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Impacts of Land-use and Land-cover Changes on River Runoff in Yellow River Basin for Period of 1956–2012

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Abstract: River runoff is affected by many factors, including long-term effects such as climate change that alter rainfall-runoff relationships, and short-term effects related to human intervention (e.g., dam construction, land-use and land-cover change (LUCC)). Discharge from the Yellow River system has been modified in numerous ways over the past century, not only as a result of increased demands for water from agriculture and industry, but also due to hydrological disturbance from LUCC, climate change and the construction of dams. The combined effect of these disturbances may have led to water shortages. Considering that there has been little change in long-term precipitation, dramatic decreases in water discharge may be attributed mainly to human activities, such as water usage, water transportation and dam construction. LUCC may also affect water availability, but the relative contribution of LUCC to changing discharge is unclear. In this study, the impact of LUCC on natural discharge (not including anthropogenic usage) is quantified using an attribution approach based on satellite land cover and discharge data. A retention parameter is used to relate LUCC to changes in discharge. We find that LUCC is the primary factor, and more dominant than climate change, in driving the reduction in discharge during 1956–2012, especially from the mid-1980s to the end-1990s. The ratio of each land class to total basin area changed significantly over the study period. Forestland and cropland increased by about 0.58% and 1.41%, respectively, and unused land decreased by 1.16%. Together, these variations resulted in changes in the retention parameter, and runoff generation showed a significant decrease after the mid-1980s. Our findings highlight the importance of LUCC to runoff generation at the basin scale, and improve our understanding of the influence of LUCC on basin-scale hydrology.

Keywords: land-use and land-cover change; natural discharge; retention parameter; runoff generation; Yellow River Basin

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1 Introduction

Global river runoff has changed significantly during the 20th century (Labat *et al.*, 2004). River runoff is affected by multiple factors such as climate change, land-use and land-cover change (LUCC), construction of large reservoirs and dams, and water diversion for irrigation and industry (Milly *et al.*, 2005; de Wit and Stankiewicz, 2006; Gedney *et al.*, 2006; Oki and Kanae, 2006). Considering that the dynamic properties of the hydrological cycle depend on interrelationships between climate, soil and vegetation dynamics (Piao *et al.*, 2007), it is challenging to differentiate between natural and anthropogenic impacts on runoff change. Each hydrological process (precipitation to runoff generation, runoff convergence and channel runoff) can be affected

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by different factors; e.g., changes in precipitation relate to water supply from the atmosphere and occur before runoff, LUCC affects runoff generation on the land surface, and other anthropogenic activities (e.g., dam construction, and water diversion for irrigation, industry, domestic use, *etc.*) affect runoff transportation in river channels. In the long term, climate change directly modifies rainfall-runoff relationships, and in the short term, anthropogenic factors may have a strong effect on runoff (Vorosmarty *et al.*, 2000).

Many studies have assessed the contribution of various factors to changing river runoff. Piao *et al.* (2007) showed that the significant increase in global runoff in the 20th century was mainly a consequence of precipitation and land-use change. Land-use change (mainly widespread deforestation) has increased global runoff by 0.08 mm per year and accounts for ~50% of the change in global runoff over the last century. There has been a high degree of land use change in the Amazon River Basin, and its contribution to changing runoff is much larger than that of climate change (Costa *et al.*, 2003; Coe *et al.*, 2009). In the Mississippi River basin, increasing discharge since the 1940s has been ascribed to increasing precipitation and land use change associated with increased soybean cultivation (IPCC, 2001; Raymond and Cole, 2003; Zhang and Schilling, 2006; Raymond *et al.*, 2008). These studies all show that LUCC is playing an increasingly important role in large-scale changes in river runoff.

There have been many methods to be used to study the impact of land use change on river runoff. The first method from the literature (Burnash *et al.*, 1973; Beven and Kirkby, 1979; Beven *et al.*, 1997; Arnold *et al.*, 1998; Karvonen *et al.*, 1999) relies on a hydrological model such as Sacramento model (SAC), Soil and Water Assessment Tool (SWAT) and Topmodel . It offers the advantage of considering many of hydrological processes like runoff generation, runoff convergence and evapotranspiration. However, it may be difficult to accurately parameterize each of hydrological processes, and often has some uncertainties. The second method (USDA, SCS, 1985; Conway, 2001; Li *et al.*, 2010; Tessema *et al.*, 2014) for evaluating LUCC effect on runoff is based on analysis of statistics changes of hydrological characteristic variables such as runoff coefficient, curve number, retention parameter and evapotranspiration. This method is easy to operate, given the long time series of each variable. But it is not enough to explain the mechanism of hydrological change. In addition, an attribution method was recently used in hydrological studies (Kauppi *et al.*, 2006; Raupach *et al.*, 2007; Wang *et al.*, 2016). For example, Wang *et al.* (2016) used the method to estimate the anthropogenic contribution to river sediment change. This method is suitable for quantifying the contribution of each driver factor, but it does not involved complicated hydrological processes.

