Investigation into the Impacts of Land-Use Change on Runoff Generation Characteristics in the Upper Huaihe River Basin, China

Qiongfang Li[1]; Tao Cai[2]; Meixiu Yu[3]; Guobin Lu[4]; Wei Xie[5]; and Xue Bai[6]

Abstract: Land-use change has significant impacts on hydrologic processes at the watershed level; thus, quantitative assessment on the impacts of land-use change is vital for basin environment protection and water resources sustainable development. Owing largely to computer and geographical information system (GIS) technology improvements, the distributed hydrological models, which allow describing the temporal variability and spatial distribution of water-balance components, offer an effective approach to quantify the land-use change effects on watershed water quantity. In this study, a soil and water assessment tool model was used to simulate land-use change effects on water quantity in the upper Huaihe River basin in China above the Xixian hydrological controlling station with a catchment area of 10,190 km^2 by the use of temporal three-phase (1980s, 1990s, 2000s) land-use maps, soil type map (1:200,000 scale), and 1980–2008 daily time series of rainfall from the upper Huaihe River basin. Within the model, potential evapotranspiration was computed using the Penman-Monteith method coupled with a simplified plant growth model. On the basis of the simulated time series of daily runoff, land-use change effects on spatio-temporal change patterns of runoff coefficients and runoff modules, the rainfall-runoff relationship, the sensitivity of rainfall-runoff relationship to rainfall for different types of land use, and impact of land-use patterns on rainfall-runoff relationships were investigated. The results revealed that under the same condition of soil texture and terrain slope, the advantage for runoff generation and the sensitivity of rainfall-runoff relationship to rainfall decreased by farmland, paddy field, and woodland. With the same rainfall, the advantage for runoff generation increased by the 1990s, 2000s, and 1980s land-use patterns. The outputs could provide important references for soil and water conservation and river health protection in the upper stream reach of the Huaihe River. **DOI: 10.1061/(ASCE)HE.1943-5584.0000489.**

CE Database subject headings: River basins; Hydrologic models; Runoff; Land use; China.

Author keywords: Upper stream of Huaihe River; Soil and water assessment tool (SWAT) model; Land-use change; Runoff generation characteristics.

Introduction

Global river-land ecosystems have been intensively altered by human activities, particularly land-use change. Land-use change, a major reflection of the land ecosystem change, plays a significant role in affecting the global water systems and energy balance. Recently, the impacts of land-use change on water resources, sedimentary movements, and hydrology processes have received increasingly widespread concern (LØrup et al. 1998; Karvonen et al. 1999; Calder et al. 1995; Costa et al. 2003; Romanowicz et al. 2005; Brath et al. 2006; Wei et al. 2007; Cai et al. 2009; Mao and Cherkauer 2009). Land-use change is a major force altering the hydrological processes over a range of temporal and spatial scales by altering hydrological factors such as interception, infiltration, and evaporation (Potter 1991; DeFries and Eshleman 2004; Wang et al. 2007; Chen et al. 2009). It is well documented that land-use changes have profound impacts on river basin hydrology, primarily through changes in flood frequency (Brath et al. 2006), base flow (Wang et al. 2006), and annual mean discharge (Costa et al. 2003). Yu et al. (2003) explored the effects of land-use change on runoff response in the ungauged Ta-Chou basin, and the results from a distributed rainfall-runoff model revealed that the observed land-use change caused increases in both peak discharge and total runoff. The investigation into the impacts of land-use change on hydrologic responses in the Great Lakes region conducted by Mao and Cherkauer (2009) indicated that the simulated change of average annual runoff resulting from

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land-use modifications varied spatially and seasonally, but was strongly correlated to the type of vegetation conversion and the geographic location of the land-use type centroid. At a watershed scale, such impacts on hydrological processes in turn will significantly influence ecosystem, environment, and economy. Hence, better understanding and assessment of land-use change impacts on watershed hydrologic processes are of great importance for basin environment protection and the sustainable development of water resources.

Recently, the study of human impacts on river basin hydrological processes, as an important topic associated with the world water cycle, the world sediment cycle, and land–ocean interactions, attracted worldwide attention, particularly in large river basins (Li et al. 2007). This is more apparent where human-induced alterations in river hydrological processes are becoming increasingly crucial with intensive and extensive land-use change.

