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Impact of Land Use Change on Hydrologic Processes in a Large Plain Irrigation District

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Abstract Land use is the main factor that influences catchment hydrologic processes, and a better understanding of its effect is important for future land use planning and water resource management. By applying the Soil and Water Assessment Tool (SWAT), we assessed the effects of land use changes on major hydrologic processes (evapotranspiration (ET), discharge, river) on a large plain irrigation district, the Hetao Irrigation District (HID), China. The results indicated that SWAT was a useful tool for simulating the effects of land use changes on regional hydrologic processes. Human activities were the main factors that directly influenced land use in the HID. Land use changes had important impacts on the hydrologic processes of the HID. During 1995–2010, the land use changed greatly in the HID, leading to the changes in ET and discharge. The peak value of ET coincided with the exuberant crop growth period in the maximized sown crop area. In 1995s, wheat maximized the sown area and ET peaked in June; when sunflower and corn maximized the sown area in 2010s, ET peaked in July and August. The increased ET reduced discharge in the same period in the HID. Land use change affected the period and quantity of water diversion in the irrigation district. The quantity of water diverted in 1995 was greater than that in 2010, indicating that land use change significantly impacted the water quantity of the river, which was the water

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source of the irrigation district. This study will be a reference for future land use planning and water resource management in the irrigation district.

Keywords SWAT · Land use · Evapotranspiration · Discharge · Streamflow · Hetao Irrigation District

1 Introduction

Land use is one of the most important parts of a terrestrial environment system (Foley et al. 2005), as it affects stream flow, flood frequency (Sriwongsitanon and Taesombat 2011), surface runoff (Yan et al. 2013), sediment transport (Bakker et al. 2008), and nutrient transfer (Jordan et al. 1997) and is influenced by precipitation, evapotranspiration (ET), and soil hydraulic properties (Zierl and Bugmann 2005). Land use and climate are key factors that influence catchment hydrologic processes (Feddema et al. 2005). Climate change may affect precipitation frequency (Simonovic and Li 2004), precipitation intensity (Chien et al. 2013), precipitation quantity and stream flow (Chaplot 2007). However, research has shown that climate change has a more obvious impact on long-term hydrologic processes, whereas in the short-term, land use is one of the main factors that influences catchment hydrologic processes (López-Moreno et al. 2013; Ficklin et al. 2015).

Currently, research on the impact of land use change on regional hydrologic processes is a popular issue, as it affects regional river flow (Siriwardena et al. 2006), water quality (Turner and Rabalais 2013), the local water supply of groundwater and surface water (Cho et al. 2009), and the distribution of river water in upper and lower reaches (Petts 1996); it has also created social and political problems at both the local and national levels (Poff et al. 2003). The effects caused by land use change are very important to an irrigation district, especially in a large irrigation district, because it consumes a large amount of water resources and is strongly influenced by human activities (Brath et al. 2006; Niu et al. 2016). Human activities (e.g., water diversion, irrigation) influence runoff, ET, nutrient transfer and stream flow (Zhang et al. 2001; Shibuo et al. 2007; Neupane and Kumar 2015). In addition, with economic development and population growth, the demand for water resources increases, as do surface water and groundwater exploitation pressure; however, total water resources are shrinking and regional water resource management is facing a hitherto unknown challenge (Stonestrom et al. 2009; Sun et al. 2016).

Using a hydrological model is one of the most efficient ways to assess the impacts of land use change at different spatial and temporal scales. The SWAT (Soil and Water Assessment Tool), which was developed by USDA Agricultural Research Service Agency and Texas A&M University, is the most commonly used model in land use change assessment (Arnold et al. 1998). For example, Heuvelmans et al. (2005) used the SWAT model to evaluate land use impact in a life cycle study of CO2 emission reduction scenarios. Nie et al. (2011) assessed the impacts of land use and land cover changes on the hydrology of the Upper San Pedro watershed using the SWAT model. Similarly, Li et al. (2016) quantified the effect of land surface change on annual runoff considering precipitation variability using SWAT. SWAT can also be used to assess the impacts of land management practices (Chiang et al. 2010), climate change (Zhang et al. 2015), soil erosion (Sun et al. 2013a), and non-point source pollution.

Currently, many scholars have assessed the impact of land use change and have used SWAT to evaluate its impact, as mentioned above. However, these studies have certain shortcomings.