The Yellow River is the second largest river in China with a drainage area of 752 443 km^2. The basin acts as an important source of water in the northern and northwestern China; however, these regions are also areas with limited water resources. Since the mid-1980s, discharge in the lower Yellow River has decreased significantly. Mean annual discharge in 1956–1980 was about 40.3 km^3, but this decreased to 15.1 km^3 in 1990–2012. Previous studies suggest that the dramatic decrease in discharge from the Yellow River resulted from slightly reduced precipitation and increasing water use for irrigation and industrial purposes (Liu and Zhang, 2004; Mu *et al.*, 2007; Wang *et al.*, 2013; Zuo *et al.*, 2013), while the relative contribution of LUCC across the entire basin is still unclear, although several studies discussed this point only based on some sub-catchments (Huang *et al.*, 1999; Fu *et al.*, 2002; Hao *et al.*, 2004; Wang, 2006; Song *et al.*, 2008; Li *et al.*, 2010).

In this paper, we estimate the effect of large-scale LUCC on natural discharge in the Yellow River, with the aim of relating LUCC to discharge using a retention parameter (the second method), and to separately quantify the contributions of the driving factors by applying an attribution method (the third method).

2 Materials and Methods

2.1 Study area and data sources

The Yellow River is the sixth-longest river in the world and the second-longest in China. It originates in the Bayan Har Mountains in Qinghai Province, the western China, and flows west into the eastern Bohai Sea. Figure 1 shows the entire Yellow River Basin, including 67 sub-catchments. The basin has an east-west extent of ~1900 km and a north-south extent of ~1100 km. The total basin length is 5464 km, and the total basin area is 752 443 km^2 (Fig. 1). The Yellow River Basin lies between latitudes 32.16°and 41.83°N, and longitude

95.88° to 119.08°E. Elevation in the basin range from 0 to 4800 m, and average annual precipitation varies from 250 to 550 mm.

Natural discharge data were provided by the Yellow River Conservancy Commission (YRCC) of the Chinese Ministry of Water Resources. The data for 1956–2000 were obtained from the monthly natural discharge dataset with 53 stations (Fig. 1), and the data for 2001–2012 were obtained from the released data in the Yellow River Water Resources Bulletin with annual discharge data of 6 stations (Lanzhou, Tangnaihai, Longmen, Sanmenxia, Huayuankou and Lijin stations). Natural discharge data were obtained by removing anthropogenic (irrigation, industrial usage, domestic usage, *etc.*) and engineering-related water withdrawal from observed discharge data. This allowed the remaining changes to be attributed to climate change and LUCC. Natural discharge data have been widely applied in many related studies on the Yellow River (Wang, 2005; Li *et al.*, 2012).

Precipitation data were obtained from daily and annual surface climate datasets for 1951–2013, provided by the China Meteorological Administration (CMA). Data were selected from 93 stations (Fig. 1), including national reference climate stations and basic meteorological stations. The National Meteorological Information Center (NMIC) of the CMA performed quality control of the precipitation data, using methods such as cross-checking synoptic and climatological characteristics (e.g., annual and seasonal spatial distributions, annual and seasonal distribution trends, differences in interannual mean temperature, and correlations). Some possible erroneous records, such as extreme singular values, were removed from the dataset.

Land data were obtained from the Chinese land-use database developed by the Chinese Academy of Sciences (CAS) (Liu *et al.*, 2002; 2005). Raw data were derived from remotely sensed satellite data. The satellite data were provided by U.S. Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) images with the spatial resolutions of 30 m × 30 m and 78 m × 78 m (Vogelmann *et al.*, 2001). These images were then aggregated by CAS into 100 m × 100 m elements. The data of TM and ETM were updated every 5 years from 1980s onwards and the data of MSS were for 1978. All data were strictly quality-controlled by the CAS, who cross-checked images and land-cover classifications against field surveys (Liu *et al.*, 2002). A hierarchical classification system of 25 land-use classes was applied to the data, and the CAS team then aggregated these further into six classes of land use: cropland, forestland, grassland, water body, urban land (residential and industrial land) and unused land.

2.2 Methods

2.2.1 Relative contributions of drivers of discharge change

An attribution method (proportion of the relative rate of change) can separately quantify the contributions of multiple drivers of discharge change (Kauppi *et al.*,