Developing an approach for simulating and assessing the effects of land-use change on hydrological processes at the watershed level is essential in land use and water-resource planning management (Turner et al. 2001). Owing largely to recent computer and geographical information system (GIS) technology improvements, the distributed hydrological models, which allow describing the temporal variability and spatial distribution of water balance components, offer an effective approach to quantify the land-use change effects on watershed water quantity (Bronstert et al. 2002; VanShaar et al. 2002; Klöcking and Haberlandt 2002; Legesse et al. 2003; Bathurst et al. 2004; Bronstert 2004; Jiang et al. 2004; Haverkamp et al. 2005; Wang et al. 2006; Burns et al. 2005). In this study, the soil and water assessment tool (SWAT) model was used to quantify the effects of land-use change on runoff characteristics in the upper Huaihe River basin. The Huaihe River, a major river in China, has a catchment area of 1.912×10^5 km^2. The soil and water loss induced by land use/cover change in the upper Huaihe River basin is a serious environmental and ecological problem, but was poorly understood. Therefore, a comprehensive investigation was needed to determine the alterations of runoff generation characteristics resulting from the land-use change by use of long data series with recent data.

The investigation and assessment of land-use change effects on hydrological processes could provide a vital basis for soil and water conservation and river health protection. This is also the aim of the present study, with the upper Huaihe River in China as a study case. On the basis of the topographic, land-use/cover, soil and hydro-meteorological data, an attempt focusing on the upper Huaihe River basin, was made to quantitatively investigate the effects of land-use change on runoff generation characteristics.

Study Area and Data

Study Area

With intensified human activities, the land-use pattern in the Huaihe River basin has been altered to some extent. This paper focuses on the impacts of land-use change on runoff generation characteristics in the upper Huaihe River basin. The Huaihe River is a major river in China and is located about mid-way between the Yellow River and Yangtze River, the two largest rivers in China. Like them, the Huaihe flows from west to east. The Huaihe River has a drainage area of 174,000 km^2, and is situated between latitudes 31°0′0″ N and 35°0′0″ N and between longitudes 112°0′0″ E and 121°0′0″ E. Originating from the Tongbai Mountains of Henan province, it flows 1,000 km through four provinces, i.e., Henan, Jiangsu, Anhui and Shangdong, before discharging into the Yangtze River. The Huaihe River can be divided into the upper, middle and lower stream reaches. This paper selected the upper Huaihe River above the Xixian hydrologic station as a case study site, where the channel bed slope is steep and the flow velocity is large. The Xixian hydrological controlling station has a catchment of 1.019×10^4 km^2 (Fig. 1), where the soils are light silt loam and sandy loam, with a small part underlain by silty clay. The main land use types in the catchment are farmland, paddy field and woodland. Since the percentage of farmland area plus paddy field area in the whole catchment area is always more than 50%, the catchment is a typical agricultural one. The Xixian subbasin, with an average annual rainfall of 1,145 mm, an average annual runoff of 371 mm and an average annual pan evaporation of 922 mm, is seated in the transition zone of northern subtropical region and warm temperate zone, where the rainfall for the flood seasons is primarily affected by monsoon, and much of the annual precipitation (~50%) falls between June and September.

Study Period

Since the land use in the upper Huaihe changes with decades, to quantitatively analyze the impacts of the changes in land-use patterns in different decades on water quantity in the upper Huaihe River basin, the whole study period was split into these three subperiods, i.e., 1980s, 1990s, and 2000s.

Data Collection and Processing

The topographic, land-use/cover, soil and hydro-meteorological data required by SWAT for this study were collected and/or processed as follows: (1) the digital elevation model (DEM) data were downloaded from the Global Land One kilometer Base Elevation database (http://www.ngdc.Noaa.gov/mgg/global.html) with a spatial resolution of 30 × 30 s, and the Archydro tool was used to generate the river network and catchment boundary; (2) the soil type map (1:200,000) for the study area was derived from the Chinese Soil Database of the Institute of Soil Science; (3) the national land-use maps for three time periods (1980s, 1990s, and 2000s) were collected from the Chinese Academy of Science and used to develop the three-phase land-use maps for the study area (Fig. 2); (4) the daily time series of rainfall at 63 rainfall gauges and the daily time series of discharge at the Xixian hydrology gauge during 1980–2008 were collected; (5) the meteorological data at five weather stations in or neighboring the study area during 1980–2008 were collected from the China Meteorological Administration (CMA), including daily maximum and minimum temperature, solar radiation, humidity, wind speed and direction. The homogeneity and reliability of the hydrological data have been

