variation of the Guxian Dam, the efficiency coefficient of the Yi-Luohe River will be improved from −0.94 to −0.06 for the period of 1991–1999. Therefore, interannual runoff regulation of reservoirs in the 1990s is the main reason for the low prediction accuracy of runoff in the Yi-Luohe River.

4.5. Contributions of climate change and water and soil conservation measures to runoff change in the middle Yellow River

Based on models of the 110 watersheds built above and the data of climate and water and soil conservation measures, computation is done on the runoff reduction due to water consumption through reservoir impoundment and water diversion, soil erosion control practices and climate change. Fig. 8 shows estimates of runoff reduction owing to water and soil conservation practices for the drainage area between Toudaoguai and Sanmenxia and the whole middle Yellow River. It can be seen that the runoff reduction by water consumption is larger than that by soil erosion control practices, and both of them had increased gradually before the middle 1980s and undulated around a high average then after. Clearly, although aimed at controlling soil erosion, soil conservation measures not only reduce sediment yield, but cut down the runoff. In the last decade of the 20th century, water and soil conservation measures reduced runoff by about 2.3 billion m^3 annually for the drainage area between Toudaoguai and Sanmenxia and by 3.2 billion m^3 annually in the whole middle Yellow River. On the other

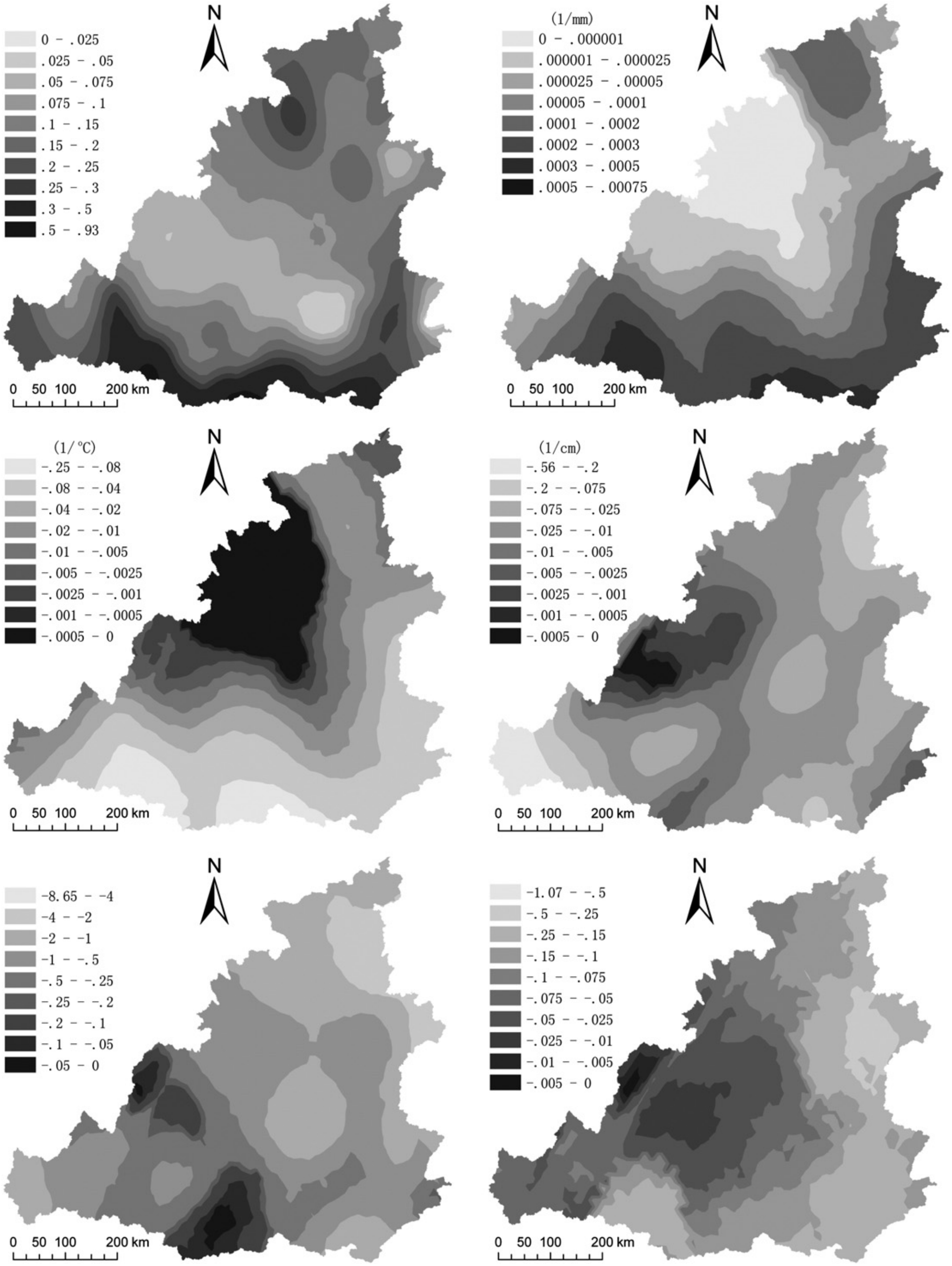