First, most studies have focused on the impact of either land use/land cover change in natural watersheds or climate change on hydrological processes. Less research exists on the influence of human activities on regional hydrological processes based on the type of land use change, particularly in regions that are strongly affected by human activity, such as irrigation districts. In such areas, farmland is artificially irrigated with large amounts of water, intensely affecting the hydrological cycle in the area. Second, at present, the application of the SWAT model to research related to irrigation areas is less reported. In this study, the SWAT model was applied to an irrigation district to evaluate the impact of land use change on hydrological processes. This study extends beyond the scope of the SWAT model. In addition, understanding the effect of land use change on annual or seasonal hydrologic processes in the irrigation district will improve the predictability of the hydrologic consequences of these changes, which is significant for future land use planning and water resource management in this type of agricultural production area.

The aim of this study is to assess the impact of land use change on hydrologic processes in the Hetao Irrigation District (HID). The main components of this study are: (1) to assess how land use change affects ET in the HID by applying the SWAT model, (2) to model the effect of land use change on discharge in the HID, and (3) to estimate the effect of land use change on river quantity. This study will provide suggestions for improving future regional land use planning and water resource management.

2 Materials and Methods

2.1 Study Site

The Hetao irrigation district (HID) is one of the three largest irrigation districts in China; it is centrally located in the Yellow River basin in western Inner Mongolia, China (Fig. 1). The HID has an area of 1.12×10^4 km^2 and an average elevation of 1005–1060 m. The HID has a continental monsoon climate; the lowest temperature occurs in January (average − 10 °C, lowest −32 °C), the highest temperature occurs in July (average 23 °C, highest 35 °C), the annual precipitation is 145–216 mm, and the annual evaporation is 1987–2375 mm. The major crops are wheat, sunflower, corn and honeydew melon. The irrigation water is diverted from

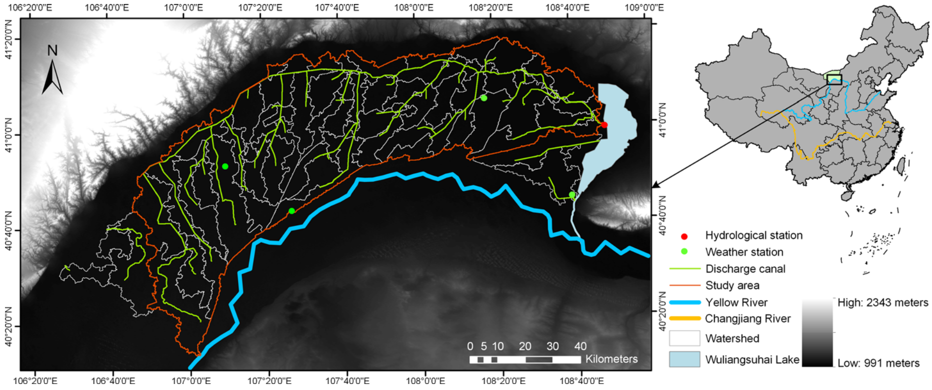

Fig. 1 Location of the Hetao Irrigation District (HID) in China (modified from Luan et al. 2018)

the Yellow River, and surface irrigation is the main technology used in the HID (Sun et al. 2013b). The irrigation and drainage systems in the HID are composed of irrigation canals and drainage ditches. The irrigation system has a general main canal (228.9 km) and 12 main canals (total 755 km), and the drainage system has a general main ditch (227 km) and 12 main ditches (total 523 km) (AHID 2015).

2.2 Model Description

SWAT is a small watershed-to-river basin-scale, physically based distributed hydrologic model that simulates the quality and quantity of surface and ground water and predicts the environmental impact of land use, land management practices, and climate change (Arnold et al. 1998; SWAT, http://swat.tamu.edu/); it incorporates the effects of water, evapotranspiration, runoff, topography, and agricultural management practices. The model partitions a watershed into subbasins based on topography and then partitions a subbasin into hydrologic response units (HRU) based on the soil type and land use in order to assess soil erosion, non-point pollution, and hydrologic processes (Haverkamp et al. 2002).

2.3 Data Collection

The data required by the SWAT model include digital elevation model (DEM), soil, land use, discharge and climate data (Table 1). The four weather stations in the HID are shown in Fig. 1.

HID discharge data (AHID 2015) include monthly data from 1987 to 2012. Due to the gentle slope, less precipitation and strong evaporation, the drainage network based on the DEM is inconsistent with the actual water system; therefore, we defined the drainage ditch as the stream (AHID 2015) and burned it into the DEM to divide the sub basins. The discharge data were used to verify the simulation results.