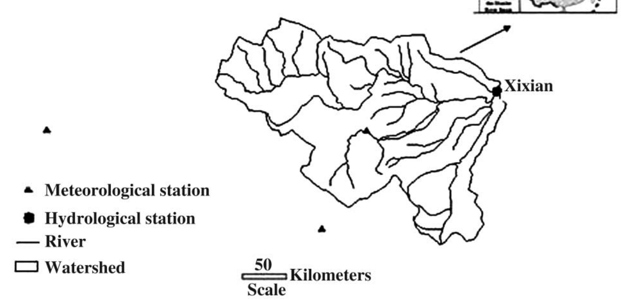

Fig. 1. Location of the Xixian catchment

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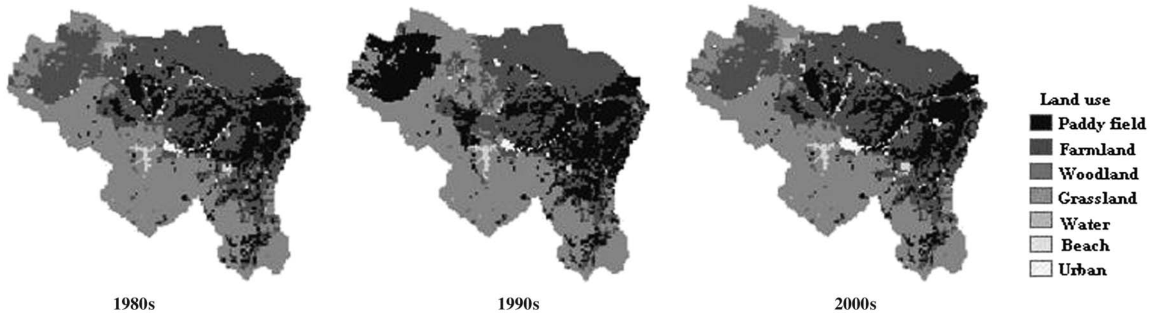

Fig. 2. Land use of the Xixian catchment in different decades

checked and firmly controlled by Huai River Water Resources Commission before their release.

Methods

Model Selection

To quantify the land-use effects on water quantity in the upper Huaihe River basin, the SWAT model was selected to simulate daily runoff under three types of land-use patterns. The physically based SWAT model is considered to be one of the most suitable models for predicting long-term impacts of land-use on water, sediment and agricultural chemical yield (nutrient loss) in large complex watersheds with varying soils, land-use and management conditions (Arnold and Fohrer 2005). In the model, a watershed is divided into multiple subwatersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land-use, management, and soil characteristics. The SWAT model provides three methods to simulate surface runoff, and the SCS Curve Number method (Arnold et al. 1998) was chosen in this study. The Muskingum method was used for channel water routing, and the potential evapotranspiration (PET) was computed by the Penman-Monteith method coupled with EPIC model (simplified plant growth model). A more detailed description of the SWAT model can be found in Arnold et al. (1998).

Investigation of the Effects of Land-Use Change on Runoff Generation Characteristics

Land-use change may lead to alterations in runoff generation characteristics. Therefore, it is necessary to investigate the effects of land-use change on runoff generation characteristics. Based on the daily simulated runoff from different HRUs during 1980–2008, the runoff coefficients and runoff modules of each subbasin were computed and their spatial distributions were illustrated by using the ArcGIS technology. On the basis of the three-phase land use maps, spatial distributions of runoff coefficients and runoff modules, the effects of land-use change on the spatio-temporal change patterns runoff coefficients and runoff modules were investigated at the subbasin scale. The rainfall-runoff relationships for different types of land use and their sensitivity to rainfall were compared and analyzed, and impacts of three-phase land-use patterns on rainfall-runoff relationship were explored at the catchment scale.