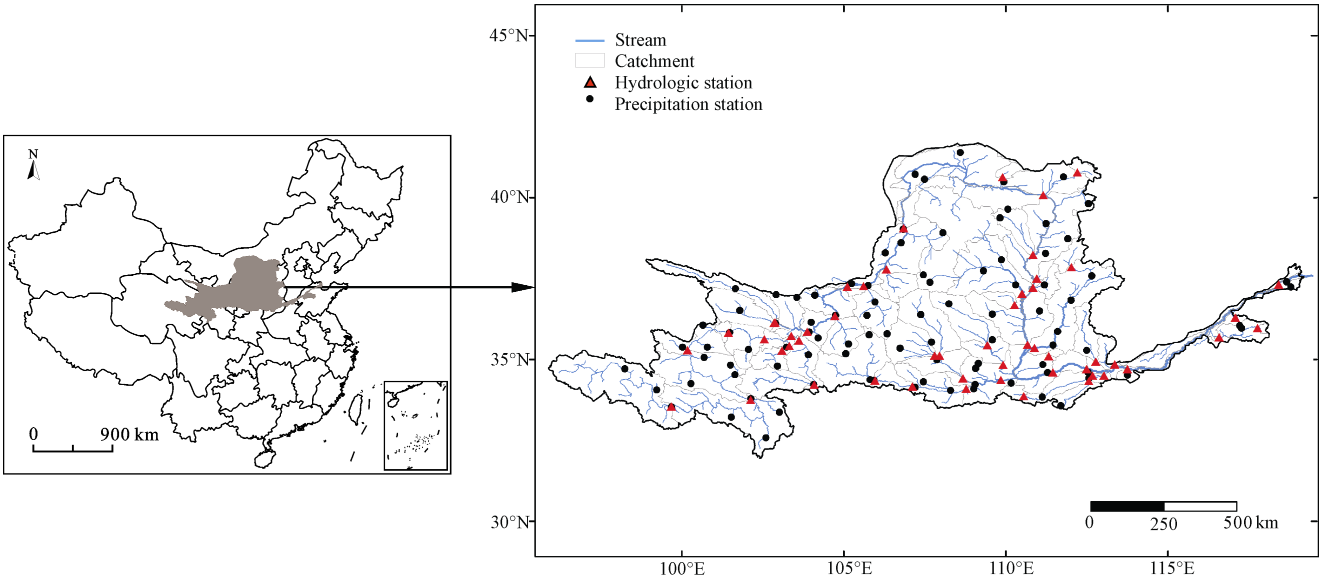

Fig. 1 Location of study area, showing hydrologic and meteorological stations

2006; Raupach *et al.*, 2007; Wang *et al.*, 2016), and it is appropriate for attributing discharge change to various driver factors. This method is applied as follows. Firstly, discharge (Q) is decomposed into two variables: precipitation (P) and the ratio of discharge to precipitation (Q/P) (analogous to the Kaya Identity principle), as follows:

$$Q = P \times \frac{Q}{P} \tag{1}$$

where P is regional average precipitation and Q/P is a runoff coefficient that reflects the runoff-generation capacity (see Table A1 for explanation of terms). Secondly, three time series of Q, P and Q/P are established. Thirdly, the relative rate of change of each variable over different periods is calculated according to

$$r(X) = \frac{\mathrm{d}X/\mathrm{d}t}{X} \tag{2}$$

where X represents each variable, t represents time, and $r(X)$ is the relative rate of change of X. Fourthly, the contribution of each driver to the change in Q is estimated according to the proportional relative rate of change from different driving factors. Theoretically, the relative rate of change of two factors will sum to approximately the change in Q.

2.2.2 Retention parameter

We use a characteristic retention parameter (S) to relate LUCC to changes in discharge. S represents the potential maximum precipitation retention. It is not only dependent on land properties, but also reflects runoff generation from the basin. Four steps are required to calculate S for the whole basin. Firstly, S is calculated as

$$S = 25400/\mathrm{CN} - 254 \tag{3}$$

where CN is a runoff curve number for hydrologic soil-cover complexes, which reflects basin characteristics before rainfall. The equation was developed by Soil Conservation Services (SCS), U.S. Department of Agriculture (USDA) (USDA, SCS, 1985; Hobor, 1994; Grove *et al.*, 1998).

Secondly, a table is used to determine CNs for each land use and soil type (USDA, 1985). The variability in CN results from LUCC type, soil type and soil moisture conditions (ARC, Antecedent Runoff Condition). LUCC types in this study were determined from land cover data. Soil types are divided into four groups (A, B, C and D) that refer to soil texture and minimum permeability by SCS. The Yellow River Basin belongs to group B due to the dominance of silt, sandy loam and loam soils (ISS, 1986). ARC is divided into three classes: I for dry conditions, II for average conditions, and III for wet conditions. Table 1 gives the CN values for different classes in the Yellow River Basin. CN values, from low to high, refer to forestland, grassland, cropland, urban land, unused land and water body.

The third step is to calculate the area-weighted CN for the whole basin, which typically changes over time due to LUCC change. Fourthly, the S value for the whole watershed is calculated according to Equation (3). As shown in Table 1, the higher the CN, the lower the S. Furthermore, S decreases as land use changes from forestland to grassland or farmland, or from grassland to urban areas or farmland, while S increases when land use changes from grassland to forestland. Other types of land conversion can also be inferred from changes in S.

2.2.3 Relationship between LUCC and runoff generation

The analysis of statistical changes of hydrological characteristic parameters (retention parameter, runoff coefficient) is used here to evaluate the influence of LUCC on runoff generation. This method is suitable for assessing temporal evolution of each variable, and is easy to operate given the long time series of each variable, which avoided the uncertainties from parameterization of complicated hydrological processes. We examine correlations between S and Q/P. Q/P is a dimensionless factor that is used to convert rainfall amounts to runoff, which reflects the runoff-generation capacity. S reflects LUCC properties. Some common scenarios of land use change are shown in Table 2, including farmland expansion (forest or pasture to farmland), grain for green project

Table 1 CN and S values for different land classes in Yellow River Basin

Land class	CN			S		
	II	I	III	II	I	III
Forest	55	35	74	208	472	89
Grassland	64	44	81	143	323	60
Cropland	68	48	84	120	275	48
Urban land	74	55	88	89	208	35
Water body	100	100	100	0	0	0
Unused land	86	72	94	41	99	16