2.4 Management Operations

The management operations in the HID include planting, irrigation, and harvesting. The climate allows only one farming season per year; the crop growth period is from April to

Table 1 Data used in the study

Dataset	Data description	Resolution	Data sources
DEM	–	30 × 30 m	Geospatial Data Cloud (CAS 2009a)
Soil	Soil type map, Soil physical and chemical properties	1:1000000	China Soil Scientific Database (CAS 2009b)
Land use	–	1:100000 (1995, 2010)	Data Center for Resources and Environmental Sciences (CAS 2010)
Climate	Precipitation, Wind speed, Solar radiation, Maximum temperature, Minimum temperature, Relative humidity	Daily (1980–2012)	China Meteorological Data Network (NMIC 2015), The Administration of Hetao Irrigation District (AHID 2015)
Hydrologic	Stream map, Discharge	Monthly (1990–2012)	The Administration of Hetao Irrigation District (AHID 2015)

October, and croplands are irrigated after the harvest in October to leach the salt that accumulates on the soil surface by evaporation. The wheat growth period is from April to July; that of corn and sunflower is from May to September, and that of honeydew melon is from June to August.

2.5 Calibration, Validation, and Sensitivity Analysis

The Sequential Uncertainty Fitting (SUFI-2) algorithm in SWAT-CUP was applied for calibration and validation (Abbaspour et al. 2007; Abbaspour 2012) by comparing model-simulated stream discharge data with measured discharge data. Land use data from 1995 and 2010 were used to represent the land use patterns of 1995s (1987–1996) and 2010s (2003–2012) as two time-slices to future evaluate the effects of land use changes. For 1995s, the calibration (1987–1993) and validation (1994–1996) periods were used; for 2010s, the calibration (2003–2009) and validation (2010–2012) periods were used. The global sensitivity analysis integrated within SUFI-2 was used to evaluate the hydrologic parameters for discharge simulation.

For calibration and validation analysis, the monthly measured discharge was compared with the simulated discharge data, and the model performance was judged using the coefficient of determination (R^2) (Krause et al. 2005), the Nash efficiency coefficient (NSE) (Nash and Sutcliffe 1970; Moriasi et al. 2007) and the percentage deviation (PBIAS) (Gupta et al. 1999). The calculation formula is as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_m - \overline{Q}_m\right)\left(Q_s - \overline{Q}_s\right)\right]^2}{\sum_{i=1}^{n}\left(Q_m - \overline{Q}_m\right)^2 \sum_{i=1}^{n}\left(Q_s - \overline{Q}_s\right)^2} \tag{1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_m - Q_s\right)^2}{\sum_{i=1}^{n}\left(Q_m - \overline{Q}_m\right)^2} \tag{2}$$

$$PBIAS = \frac{\sum\left(Q_m - Q_s\right)}{\sum Q_m} \times 100 \tag{3}$$

where Q_m is the measured data, $\overline{Q}_m$ is the mean of the measured data, Q_s is the model simulation data, and $\overline{Q}_s$ is the mean of the model simulation data.

R^2 measures the simulated and measured values of goodness; the closer the value is to 1, the higher the agreement is between the simulated and measured discharge. NSE is widely applied in hydrologic models that range from negative infinity to 1, with 1 being the ideal value (Moriasi et al. 2007). The PBIAS assesses the average deviation of the simulated values from the observed values, with 0 as the ideal value, and a positive (negative) PBIAS value representing an underestimation (overestimation) bias of the simulated variable compared to the measured variable (Gupta et al. 1999). The model simulation results can be classified as satisfactory if $R^2 > 0.6$, $NSE > 0.5$ and $PBIAS < \pm 25$ (Moriasi et al. 2007; Neupane and Kumar 2015). These statistical measures were evaluated for the monthly discharge simulation and used to assess the effects of land use changes on hydrologic processes in the irrigation district.

Table 2 Land use patterns in 1995 and 2010

	Wheat	Sunflower	Corn	Honeydew melon	Grassland	Construction land	Barren land	Water	Forest
1995									
Area km^2	2302.0	1171.8	290.8	0	1852.0	1060.0	758.9	94.3	12.6
% area	30.5	15.5	3.9	0	24.6	14.1	10.1	1.3	0.2
2010									
Area km^2	632.7	1907.7	761.3	432.9	1789.8	959.9	941.7	91.3	25.5
% area	8.4	25.3	10.1	5.7	23.7	12.7	12.5	1.2	0.3
Change									
Area km^2	−1669.3	735.9	470.5	432.9	−62.2	−100.1	182.8	−3	12.9
% area	−22.1	9.8	6.2	5.7	−0.9	−1.4	2.4	−0.1	0.1

3 Results

3.1 Land Use Change in the HID

The main land uses in the HID were wheat field, sunflower field, corn field, grassland, barren land and construction land (Table 2). From 1995s to 2010s, the areas of grassland, barren land and construction land changed slightly, while the crop field areas changed significantly. Compared with 1995s, the area of wheat decreased from 2302.0 km^2 to 632.7 km^2 and the proportion of wheat decreased by 22.1%. The sown area of sunflower increased from 1171.8 km^2 to 1907.7 km^2, representing an increase of 9.8%. The sown area of corn increased by 6.2%, and the area of honeydew melon increased by 5.7%.