Results and Discussion

Results of Model Calibration and Validation

After the necessary maps (land use, soil, and DEM) and database files (e.g., climate, soil properties) were prepared, the SWAT model was calibrated and validated by the use of observed rainfall and discharge data. The calibration periods for three phases (1980s, 1990s, and 2000s) were 1980–1986, 1990–1996 and 2000–2005, respectively, and their validation periods were 1987–1989, 1997–1999 and 2006–2008, respectively. Based on the parameter sensitivity analysis by Latin Hypercube One-factor-At-a-Time (LH-OAT) method and previous studies (Wu and Johnston 2008; Li et al. 2009), eight SWAT parameters, the most sensitive to the runoff simulation, were determined for model calibration (Table 1), including two evapotranspiration related parameters (EPCO, ESCO), three surface-flow–related parameters (CN_2, SOL_AWC and OV_N), and three base-flow-related parameters (GW_REVAP, GW_ALPHA and GWQMN). The parameters were optimized based on Nash-Sutcliffe efficiency (Ens) and the relative error of annual runoff depth (BIAS). Nash-Sutcliffe efficiency and relative error can be computed by the following formulas:

$$\mathrm{Ens} = 1 - \frac{\sum_{i=1}^{n} (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2}{\sum_{i=1}^{n} (Q_{obs} - \bar{Q}_{\mathrm{obs}})^2} \tag{1}$$

Table 1. Calibrated Parameter Values of the SWAT Model on the Xixian Catchment in Different Decades

Parameter	Physical meaning	Periods 1980–1986	1990–1996	2000–2006
CN_2	Moisture condition II curve number	78	76	81
OV_N	Manning's n value for overland flow	0.04	0.04	0.03
SURLAG	Surface runoff lag coefficient (day)	1	1	1
ESCO	Soil evaporation compensation coefficient	0.65	0.70	0.63
SOL_AWC	Available water capacity	0.021	0.022	0.022
ALPHA_BF	Base-flow recession constant	0.08	0.08	0.07
GWQMN	Threshold water level in shallow aquifer for base flow (mm)	1,000	1,000	1,000
GW_DELAY	Delay time for aquifer recharge (day)	3	4	3

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Table 2. Simulation Performance of the SWAT Model on the Xixian Catchment during 1980–2008

Decade	Application	Year	R_{obs} (mm)	R_{sim} (mm)	BIAS (%)	Ens
1980s	Calibration	1980	484.5	525.3	8.42	0.711
		1981	409.0	385.2	5.82	0.723
		1982	653.0	694.1	6.31	0.775
		1983	450.2	415.8	−9.6	0.750
		1984	436.3	415.6	−4.64	0.784
		1985	290.7	300.5	3.35	0.766
		1986	155.5	175.2	12.3	0.676
	Validation	1987	714.3	678.9	−4.94	0.795
		1988	390.2	410.4	4.92	0.725
		1989	457.1	443.5	−7.02	0.770
		Average	444.1	444.5	1.49	0.748
1990s	Calibration	1990	300.5	267.9	10.98	0.701
		1991	612.3	569.8	6.95	0.711
		1992	150.4	135.2	10.12	0.695
		1993	228.0	252.4	−9.66	0.73
		1994	181.8	174.3	4.14	0.744
		1995	215.7	214.9	0.36	0.776
		1996	523.2	545.6	−4.29	0.774
	Validation	1997	229.6	232.5	−1.28	0.783
		1998	626.2	601.6	3.92	0.711
		1999	81.6	90.2	−10.55	0.677
		Average	314.9	308.4	1.07	0.730
2000s	Calibration	2000	580.8	600.1	−3.32	0.773
		2001	106.3	98.7	7.13	0.724
		2002	349.7	365.9	−4.63	0.755
		2003	621.1	601.3	3.19	0.743
		2004	283.4	301.7	−6.45	0.714
		2005	610.8	672.5	−10.11	0.772
		2006	197.3	225.3	−14.22	0.631
	Validation	2007	532.4	469.2	8.86	0.701
		2008	455.0	501.1	−9.12	0.715
		Average	415.2	426.2	−3.19	0.725

Note: Ens = Nash-Sutcliffe efficiency.

$$\text{BIAS} = \frac{R_{\text{sim}} - R_{\text{obs}}}{R_{\text{obs}}} \times 100\% \tag{2}$$

where Q_{obs} is the observed stream flow (m^3/s) on day i, Q_{sim} is the simulated stream flow (m^3/s) on day i, $\bar{Q}_{obs}$ is the mean of the observed values (m^3/s), R_{obs} is the observed annual runoff depth (mm), R_{sim} is the simulated annual runoff depth (mm) and n is the number of data.