Notes: I, dry conditions; II, average antecedent soil moisture; III, wet conditions

Table 2 Scenarios of effects of LUCC on runoff

Scenario	Land change	S	$P_{\text{threshold}}$	$P_{\text{effective}}$	Q
Farmland expansion	Forest or pasture to farmland	↘	↘	↗	↗
Afforestation	Unused land to forest	↗	↗	↘	↘
Grain for green project	Cultivated land to forest or pastures	↗	↗	↘	↘
Desertification	Pasture to unused land	↘	↘	↗	↗
Urban construction	Grass to industrial area	↘	↘	↗	↗
Unused land development	Unused land to farmland	↗	↗	↘	↘

(farmland to forest or pastures), desertification (pasture to bare land), urban construction (grassland to building land), afforestation (bare land to forest) and so on. Each scenario reflects the effect of LUCC on S, runoff-generation and Q. Several catchments within the basin were chosen to verify the influence of LUCC on runoff generation. For each selected catchment, the relationships between S and Q/P are compared over different time periods. To examine the impact of a single land class on runoff generation, catchments are selected in which there was a significant change in one kind of land use, but little change in other classes.

3 Results

3.1 Time series of river discharge

We evaluate natural discharge changes at gauging stations in the Yellow River Basin during the period 1956–2012 (Fig. 2). Water discharge shows a significant decreasing trend over the 57-year period at three hydrological stations in the lower reaches of the river: Sanmenxia (SMX), Huayuankou (HYK) and Lijin (LJ). The most significant decrease in water discharge (mean value of −0.345 km^3 per year or −0.6% per year) (P = 0.001) is observed at LJ station near the estuary. This trend was particularly strong from the mid-1980s to the late 1990s, when it was −1.889 km^3 per year (−3.9% per year; P = 0.025). Changes in water discharge were less pronounced at Maqu (MQ) (−0.002 km^3/yr; P = 0.959), Lanzhou (LZ) (−0.074 km^3/yr; P = 0.202) and Toudaoguai (TDG) (−0.103 km^3/yr; P = 0.084) in the middle and upper reaches of the river. Average annual discharge increases gradually from the headwaters to the lower reaches, and the increases are larger between MQ and LZ, and TDG and SMX than between other stations (Fig. 2; inset at top right).

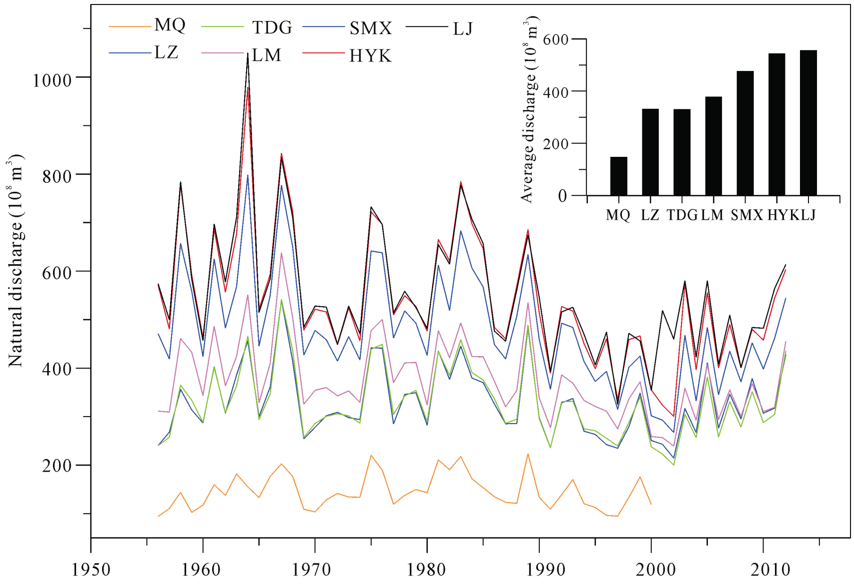

Fig. 2 Time series of annual natural discharge at gauging stations during 1956–2012. The data of Maqu (MQ) for 2001−2012 are not available. Inset: average annual discharge over 57 years at Maqu (MQ), Lanzhou (LZ), Toudaoguai (TDG), Longmen (LM), Sanmenxia (SMX), Huayuankou (HYK), Lijin (LJ) stations

We decompose discharge into two key drivers: precipitation and the ratio of discharge to precipitation based on the Kaya identity equation (Equation 1). P is the mean regional precipitation, and Q/P is the ratio of discharge to mean precipitation and reflects the runoff-generation capacity. Time series of the three variables (Q, P and Q/P) are given in Fig. 3. Both Q and Q/P show significant decreasing trends, with changes in Q of −0.459 mm/yr (P = 0.001) and Q/P of −0.001/yr (P = 0.000). This trend was particularly strong from the mid-1980s to the end-1990s, with changes in Q of −2.513 mm/yr (P= 0.025) and Q/P of −0.006/yr (P = 0.021) (Fig. 3a; 3c), while the trend in precipitation was not significant (P = 0.444) (Fig. 3b).