In 1995s, the total area of wheat, sunflower and corn in the HID totaled 3764.4 km^2, accounting for 49.9% of the total area of the HID. In 2010s, the total area of wheat, sunflower, corn and honeydew melon was 3734.7 km^2, accounting for 49.5% of the total area of the HID; the crop area decreased by 19.7 km^2.

3.2 Calibration and Validation Analysis

The global sensitivity analysis procedure integrated within SUFI-2 showed that CN2, ESCO, SOL_AWC, GW_REVAP and ALPHA_BF were the sensitive parameters. The hydrographs obtained after the model calibration substantially improved the fit of the modeled vs measured discharge values (Fig. 2). The final values of these parameters are shown in Table 3.

The evaluation coefficients of the simulated discharge obtained by various indices are presented in Table 4. In 1995s, the measured and simulated average annual discharge values during the calibration were 5.7×10^8 m^3 and 4.9×10^8 m^3, respectively. The R^2, NSE, and PBIAS values for the period were 0.71, 0.65 and 13, respectively. The R^2, NSE, and PBIAS values for the validation period were 0.65, 0.63 and 23, respectively. In 2010s, the measured and simulated average annual discharge values during the calibration period were 4.8×10^8 m^3 and 4.3×10^8 m^3, respectively. The R^2, NSE, and PBIAS values for the period were 0.77, 0.65

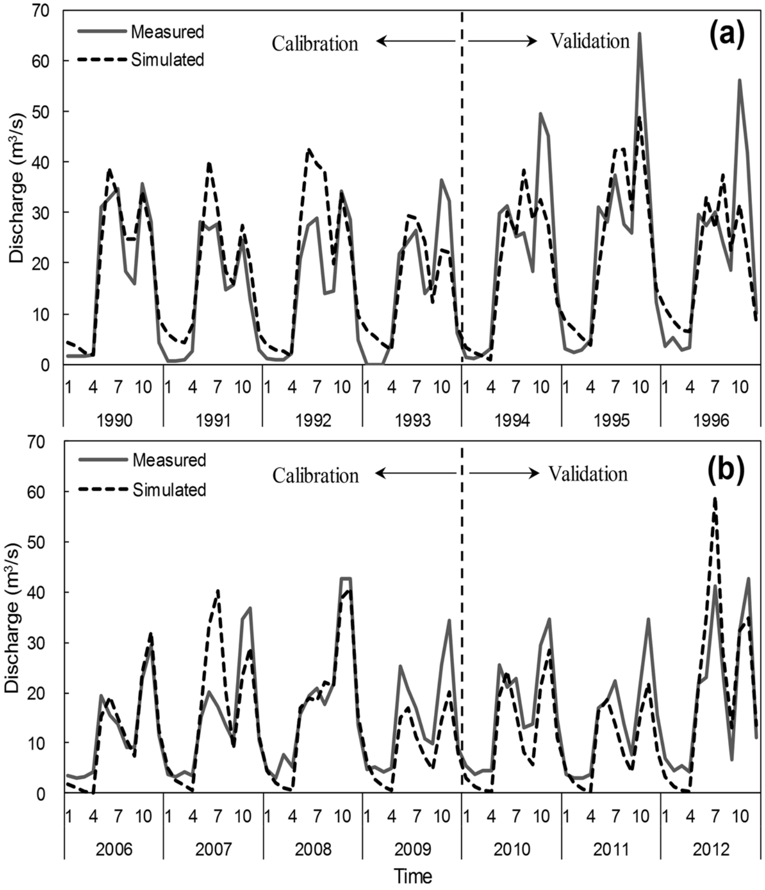

Fig. 2 Observed and simulated discharge in the HID: (**a**) 1995s, (**b**) 2010s

and 17, respectively. The R^2, NSE, and PBIAS values for the validation period were 0.68, 0.61 and 21, respectively. Therefore, the results showed that the SWAT model was applicable to the HID large-scale plain irrigation district for the assessment of hydrologic processes with changes in land use (Moriasi et al. 2007; Neupane and Kumar 2015).