Fig. 6. Distribution of coefficients of the relationships between runoff coefficient and factors of climate, water and soil conservation measures in the middle Yellow River (up left, constant; up right, coefficient of precipitation; middle left, coefficient of temperature; middle right, coefficient of dam; bottom left, coefficient of irrigation; bottom right, coefficient of weighted area of soil conservation measures).

hand, the rate of runoff reduction by climate change was about 0.162 billion m^3 per year for the whole middle Yellow River basin, and 0.121 billion m^3 per year in the drainage area between Toudaoguai and Sanmenxia over 1956–1999 (Fig. 9). Table 3 shows the average runoff reduction due to water consumption, soil erosion control, and climate change in the drainage areas upstream of some hydrological stations. The proportions of runoff changes (mostly reduction) to the annual mean runoff over the period of 1956–1959 and the percentages of contributions from climate change and from human activities are given in Table 4. The runoff reduction by climate change is the difference between the computed runoff under the rainfall and temperature in a year and that under the average rainfall and temperature over the period of 1956–1959.

It is clear that the decade means of runoff reduction by water consumption, soil erosion control practices, and climate change has a general increasing trend in different drainage areas (Table 3). For the whole middle Yellow River, the proportion of the total runoff reduction in the annual mean runoff over the period of 1956–1959 increased from 14.2% in the 1960s to 57.7% in the 1990s (Table 4). Runoff reduction associated with climate change was much higher in the 1970s and 1990s (Table 3) and its contribution to total runoff