The simulation performance of model calibration and validation for the three phases are presented in Table 2. From Table 2 it is apparent that the SWAT model can be applied to the study area with satisfactory accuracy. The Ens values for both calibration and validation periods were more than 0.70, and the BIAS values for both calibration and validation periods were generally less than 10% except for the years of 1986, 1992, 2006, and 1999 with small annual rainfall.

Effects of Land-Use Change on the Runoff Coefficients and Runoff Modules at Subbasin Scale

Since too many years of simulated results were achieved, only three typical years (1984, 1996, 2003) of results with similar annual precipitation for three decades were selected to present their subbasin-based spatial distributions of runoff coefficient and runoff modules (Figs. 3 and 4). From Figs. 3 and 4, it can be seen that the runoff coefficient and the runoff module in the southern area are generally larger than those in the northern area. This is primarily due to uneven spatial distribution of precipitation with higher precipitation occurring in the southern area and lower precipitation in the northern subarea.

To assess the effects of land use on the runoff coefficients and runoff modules, two subbasins numbered 2# and 14#, respectively, in which the land use changed in different decades, were selected. By use of three typical years (i.e., 1984, 1996, 2003) of simulated results, the corresponding runoff coefficients and the runoff modules were calculated and presented in Table 3. The dominant land use of 2# subbasin was woodland in 1984, while in 1996 and in 2003 the dominant land use changed to farmland and paddy field, respectively, (Table 3). Its runoff coefficient (module) changed to 0.41 (4.71) in 1996 and 0.31 (4.01) in 2003, respectively, from 0.27 (3.14) in 1984. The dominant land-use of 14# subbasin was paddy field in 1984 which changed to farmland in 1996 and urban in 2003, respectively. Its runoff coefficient (module) increased to 0.58 (6.34) in 1996 and 0.72 (7.17) in 2003, respectively, from 0.45 (5.11) in 1984. The above analysis indicated that under the same precipitation, basin slope and soil texture conditions the

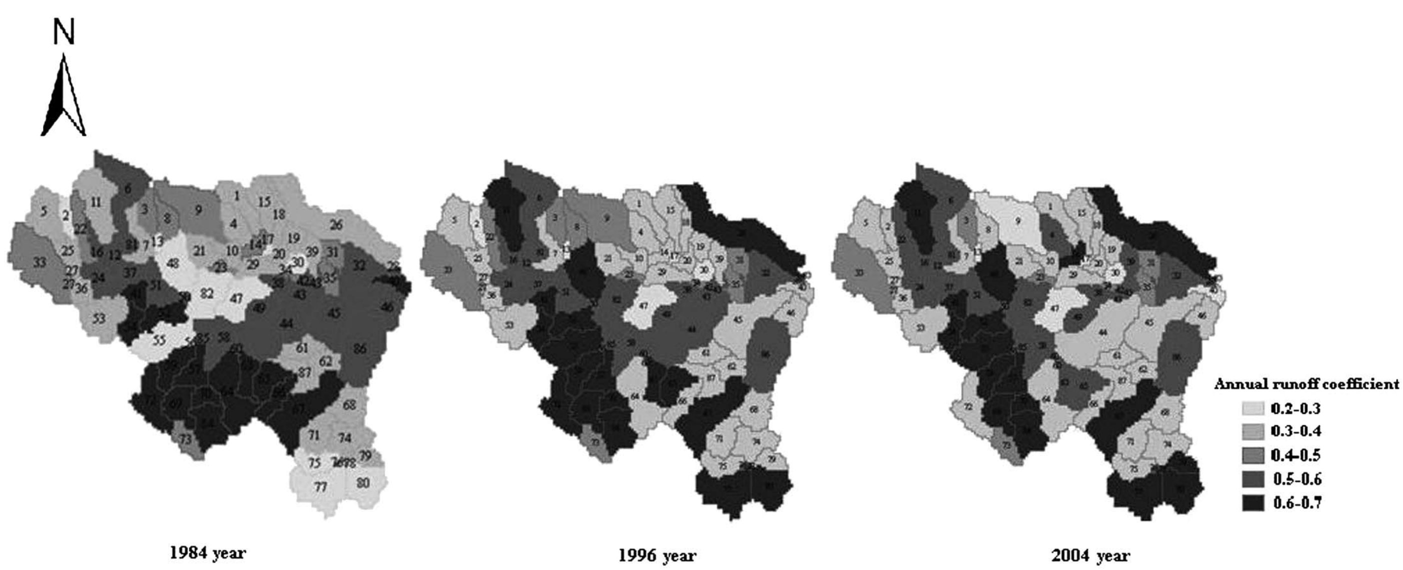

Fig. 3. Spatial distribution of the annual runoff coefficient for 1984, 1996, and 2003