Table 3 The values of sensitive parameters

Parameter	Definition	Range	Last value	
			1995	2010
r__CN2	SCS curve number	(−0.4)–0.4	−0.29	−0.38
v__ESCO	Soil evaporation compensation factor	0.3–0.9	0.5	0.5
r__SOL_AWC	Available water capacity of the soil layer	(−0.2)–0.4	0.21	−0.2
v__GW_REVAP	Groundwater "revap" coefficient	0.01–0.2	0.03	0.05
v__ALPHA_BF	Baseflow alpha factor (days)	0.3–1	0.61	0.56

r__ indicates that the existing parameter value is multiplied by (1+ a given value): v__ indicates that the existing parameter value is to be replaced by the given value

Table 4 Model performance statistics for calibration and validation simulations in 1995s and 2010s

	Calibration		Validation	
	1995s	2010s	1995s	2010s
R^2	0.71	0.77	0.65	0.68
NSE	0.71	0.65	0.63	0.61
PBIAS	13	17	23	21

3.3 Impacts of Land Use Change on Hydrologic Processes

Irrigated areas are strongly affected by human activities. The main land use types in the HID are cropland, construction land, forest, grassland, barren land and water. Based on the water sources of the land, the land can be divided into two parts. The first is cropland, including wheat, corn, sunflower and melon, and the second is non-cropland, including construction land, forest, grassland, desert and water. The main water sources of the cropland are precipitation and irrigation. The main water source of non-cropland is precipitation, and its main water outputs are ET and drainage.

Figure 3 present the major water inputs and outputs in the HID during 1995s and 2010s. Precipitation and irrigation are the major water input sources of the HID, while evapotranspiration and drainage are the major water outputs of the HID. Irrigation is the main water input in the irrigation area and evapotranspiration is the water output of the irrigation area (Fig. 3). In 1995s and 2010s, the contributions of irrigation to water input were 74.9 and 73.3%, respectively, while the contributions of evapotranspiration to water output were 86.7 and 89.9%, respectively. The Fig. 3 also shows that the water input is greater than the water output; this excess water may infiltrate into the ground.

3.3.1 Impact on ET

Land use changes affect the annual and monthly regional ET. The monthly ET simulated by SWAT under different land use types in the HID during 1995s and 2010s are presented in Fig. 4. Figure 4a shows that ET changed during 1995s and 2010s, as the annual ET of the HID in 1995s was 31.4×10^8 m^3 but that in 2010s was 34.0×10^8 m^3; the monthly ET values of the HID in