We calculated the relative rate of change of each variable and their contributions to changing discharge for the whole period and for specific time periods (Table 3). The study period can be divided according to the double cumulative curve relation between precipitation and discharge. There were three abrupt decreases in discharge around 1972, 1987 and 1998, and so the 57-year period can be divided into four parts: 1956–1972, 1973–1987, 1988–1998 and 1999–2012. For the periods 1956–1972, 1973–1987 and 1999–2012, there were no significant changes in the three variables. For the period 1988–1998, P did not change significantly, but Q and Q/P decreased significantly, with changes in Q of −3.875%/yr or −38.8%/10yr and changes in Q/P of −3.276%/yr or −32.8%/10yr. Thus, the contribution of decreasing Q/P to decreasing Q is about 84.5% for 1988–1998. For the whole period, the relative rate of change of Q/P is −0.528 %/yr or −30.1%/57 yr, and that of Q is about −0.622%/yr or –35.4%/57 yr. The contribution of decreased Q/P (runoff-generation capacity) (83.8%) to decreased discharge is higher than that of precipitation, which only changed by 16.2%.

3.2 Effect of LUCC on discharge

3.2.1 LUCC

Land data include six datasets measured in 1978, 1985, 1995, 2000, 2005 and 2010, which reflect LUCC for the period 1978–2010 (Fig. 4). Grassland occupies the largest proportion of basin area (annual mean 47.6% and 353 422 km^2), while cropland occupies 27.5% (annual mean 203 912 km^2), forestland 13.6% (100 756 km^2), unused land 7.5% (55 650 km^2), urban land 2.2% (16 556 km^2) and water body 1.7% (12 690 km^2). Forestland and cropland areas show similar patterns of temporal change. Forestland areas decreased by 4309 km^2 during 1978–1985, and then increased by 6864 km^2 during 1985–2010. Cropland areas decreased by 7723 km^2 during 1978–1985, increased by 10 510 km^2 during 1985–2000, and then decreased by 4161 km^2 during 2000–2010. Grassland and unused land show opposite temporal changes. Grassland areas increased by 7317 km^2 from 1978 to 1995 and then decreased by 11 145 km^2 during 1995–2010. Unused land areas increased by 8194 km^2 from 1978 to 1985, and then decreased by 7814 km^2 from 1985 to 2010. Urban land areas increased gradually by 3369 km^2 from 1978 to 2010. Water body areas decreased by 1092 km^2 from 1978 to 2010.

Table 3 Relative change rates of annual discharge and driving factors in Yellow River Basin

Factor	1956–1972	1973–1987	1988–1998	1999–2012	1956–2012
Q (%/yr)	−0.631	0.149	−3.875*	1.526	−0.622*
P (%/yr)	−0.598	−0.983	−0.603	1.423	−0.102
Q/P (%/yr)	−0.075	1.045	−3.276*	0.043	−0.528*

Note: first column indicates three variables of discharge (Q), precipitation (P) and the ratio of discharge to precipitation (Q/P). * means $P < 0.05$

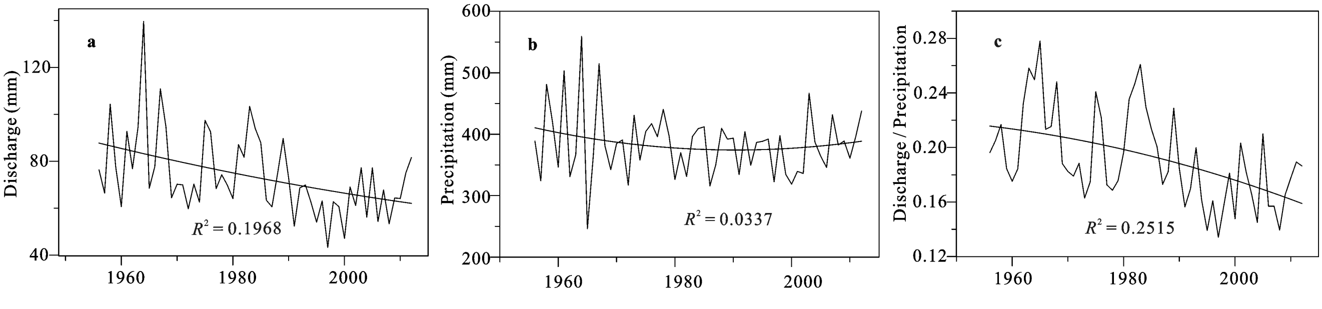

Fig. 3 Time series of annual discharge and precipitation during 1956–2012: a) natural discharge (Q); b) precipitation (P); c) the ratio of natural discharge to precipitation. The black smooth lines show a polynomial fit