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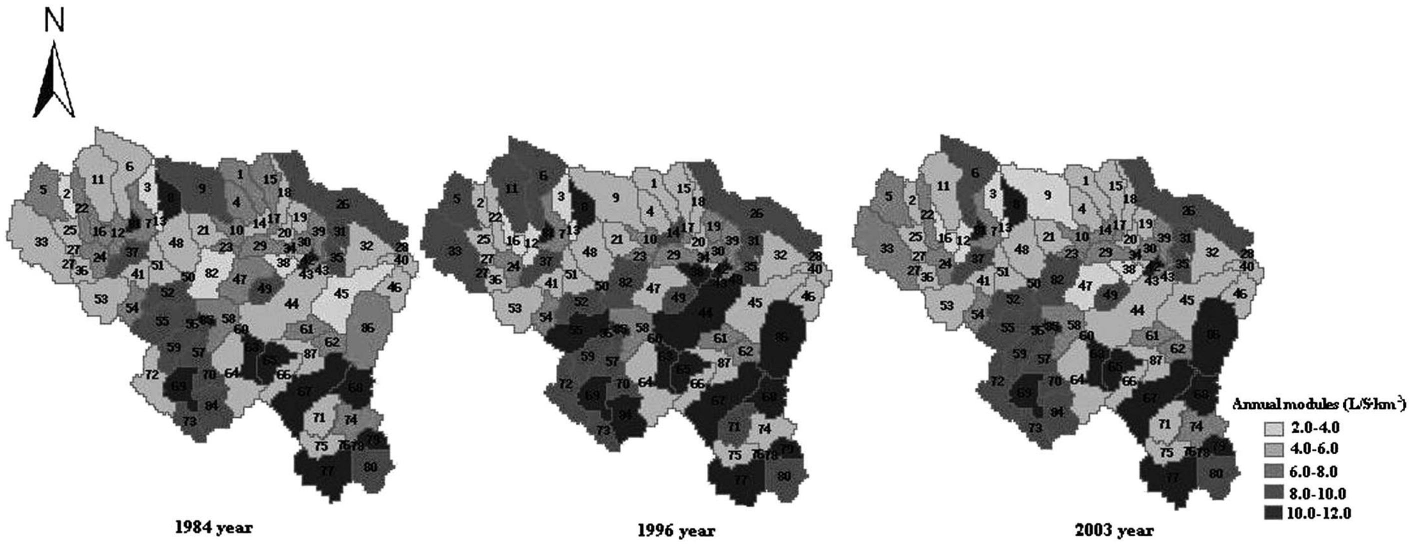

Fig. 4. Spatial distribution of the annual runoff modules for 1984, 1996, and 2003

Table 3. Change in Land Use, Runoff Coefficients, and Runoff Modules Change in Different Subbasins

	Dominant land use			Runoff coefficient			Runoff modules ($L/S \cdot km^2$)		
Number of Subbasin	1980s	1990s	2000s	1984	1996	2003	1984	1996	2003
2#	Woodland	Farmland	Paddy field	0.27	0.41	0.31	3.14	4.71	4.01
14#	Paddy field	Farmland	Urban	0.45	0.58	0.72	5.11	6.34	7.17