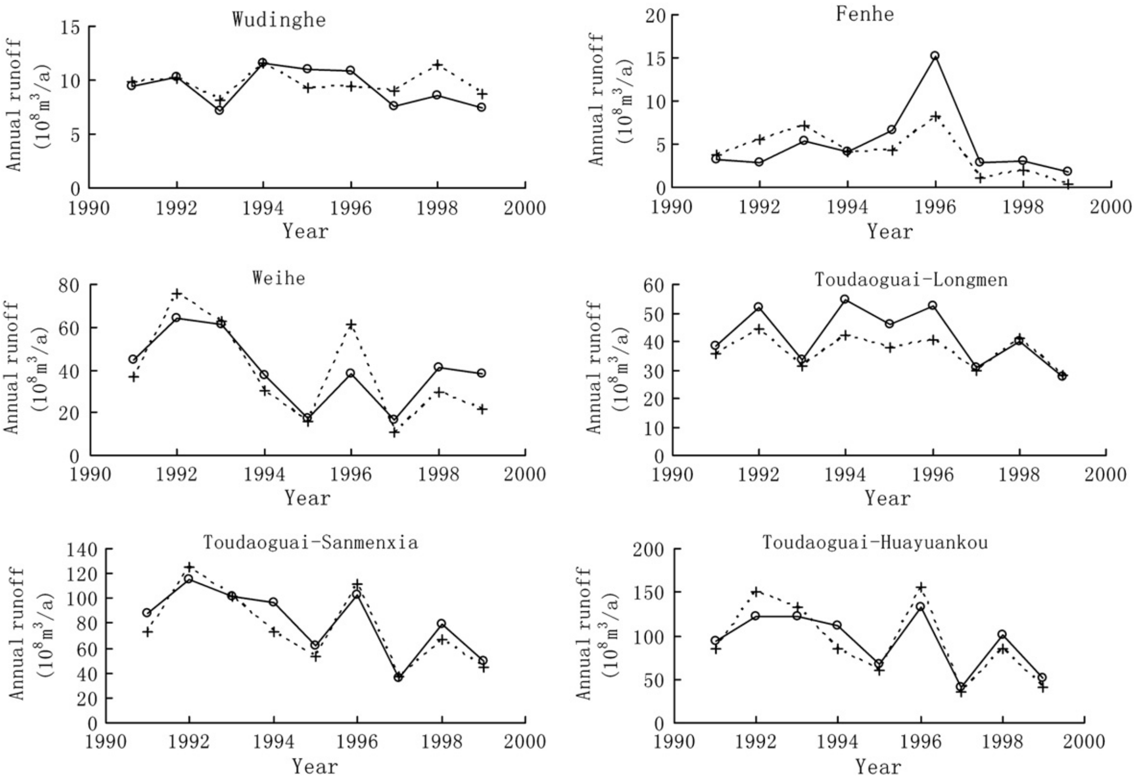

Fig. 7. Comparison between the calculated (plus) and measured annual runoff (circle) of some first-order tributaries and of the drainage areas between Toudaoguai and three hydrological stations on the mainstream of the middle Yellow River over the period of 1991–1999.

deviations was over 40% in the 1960s, 1970s and 1990s (Table 4). Water consumption contributed also over 40% to the total runoff deviation in the 1960s, 1970s and 1980s, and even over 50% in the 1980s. The runoff reduction by water consumption was 2–3 times of that by soil erosion control practices according to their decade means. The total contribution of water consumption and soil erosion control practices, or the principal human activities, to runoff deviations was higher than that due to climate change in the period from the 1960s through 1990s. For different drainage areas the runoff deviations and contributions of different causes were different. The drainage area between Toudaoguai and Longmen occupies about 35.8% of the middle Yellow River basin and is located mostly in the north and west of the middle Yellow River, which is characterized by a lower precipitation than the others. The runoff reduction and contribution of climate change to runoff reduction in this area were generally lower than the others. In the basin of the Wudinghe River, the first largest tributary in the Toudaoguai to Longmen reach, the proportion of runoff reduction in the river's runoff was lower than the regional average, but water consumption caused over 50% of the runoff reduction and climate change contributed a proportion around 27% in the 1960s and 1970s and 7.4% in the 1990s. The Weihe River is the first largest tributary of the Yellow River and has a drainage area of 29.4% of the middle reaches of the river with a precipitation higher than the north drainage areas. The runoff deviation accounted for a slightly lower proportion of total runoff in this drainage area than the average of the whole middle Yellow River, and the contribution of climate change to the runoff deviation varied obviously over time. In the 1990s, the climate change resulted in a runoff deviation larger than the total induced by water consumption and soil erosion control practices. The Fenhe, Yi-Luohe, and Qinhe rivers occupy the semi-humid east part of the middle Yellow River. The runoff reduction had a higher proportion in the runoff of these rivers than the average of the middle Yellow River. In the Yi-Luohe River, the climate change resulted in over 50% of the runoff reduction in the 1960s, 1970s, and 1990s, so did in the Qinhe River in the 1990s. It was the human activities that caused over half of the runoff reduction in the Yi-Luohe and Qinhe rivers in other times and in the Fenhe River in all the four decades from the 1960s to 1990s.

Clearly, human activities including water consumption and soil erosion control practices played an important role in runoff reduction in the middle Yellow River from the 1960s to 1990s. This is not unexpected because the middle Yellow River is the cradle of the Chinese civilization, the water resources have been much scarce in the semi-arid land, and large scale soil conservation practices have been carried out on there in recent decades for reducing the sediment output from the Loess Plateau. Nevertheless, our results also show that the climate change has a sizeable contribution to the runoff decrease in the study area. Similar cases have been reported for many worldwide

Table 2
The Nash–Sutcliffe efficiency coefficient for the calculated annual runoff of main primary tributaries (expressed as the tributary/outlet station) and of the drainage areas between Toudaoguai and three hydrological stations on mainstream of the middle Yellow River over the period of 1991–1999.