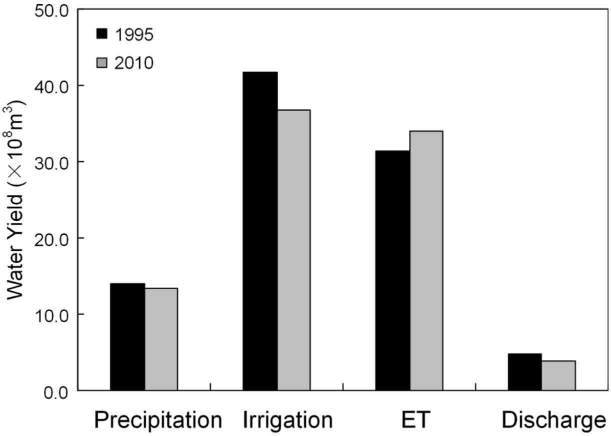

Fig. 3 The major water input and output quantities in the HID in 1995s and 2010s

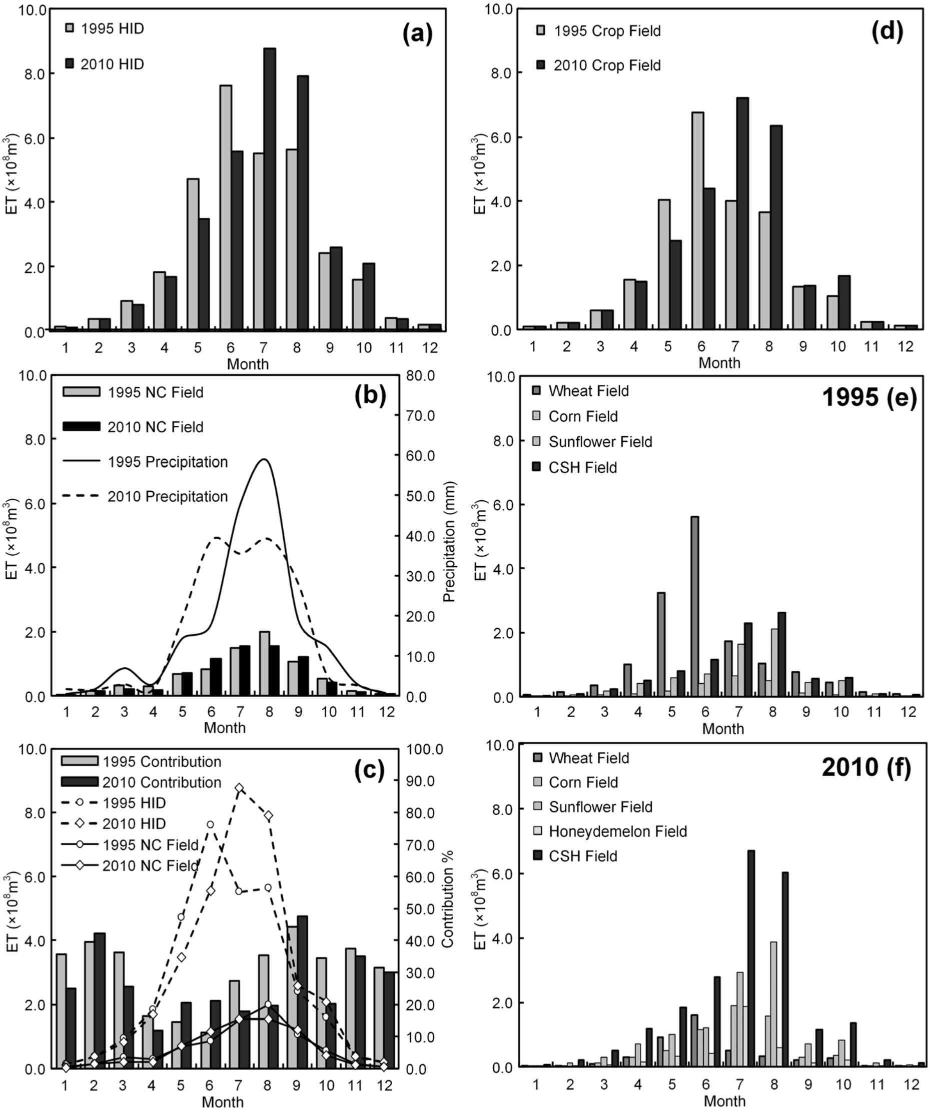

Fig. 4 HID (**a**) 1995s, 2010s monthly ET; (**b**) 1995s, 2010s NC land monthly ET and precipitation; (**c**) 1995s, 2010s monthly ET, NC land ET and contribution; (**d**) cropland ET; (**e**) 1995s crops ET and CSH's ET (sum of ET of sunflower, corn and honeydew melon); (**f**) 2010s crops ET and CSH's ET

April and May in 1995s were higher than those in the same period in 2010s, but the monthly ET values of the HID in July and August in 1995s were much lower than those in the same period in 2010s. Figure 4b shows that the annual ET values of non-crop (NC) land varied slightly between 1995s and 2010s, with values of 7.7×10^8 m^3 and 7.4×10^8 m^3, respectively. The monthly ET and precipitation trends were consistent. Figure 4c shows that the monthly ET contribution rate of NC land to the HID was clearly influenced by crop ET. From April to August (the crop growth period), the contributions in both 1995s and 2010s were less than 30%, except in August of 1995s; the lowest contribution was 11.8% in April of 2010s and the highest contribution was 35.3% in August of 1995s. This may be because the ET of cropland was higher (lower) in that month, resulting in the contribution of NC land ET in this month decreasing (increasing); the contribution situation in September was similar. In October, due to the increased cropland irrigation and cropland ET, the contribution of NC land ET decreased. The contribution of NC land ET was maintained at 30–40% from November to March of the following year.

The monthly cropland ET and monthly HID ET trends were consistent (Fig. 4a, d). The cropland annual ET values in 1995s and 2010s were 23.7×10^8 m^3 and 26.6×10^8 m^3, respectively. These contributions to the HID annual ET were 75.4 and 78.2%, respectively. Therefore, the HID annual ET mainly came from cropland. The monthly cropland ET values in May and June in 1995s were higher than those in the same periods in 2010s, which were greater than 1.2×10^8 m^3 and 2.4×10^8 m^3, respectively. However, the monthly cropland ET values in July and August in 1995s were lower than those in the same periods in 2010s, which were less than 3.2×10^8 m^3 and 2.7×10^8 m^3, respectively. Because the growth periods of wheat are different than those of sunflower, corn and honeydew melon, wheat was defined as part one and the remaining three crops (Corn, Sunflower, Honeydew melon) were defined as part two (CSH) when calculating ET. Figure 4e and f show that in 1995s, the wheat ET values in May and June were 3.2×10^8 m^3 and 5.7×10^8 m^3, respectively, accounting for 80.2 and 83.0% of the cropland ET, respectively, which were higher than the total CSH ET. However, in 2010s, the wheat ET was lower than the total CSH ET, especially in July and August. The sums of the CSH ET accounted for 92.8 and 95.0% of the contributions to the ET of the cropland.