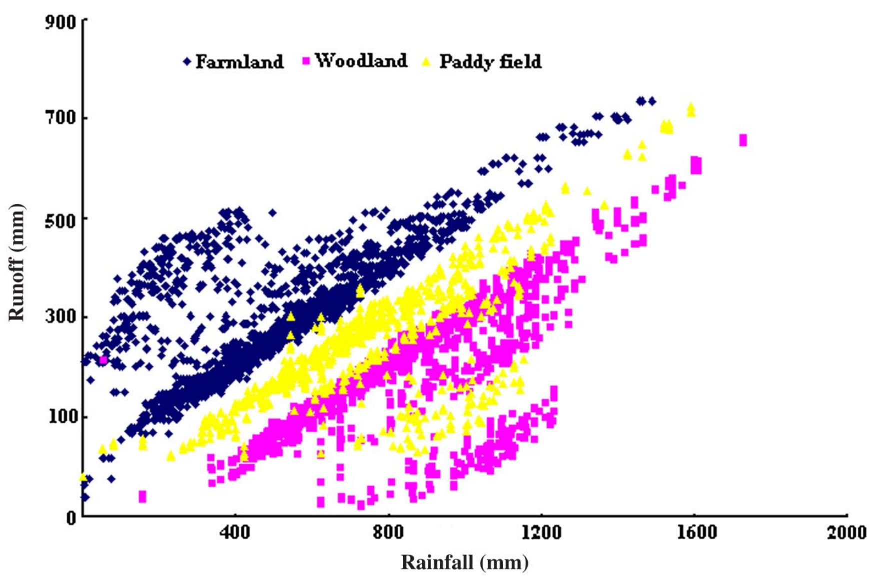

Fig. 5. The rainfall-runoff relationship of farmland, woodland, and paddy field

Table 4. Sensitivity of Rainfall-Runoff Relationship to Rainfall for Different Types of Land Use

	Runoff								
	R_1 (mm)	R_2 (mm)		R_1 (mm)	R_2 (mm)		R_1 (mm)	R_2 (mm)	
Land use	$P_1 = 1{,}500$ (mm)	$P_2 = 1{,}550$ (mm)	S	$P_1 = 1{,}000$ (mm)	$P_2 = 1{,}050$ (mm)	S	$P_1 = 600$ (mm)	$P_2 = 650$ (mm)	S
Farmland	875.3	969.8	3.27	610.2	682.5	2.36	204.1	241.5	2.20
Woodland	710.2	762.0	2.21	500.3	546.4	1.84	150.6	168.2	1.40
Paddy field	785.4	853.7	2.64	550.8	609.7	2.14	168.4	194.0	1.82

Note: R_i = the runoff responding to the same rainfall for different types of land use; S = the sensitivity of rainfall-runoff relationship to rainfall for different types of land use.

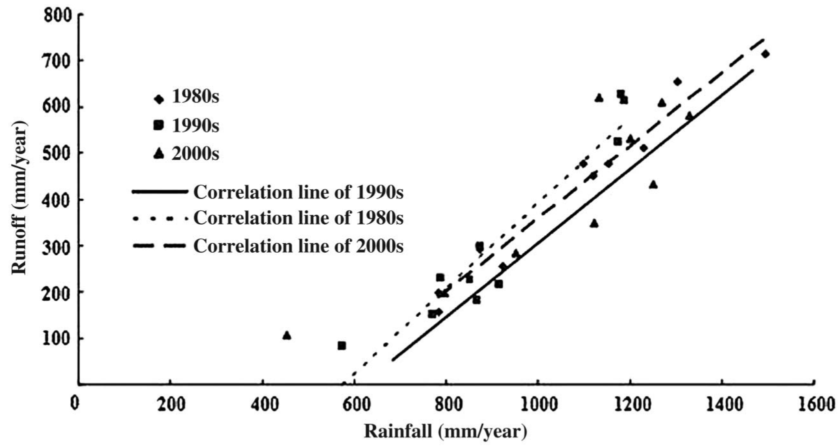

Fig. 6. Correlation between annual rainfall and annual runoff for different land-use patterns for the 1980s, 1990s, and 2000s

advantages of different types of land use for runoff generation descended by urban, farmland, paddy field and woodland.

Effects of Land-Use Change on Rainfall-Runoff Relationship at HRU Scale

To quantify the effects of land-use change on rainfall-runoff relationship, the scatter diagram between annual rainfall and annual runoff for woodland, paddy field and farmland was plotted (Fig. 5), respectively, by use of the simulated results of 1980–2008 from the HRUs with these three types of land use. Fig. 5 reveals strong positive correlation between annual rainfall and annual runoff for the three types of land use, with plotted points more concentrated along a line of increasing annual rainfall. Compared with farmland and woodland, the positive correlation between annual rainfall and annual runoff for paddy field is slightly stronger. Fig. 5 also revealed that the plot cluster of points for woodland generally took lowest position, while the plot cluster of points for farmland generally took highest position. Additionally, the plot cluster of points for paddy field is generally situated between those for farmland and woodland. With the same rainfall, farmland generally produced the most runoff, woodland generally produced the least runoff, and the runoff generated from paddy field typically fell between those generated by woodland and farmland. This implied that land-use change could result in alteration in the rainfall-runoff relationship.