Huangfuchuan/Huangfu	Kuyehe/Wenjiachuan	Wudinghe/Chuankou	Yanhe/Ganguyi	Toudaoguai-Longmen	Fenhe/Hejin	Jinghe/Zhangjiashan
0.53	0.57	0.24	0.29	0.44	0.48	0.31

Beiluohe/Zhuangtou	Weihe/Huaxian	Toudaoguai-Sanmenxia	Qinhe/Xiaodong	Yi-Luohe/Heishiguan	Toudaoguai–Huayuankou
0.52	0.42	0.80	−0.39	−0.94	0.70

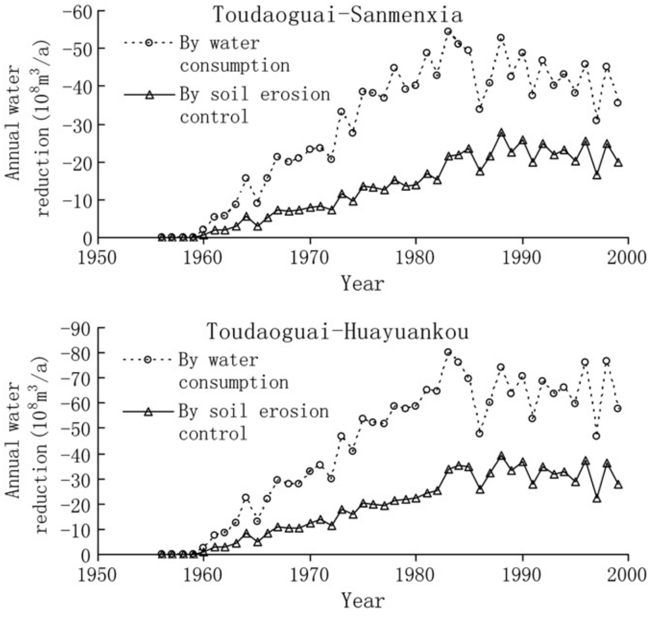

Fig. 8. Runoff reduction by water consumption and by soil conservation practices in the drainage areas between Toudaoguai and Sanmenxia stations and between Toudaoguai and Huayuankou stations in the period of 1956 to1999.

rivers (Beguería et al., 2003; Changnon and Demissie, 1996; Gerten et al., 2008; Girmay et al., 2009). In Tigray, Northern Ethiopia, the variation in total rainfall amount explained 69% of the annual runoff volume variability (Girmay et al., 2009). In two rural basins in Illinois-Indiana, the uptrends in precipitation explained about 30% of the upward trend in annual flows, while it was about 61% in a more urbanized basin and 37% in a less urbanized basin in Chicago in the period from 1940 to 1990 (Changnon and Demissie, 1996). For the whole globe, Gerten et al. (2008) disclosed that the increasing precipitation caused 80% of total global runoff rise (7.7%) over 1901–2002.