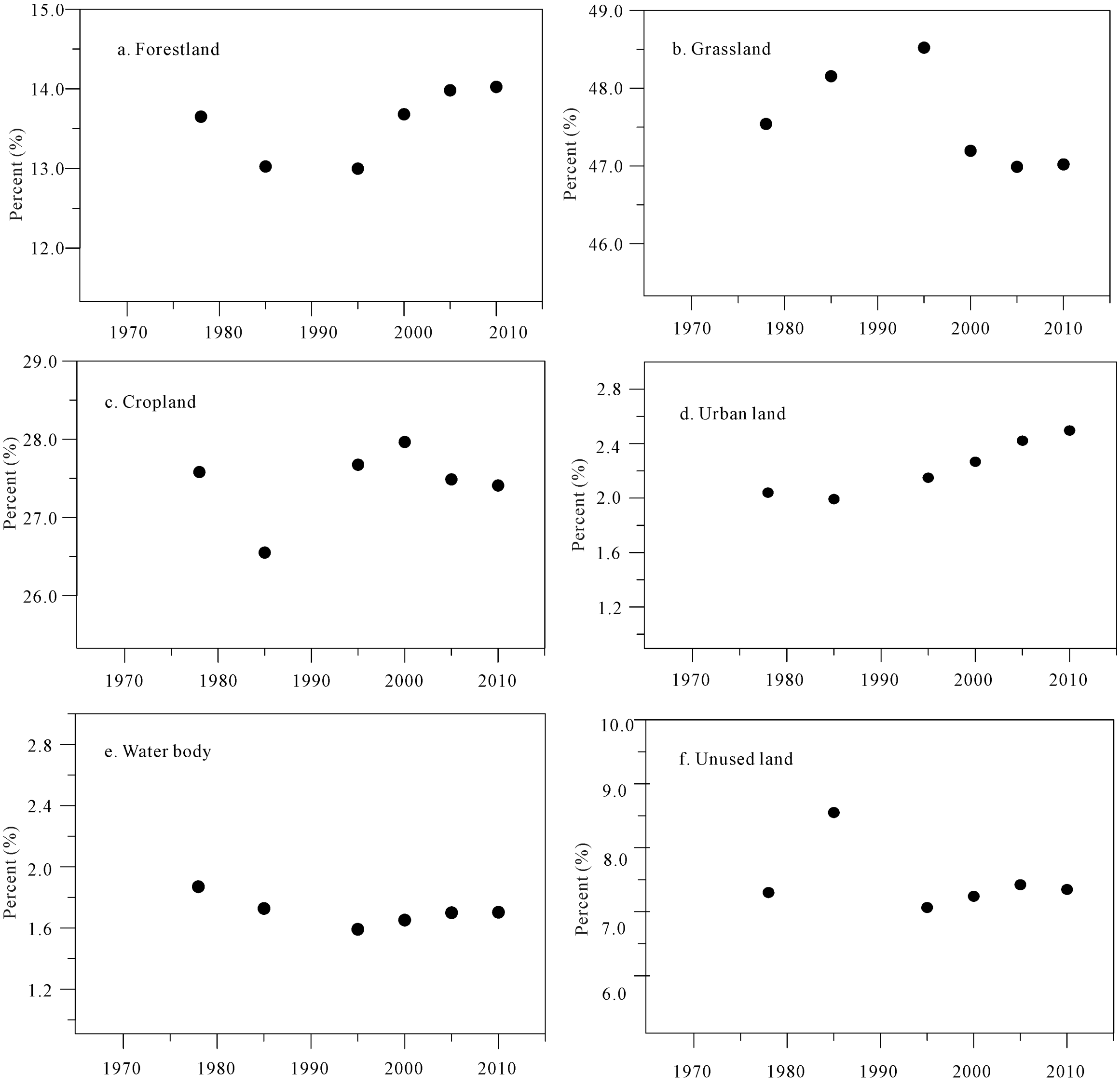

Fig. 4 Land use and land cover change in Yellow River basin

3.2.2 LUCC effect on discharge

We used a retention parameter *S*, to relate LUCC to changes in discharge. *S* is the potential maximum precipitation retention at the land surface controlled by LUCC and can be calculated using land use data. Table 1 gives *S* values for different land classes. Forestry has the highest *S* value, followed by grassland, cropland, urban land, unused land and water. The *S* value of the whole basin represents the average for the total landscape. From 1978 to 2010, *S* values in the Yellow River Basin are about 127–130 for average soil condition (II), 280–288 for dry soil condition (I), and 53–55 for wet soil condition (III) (Fig. 5). *S* firstly experiences a small decrease (from 1978 to 1985), and then a large increase (from 1985 to 1995) and another small decrease (from 1995 to 2010). The change in *S* is in response to land cover changes during the corresponding period. From 1978 to 1985, a small decrease in *S* results from decreases in forestland and cropland, and increases in grassland and unused land. From 1985 to 1995, a large increase in *S* results from increases in cropland and grassland, and a decrease in unused land. From 1995 to 2010, a small decrease in *S* results from increases in urban and unused lands, and a decrease in grassland.