Sensitivity of Rainfall-Runoff Relationship to Rainfall for Different Land-Use at HRU Scale

The sensitivity of rainfall-runoff relationship to rainfall for different land use, on the basis of the computed annual rainfall and annual runoff from a typical HRU located in 44# subbasin, in which land use changed among farmland, woodland and paddy field, was calculated by the following formula:

$$\mathrm{S} = [(R_2 - R_1)/R_1]/[(P_2 - P_1)/P_1] \tag{3}$$

Where P_1 and P_2 are rainfall with difference of 50 mm, and R_1, R_2 is corresponding runoff to rainfall P_1 and P_2, respectively.

Table 4 shows that the sensitivity of farmland responding to the same rainfall difference of 50 mm at different rainfall levels is highest while that of woodland is lowest. This indicated that the rainfall-runoff relationship of farmland is the most sensitive to rainfall change while that of woodland is the least. The sensitivity of rainfall-runoff relationship to rainfall for paddy field is higher than that of woodland and lower than that of farmland. Table 4 also demonstrates that the sensitivity of the rainfall-runoff relationship to rainfall for different types of land use varied with rainfall, the sensitivity increased with increasing rainfall. The sensitivity of rainfall-runoff relationship to rainfall may also vary with the location and soil type of HRU.

Table 5. Land-Use Pattern Changes of the Xixian Catchment in Different Decades

	Percentage change		
Land-use classification	1980s	1990s	2000s
Water	0.9	0.78	1.32
Urban	0.63	0.51	0.88
Woodland	38.55	40.69	38.06
Paddy field	17.02	27.23	17.15
Farmland	41.85	30.38	41.81
Grassland	0.57	0.06	0.54

Effects of Land-Use Change on Rainfall-Runoff Relationship at Catchment Scale

To evaluate the effects of land-use change on rainfall-runoff relationship at catchment scale, the scatter diagram between annual rainfall and annual runoff for different land-use patterns (Table 5) was plotted (Fig. 6) by use of the computed annual rainfall and annual runoff from 1980 to 2008 from the whole study area. With the same annual rainfall, the annual runoff in the 1980s was generally higher than those in the 1990s and 2000s (Fig. 6). The percentage of farmland decreased to 30.38% in the 1990s from 41.85% in the 1980s, while the percentage of woodland increased to 40.69% in the 1990s from 38.55% in the 1980s (Table 5). As a result, the land-use pattern of the 1990s has less advantage for runoff generation than that of the 1980s. In the 2000s, farmland dominated the land use in the basin again with a percentage of 41.81%; therefore, the land-use pattern of the 2000s has bigger advantage for runoff generation in comparison with that of the 1990s. The above analysis indicated that the change in land-use pattern at catchment scale could also alter its rainfall-runoff relationship.

Conclusions

This paper investigated the effects of land-use change on the runoff generation characteristics in the upper Huaihe River basin. The results can be drawn as follows:

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The SWAT model can be used to assess the effects of land-use change on runoff generation characteristics in the upper Huaihe River basin with satisfactory accuracy; under the same precipitation, basin slope and soil texture conditions, the advantages of different types of land use for runoff generation descended by urban, farmland, paddy field and woodland.

Land-use change can result in alterations in the rainfall-runoff relationship. With the same rainfall, farmland generally produced the most runoff, woodland generally produced the least runoff, and the runoff generated from paddy field generally fell between those generated, respectively, from woodland and farmland. The sensitivity of rainfall-runoff relationship to rainfall varied with the types of land use and rainfall, i.e., the sensitivity descended by farmland, paddy field, woodland and the sensitivity increased when rainfall increased. The sensitivity of rainfall-runoff relationship to rainfall may also vary with the location and soil type of the HRU. The land-use change at catchment scale can also alter its rainfall-runoff relationship.

The outputs could provide important references for soil and water conservation and river health protection in the upper stream reaches of the Huaihe River.

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