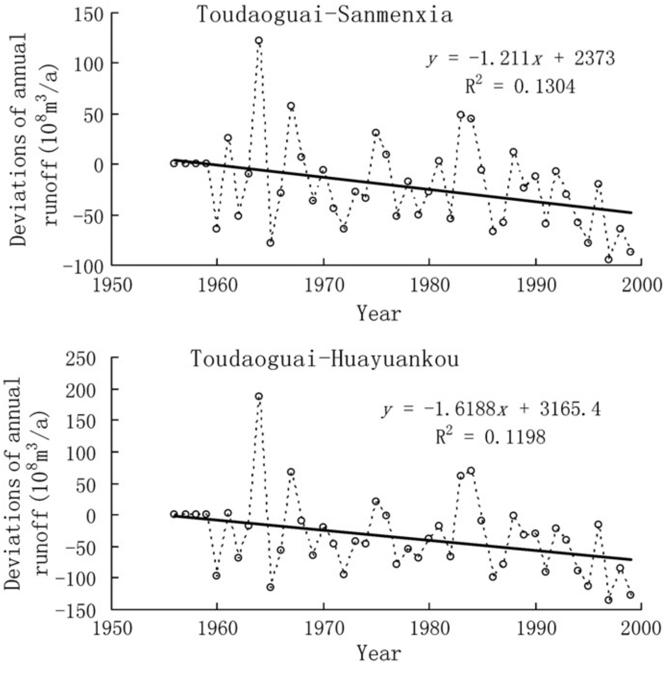

Fig. 9. Deviations of annual runoff due to changes in rainfall and temperature in the drainage areas between Toudaoguai and Sanmenxia hydrological stations and between Toudaoguai and Huayuankou hydrological stations in the period of 1956 to1999.

Many previous studies have made simulations on river discharge variations due to changes in precipitation and temperature using climate and hydrological models (Dai et al., 2010; Legesse et al., 2003; McCabe and Ayers, 1989; Němec and Schaake, 1982; Thodsen, 2007; Wilk and Hughes, 2002). McCabe and Ayers (1989) found that a warming of 4 °C might cause a 25% decrease in runoff and a 15% increase in precipitation could counteract the decrease in the Delaware River basin. It was reported that a change of 2.4% in the annual average streamflow could be induced by a change of 1% in precipitation in a forested watershed on the southeastern Atlantic coastal plain (Dai et al., 2010), a reduction of 30% in the simulated discharge by a 10% decrease in rainfall and a decrease of 15% by a 1.5 °C increase in air temperature for a catchment in tropical Africa (Legesse et al., 2003), an increase of 17% in annual runoff by an increase of 10% in annual rainfall for a large tropical catchment in southern India (Wilk and Hughes, 2002), and a decrease of 4–21% in the mean annual runoff by an increase of 2 °C to 4 °C in temperature and increases or decreases in mean annual runoff of approximately 10–20% by a change of 10–20% in annual precipitation in the Colorado River (Nash and Gleick, 1991). In the present study, the runoff reduction in the middle Yellow River was found to be associated with the precipitation reduction and temperature increase also. As shown in Fig. 10, there were a trend of decrease in precipitation and a trend of increase in temperature for the whole middle Yellow River over the period of 1956–1999. Compared to years 1956–1959, annual mean precipitation decreased by 3.0%, 10.5%, 9.7%, and 17.1% and annual mean temperature increased by 0.16 °C, 0.23 °C, 0.15 °C, and 0.84 °C on average in the four decades from the 1960s to 1990s, respectively, for the whole middle Yellow River. The mean annual runoff of the river was reduced by 3.2%, 11.2%, 5.9%, and 12.7% due to the decreases in precipitation and by 2.8% 3.5%, 1.3%, and 12.7% for the increases of temperature in the corresponding decades, respectively. Therefore, climate change could be an important factor influencing the water resources in the middle Yellow River.

In Section 4.1.1, two abrupt changes were detected in the series of runoff generated from the middle Yellow River. After the runoff reduction by climate change and human activities has been estimated as given above, the causes for the occurrence of the abrupt changes can be probed into. Fig. 11 shows a series of annual runoff reduction by climate change and soil and water conservation practices in the middle Yellow River. It can be seen that there are two major falls in the moving average of the series around the years 1971 and 1991. Thus, it can be deduced that the abrupt changes in the annual runoff generated from the middle Yellow River as shown in Figs. 2 and 3 are the result of annual runoff deviations due to climate change and human activities.

5. Conclusions

In the middle Yellow River, runoff showed a clearly decreasing trend over the past 60 years. In the general decrease trend existed two abrupt changes around the years 1971 and 1991. Mainly as a result of spatial distribution of rainfall, runoff modulus in the middle Yellow River increased from north to south and from west to east. In the period from 1956 to 1970, runoff modulus was relatively high, and its horizontal gradient increased from the northwest to the south and the east. The runoff modulus and its horizontal gradient declined in the period of 1971–1990 and further in the period of 1991–2009. Moreover, the rate of changes in runoff modulus and its horizontal gradient over the period of 1954–2009 increased outward from the northwest of the middle Yellow River.