3.3.2 Impact on Discharge

Land use change will affect the regional discharge quantity and discharge period. The discharge values simulated by SWAT under different land use conditions during 1995s and 2010s are presented in Fig. 5. The results showed that the trends of the HID discharge in 1995s and 2010s were consistent but that the annual discharge values of the two periods in the HID were different: that in 1995s was 4.8×10^8 m^3 and that in 2010s was 3.8×10^8 m^3. Figure 5b shows that the trends of NC land discharge during 1995s and 2010s were consistent but inconsistent with those of HID discharge, whereas the trends of NC land discharge were consistent with those of precipitation in 1995s and 2010s, respectively. The annual discharge of NC land during two periods was 0.3×10^8 m^3. Figure 5c shows that the discharge in NC land was smaller and concentrated in the rainy season (from May to September), and its contribution to regional total discharge was small, with the highest contributions being 21.6% in August 1995s and 22.7% in September 2010s, mainly because cropland discharge decreased in August and September (Fig. 5d), thus causing an increase in the discharge contribution rate from NC land. Figure 5d shows that the trend of discharge between cropland and HID was consistent. The monthly discharge in 1995s was higher than that during the same periods in 2010s, with annual discharge values during these two periods of 4.5×10^8 m^3 and 3.5×10^8 m^3, respectively, accounting for 93.8 and 92.4% of the total discharge in the HID. Therefore, the HID discharge mainly came from cropland. Figure 5e and f show the cropland water input (irrigation, precipitation) and output (ET, discharge). Irrigation was the main cropland water input method, accounting for 72.1 and 71.7% of the total water input in the HID in 1995s and 2010s, respectively. ET was the main cropland water output method, accounting for 84.0 and 88.3% of the total water output in the HID in 1995s and 2010s, respectively. The discharge changed with the volume of irrigation (Fig. 5d, e, f). The discharge increased with increasing irrigation volume; when irrigation decreased or stopped, the discharge gradually decreased.