The changes in *S* lead to changes in runoff generation, and dictate how much precipitation can be transferred to runoff. According to the SCS runoff model (USDA, 1985; Hobor, 1994; Grove *et al.*, 1998), runoff only occurs when $P > \lambda S$ (λ takes a value between 0 and 1), and runoff is zero when $P < \lambda S$. Here, precipitation

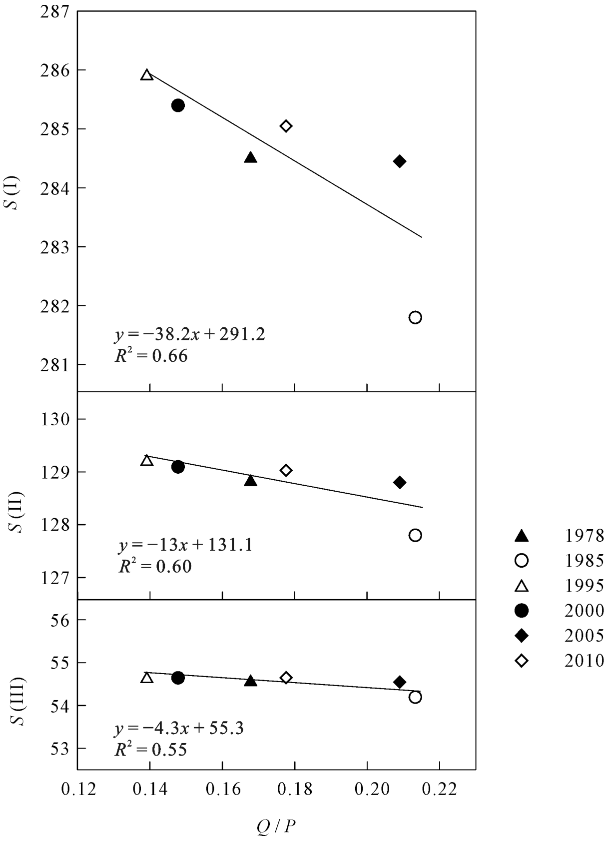

Fig. 5 Relationship between *S* and *Q/P* for the Yellow River basin. Classes I, II and III indicate dry, average and wet soil conditions, respectively

transferred to runoff is referred to as effective precipitation ($P_{\text{effective}}$), and minimum effective precipitation is a threshold for runoff ($P_{\text{threshold}} = \lambda S$) (Table A1). Effective precipitation should thus be equal to the difference between actual precipitation and threshold precipitation ($P_{\text{effective}} = P - P_{\text{threshold}}$). $P_{\text{threshold}}$ and $P_{\text{effective}}$ both change in response to *S*, and runoff generation is also influenced by these changes. Table 2 shows some common scenarios for the effect of LUCC on *S*, *P* and *Q*. For example, desertification, farmland expansion (from forestry), or urban construction (from grassland) result in reduced values of *S* and $P_{\text{threshold}}$, and increased values of $P_{\text{effective}}$ and discharge. In contrast, afforestation, returning farmland to grassland, or increases in unused land result in increased *S* and $P_{\text{threshold}}$, and decreased $P_{\text{effective}}$ and discharge.

There is also a clear negative relationship between *S* and runoff generation. Runoff production is represented by the runoff coefficient (*Q/P*). The *Q/P* values for 1978, 1985, 1995, 2000, 2005 and 2010 are 0.168, 0.213, 0.139, 0.148, 0.209 and 0.178, respectively (Fig. 5). Figure 5 shows a significant negative relationship between *S* and *Q/P* (P = 0.068, significant at 90% confidence level). Thus, it is evident that LUCC has significantly changed the runoff-generation capacity of the whole basin over various periods.

4 Discussion

Specific catchments were selected to verify the influence of LUCC on runoff at smaller scales. Catchments were chosen based on two criteria: 1) a significant change in area must have occurred for only one kind of land use over a defined period, and little change for other classes, and 2) the catchment must be a tributary of the Yellow River. The latter criteria reflects the fact that small tributaries can better reflect the impact of a certain type of land use on runoff, while the mainstream is often influenced by complex land-use types in many small catchments.

Based on these criteria, we selected Longwu River Basin (upstream) and Kuye River Basin (midstream) for analysis. Table 4 lists the land use changes, retention parameters, precipitation and discharge for the two catchments. Considering that actual precipitation typically changes over time, we use $P_{\text{effective}}/P_{\text{actual}}$ to represent $P_{\text{effective}}$ in order to analyse the change in effective precipitation, and use Q/P_{actual} to analyse the change in discharge under a constant precipitation regime. The value of λ is determined using the marginal optimal method. In the Longwu River catchment during the period 1978–1985, the main change in land use was the conversion of grassland to unused land (3% of the whole catchment). This change resulted in a decrease in *S* accompanied by reductions in plant interception, soil infiltration and evapotranspiration of water, leading to a decrease in $P_{\text{threshold}}$, increase in $P_{\text{effective}}$ and improvement in runoff generation. In the Kuye River catchment during the period 1985–1995, the main land use change was the transformation of unused lands to grasslands (5.7% of the total catchment area). The replacement of unused land with grassland would cause increases in plant interception, soil infiltration and evapotranspiration of water, and increases in *S*, decreases in $P_{\text{effective}}$ and corresponding decreases in discharge. Note that values of $P_{\text{effective}}/P_{\text{actual}}$ and Q/P_{actual} from Longwu River are higher than those from Kuye River due to the steeper (catchment and river) slopes of the former.