The spatial distribution of runoff coefficient was mainly controlled by the natural conditions, and human activities were of secondary importance even after 1971 when human activities became intensive.

The annual runoff from the middle Yellow River experienced an obvious gradual reduction in the period from 1956 to 1999 and the

Table 3
Runoff deviations by climate change, water consumption, and soil erosion control practices in different drainage areas of the middle Yellow River in different periods.

	Drainage areas	1956–1959	1960–1969	1970–1979	1980–1989	1990–1999
Annual runoff reduction due to climate change (10^8 m^3/a)	Wudinghe/Chuankou	0.000	−0.547	−1.389	−1.146	−0.477
	Toudaoguai-Longmen	0.000	−5.888	−9.558	−9.609	−8.471
	Weihe/Huaxian	0.000	1.614	−11.574	−0.279	−33.688
	Fenhe/Hejin	0.000	−1.133	−2.608	−2.776	−4.725
	Yi-Luohe/Heishiguan	0.000	−8.713	−12.511	−3.167	−14.965
	Qinhe/Xiaodong	0.000	−1.440	−3.777	−4.274	−7.241
	Toudaoguai-Huayuankou	0.000	−17.622	−43.458	−21.604	−75.180
Annual runoff reduction by water use and conservation (10^8 m^3/a)	Wudinghe/Chuankou	0.000	−1.139	−2.883	−3.928	−4.125
	Toudaoguai-Longmen	0.000	−4.836	−12.489	−16.446	−17.712
	Weihe/Huaxian	0.000	−3.971	−10.523	−15.462	−12.633
	Fenhe/Hejin	0.000	−1.769	−4.573	−6.105	−4.903
	Yi-Luohe/Heishiguan	0.000	−2.345	−6.324	−9.762	−10.893
	Qinhe/Xiaodong	0.000	−1.074	−2.835	−4.224	−3.934
	Toudaoguai-Huayuankou	0.000	−17.328	−45.956	−66.082	−63.991
Annual runoff reduction by soil conservation practices (10^8 m^3/a)	Wudinghe/Chuankou	0.000	−0.363	−0.917	−1.649	−1.850
	Toudaoguai-Longmen	0.000	−1.753	−4.535	−7.671	−8.416
	Weihe/Huaxian	0.000	−1.365	−3.602	−6.399	−7.230
	Fenhe/Hejin	0.000	−0.770	−1.993	−3.115	−3.959
	Yi-Luohe/Heishiguan	0.000	−1.140	−3.104	−4.661	−3.149
	Qinhe/Xiaodong	0.000	−0.530	−1.404	−2.250	−2.411
	Toudaoguai-Huayuankou	0.000	−7.105	−18.924	−31.265	−31.706

reduction reached about 58% of the total annual runoff of the middle Yellow River in the 1990s. Climate change contributed to total runoff deviations by over 40% in the 1960s, 1970s and 1990s. Water consumption and soil erosion control practices contributed over 50% to the total runoff deviation in the 1960s, 1970s and 1980s, and even about 82% in the 1980s. The average runoff reduction by soil erosion control practices increased from about 700 million m^3 per year in the 1960s to about 3.2 billion m^3 per year in the 1990s. Water consumption induced a runoff reduction of 2–3 times of that by soil erosion control practices according to their decade means. The runoff deviations and contributions of different causes were different for different drainage areas in the middle Yellow River. In the semi-arid areas existed a decreasing trend of proportions of runoff reduction due to climate change, while in the semi-humid areas climate change induced a higher and more variable proportion of runoff deviation according to the decade means.

Table 4
The percentages of runoff reduction in the mean annual runoff over the period of 1956–1959 and the proportions of runoff deviations duo to climate change, water consumption, and soil erosion control practices in different drainage areas of the middle Yellow River in different periods.