Table 4 Land use change in Longwu and Kuye river catchments

Catchment	Gauging station	Period	Main land change		*S* (II)	$P_{\text{effective}}/P_{\text{actual}}$	Q/P_{actual}	River slope
Longwu River	Tongren	1978–1985	Grassland degradation	Grass: −3%, Unused: +3%	147.01→142.76	0.940→0.947	0.829→0.937	15.8
Kuye River	Wenjiachuan	1985–1995	Grassland increase	Grass: +5.71%, Unused: −5.68%, Crop: +0.57%, Forest: −0.58%	121.06→127.74	0.449→0.355	0.228→0.177	2.67

Previous studies have reached similar conclusions regarding the effect of individual land use change on runoff generation. Many studies indicate that deforestation causes an increase in annual mean discharge accompanied by less transpiration and water interception, while afforestation has the opposite effect (Sahin and Hall, 1996; Costa and Foley, 1997; Bari *et al.*, 2005; Jackson *et al.*, 2005). Meadow development causes increasing water infiltration and decreasing discharge (Huang *et al.*, 1999). Agricultural activity often increases infiltration of ground water by the impoundment and consumption of surface runoff, but may also lead to soil degradation and loss of structure from farm mechanization and intensive tillage, and increased surface runoff (Van der Ploeg and Schweigert, 2001; Mu *et al.*, 2004; Burns *et al.*, 2005; White and Greer, 2006).

The results of the present study are consistent with previous research. The relationship between changes in *S* and runoff coefficients for different scenarios show that some land activities, such as deforestation, desertification and urban construction, often cause a decrease in *S* and an increase in effective precipitation and runoff generation. Activities such as afforestation and return of farmland to forest or grassland often cause increasing *S*, decreasing effective precipitation and associated decreases in discharge.

The influence on runoff of landscape change in the Yellow River Basin as a whole is complicated because of frequent changes in land classes and complex coupling with runoff generation. In other large rivers, such as the Amazon and Mississippi rivers, land types are relatively homogenous and composed mainly of forestry with lesser proportions of meadow and farmland. The impact of LUCC on runoff is thus simpler to assess in these basins. Many catchments have similar LUCC patterns (replacement of natural forest with grassland or cropland) and show decreases in evaporation and associated increases in discharge (Costa and Foley, 1997; Zhang and Schiling, 2006; Raymond *et al.*, 2008). However, the Yellow River Basin has many catchments with various land types and heterogeneous landscape structures; some are primarily grassland, others are mainly forestry or farmland with a large proportion of unused land (e.g., 19%), and some have a large proportion of urban areas (e.g., 12%). Some land use changes result in increased runoff, while others result in reduced runoff. In this study, we give an average level of LUCC effect over a large spatial scale, and show that this had a significant influence on runoff generation after the mid-1980s.

This study highlights some unresolved problems that could be addressed in future studies. For example, available land data are not continuous and are only available every 5 years. A continuous series of annual land data would be more useful for the evaluation of relationships between LUCC and changes in runoff generation.

5 Conclusions

This study evaluated the impact of LUCC on runoff in the Yellow River Basin. A retention parameter was used to relate LUCC to changing discharge. The contribution of LUCC to changes in discharge was quantified using an attribution approach and multiple regression analyses. We summarize our conclusions as follows.

1) The natural discharge of the Yellow River during 1956–2012 shows a significant decreasing trend of −0.345 km^3 per year (−0.6% per year). This trend is most pronounced from the mid-1980s to the end-1990s, when it increased to −1.889 km^3 per year (−3.9% per year).

2) During 1956–2012 the relative change in natural discharge in the Yellow River was −0.622% per year, with 16.2% of this decrease being a result of the decreasing precipitation, and 83.8% being attributable to reduced runoff-generation capacity.

3) The reduced runoff-generation capacity was mainly driven by LUCC after the mid-1980s. The main LUCC changes, including increases in forestland and cropland, and decreases in unused land, resulted in an increase in the retention parameter, a decrease in effec-

tive precipitation, and a reduction in runoff-generation capacity in the Yellow River Basin.

These findings highlight the importance of LUCC in runoff generation from the land surface, and provide quantitative information for stakeholders and decision makers to guide land and water resource planning and management. In addition, the use of a retention parameter to connect LUCC and runoff for large-scale basins is shown to be an effective approach for understanding the potential impact of landscape change on water availability.

Appendix

Table A1 Definitions of terms used in this study

Subject	Term	Definition	Spatial scale	Unit
Hydrology	Runoff	Water from rain or snow that flows over the ground surface into streams	Basin, catchment	–
	Runoff generation	Runoff from precipitation after deducting the loss from interception, infiltration and evaporation		–
	Discharge	Water volume of a cross section in a unit of time		km^3, mm
	Natural discharge (Q)	Original discharge not including anthropogenic usage		km^3, mm
	Runoff coefficient (Q/P)	A dimensionless factor that is used to convert rainfall amount to runoff.		–
	Retention parameter (S)	The potential maximum retention of precipitation on the land surface (dependent upon soil cover)		–
Rainfall	Precipitation (P)	Amount of water that falls to the Earth's surface	Basin, catchment	mm
	Effective precipitation ($P_{\text{effective}}$)	Precipitation that produces runoff		mm
	Threshold precipitation ($P_{\text{threshold}}$)	The lowest precipitation amount that produces runoff		mm
Land	Land area	Surface area of a land type	Basin, 100 m × 100 m	km^2
	Land proportion	Percentage area of a land type in a basin		%

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