	Drainage areas	1960–1969	1970–1979	1980–1989	1990–1999
Ratio of annual runoff reduction to mean annual runoff during 1956–1959 (%)	Wudinghe/Chuankou	−11.5	−29.1	−37.7	−36.1
	Toudaoguai-Longmen	−15.7	−33.5	−42.5	−43.6
	Weihe/Huaxian	−3.7	−25.7	−22.1	−53.6
	Fenhe/Hejin	−18.0	−44.9	−58.7	−66.5
	Yi-Luohe/Heishiguan	−24.6	−44.2	−35.4	−58.4
	Qinhe/Xiaodong	−17.8	−46.8	−62.7	−79.3
	Toudaoguai-Huayuankou	−14.2	−36.6	−40.1	−57.7
Contribution of climate change to the total runoff deviations (%)	Wudinghe/Chuankou	26.7	26.8	17.0	7.4
	Toudaoguai-Longmen	47.2	36.0	28.5	24.5
	Weihe/Huaxian	−43.4	45.0	1.3	62.9
	Fenhe/Hejin	30.9	28.4	23.1	34.8
	Yi-Luohe/Heishiguan	71.4	57.0	18.0	51.6
	Qinhe/Xiaodong	47.3	47.1	39.8	53.3
	Toudaoguai-Huayuankou	41.9	40.1	18.2	44.0
Contribution of water use and conservation practices to the total runoff deviations (%)	Wudinghe/Chuankou	55.6	55.6	58.4	63.9
	Toudaoguai-Longmen	38.8	47.0	48.8	51.2
	Weihe/Huaxian	106.7	40.9	69.8	23.6
	Fenhe/Hejin	48.2	49.8	50.9	36.1
	Yi-Luohe/Heishiguan	19.2	28.8	55.5	37.6
	Qinhe/Xiaodong	35.3	35.4	39.3	29.0
	Toudaoguai-Huayuankou	41.2	42.4	55.6	37.4
Contribution of soil erosion control practices to the total runoff deviations (%)	Wudinghe/Chuankou	17.7	17.7	24.5	28.7
	Toudaoguai-Longmen	14.1	17.1	22.7	24.3
	Weihe/Huaxian	36.7	14.0	28.9	13.5
	Fenhe/Hejin	21.0	21.7	26.0	29.1
	Yi-Luohe/Heishiguan	9.3	14.1	26.5	10.9
	Qinhe/Xiaodong	17.4	17.5	20.9	17.7
	Toudaoguai-Huayuankou	16.9	17.5	26.3	18.6

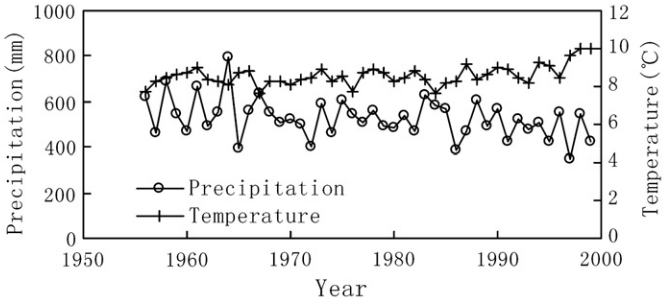

Fig. 10. Changes in annual mean precipitation and temperature in the middle Yellow River.

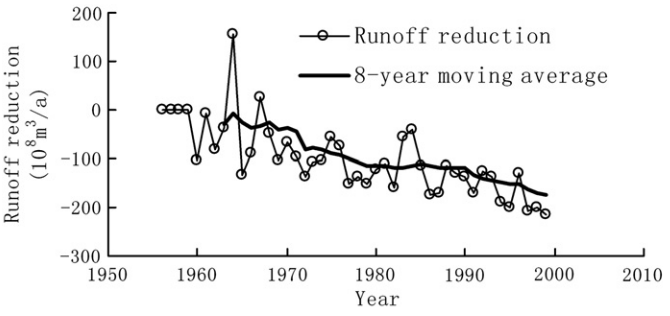

Fig. 11. The changes in annual runoff reduction in the middle Yellow River due to climate change and soil and water conservation practices, showing the obvious falls around the years 1971 and 1991.

The test for runoff prediction shows that the developed models relating runoff coefficient with factors of climate and water and soil conservation measures can be used to predict the annual runoff of the larger first-order tributaries and of the drainage areas between hydrological stations on the mainstream of the middle Yellow River, or the mean annual runoff of smaller first-order tributaries.

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