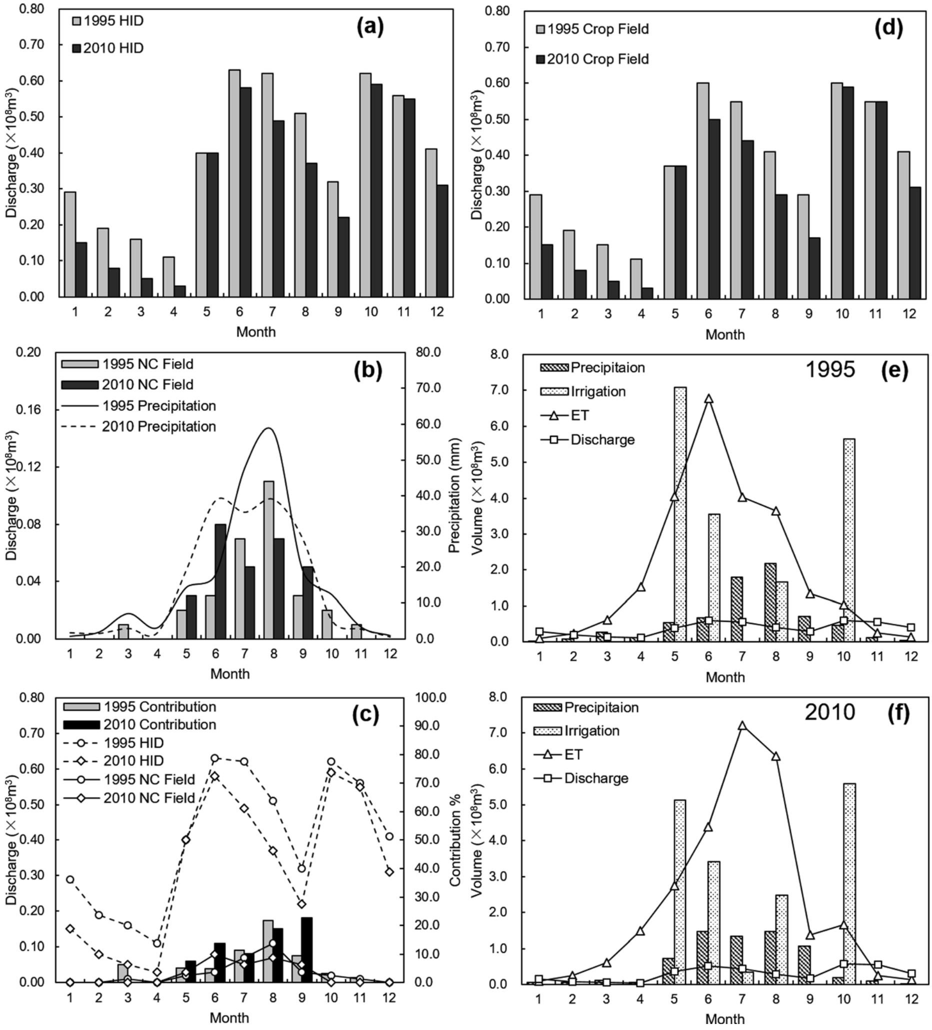

Fig. 5 HID (**a**) 1995s, 2010s monthly discharge; (**b**) 1995s, 2010s NC land discharge and precipitation; (**c**) 1995s, 2010s monthly discharge, NC land discharge and contribution; (**d**) 1995s, 2010s monthly cropland discharge; (**e**) 1995s cropland irrigation, precipitation, ET and discharge; (**f**) 2010s cropland irrigation, precipitation, ET and discharge

3.3.3 Impact on River Stream Flow

The irrigation water used in the HID was diverted from the Yellow River, and only one diversion intake exists on Yellow River. The impact of land use changes on river stream flow was assessed by analyzing the monthly water diversion quantities in 1995s and 2010s, mean monthly stream flow (1987–2012) in the Yellow River at upstream and downstream hydrological stations, Shizuishan station (upstream of HID diversion) and Bayangaole station (downstream of HID diversion) (Fig. 6). The results showed that diverted irrigation water reduced the flow in the Yellow River. Between May and October, the water yield of Yellow River was drastically reduced; these months were also the period of irrigation in the HID, and no other diversion existed between these two hydrological stations. The water diversion quantity in May of 1995s was higher than that during the same period

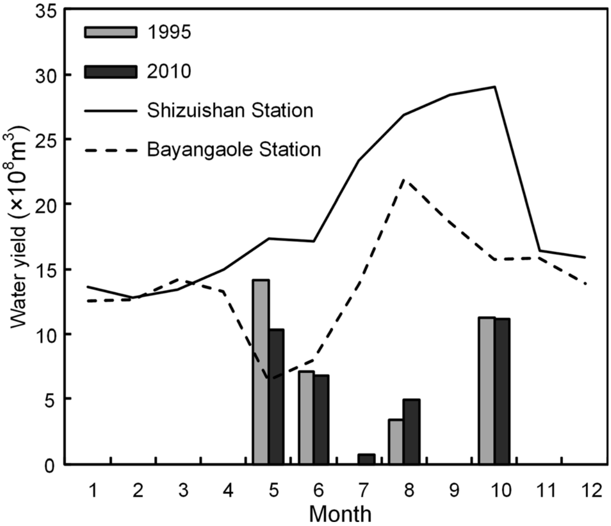

Fig. 6 1995s, 2010s HID diversion and mean monthly stream flow of two hydrological stations on the Yellow River

in 2010s, which was greater than 11.9×10^8 m^3. The diversion quantity in May in 1995s accounted for 68.9% of the Yellow River runoff, whereas it accounted for 49.8% during the same period in 2010s. May and October are not the rainy season in the Yellow River basin; the rainfall in the Yellow River and HID was small; therefore, the diversion of the HID significantly reduced the stream flow of the Yellow River, which had a serious impact on the water use in the downstream region.

4 Discussion

An irrigation district is a region where land use is critically influenced by human activities. Due to changes in farmers' willingness to plant, the HID experienced a dramatically reduced wheat area and increased sunflower, corn and honeydew melon areas from 1995 to 2010. Therefore, human activities play an important role in the change of land use in this region (Brath et al. 2006), especially in the irrigation district. Non-crop land, which changed little in the HID, has a smaller effect on the hydrologic processes in the irrigation district. The ET and discharge from NC land in the HID changed with local precipitation.

The ET of the crop depends on the characteristics of the crop, with crops having different growth periods and quantities of ET (Vedula and Jairaj 2014). Human activities change land use in an irrigation district, especially when changing the planting proportions of crops, which will affect the ET quantity and period. The growth period of wheat was between April and July, and those of sunflower and corn were between May and September. Therefore, in 1995s, the area of wheat was larger, and the peak value of ET appeared in June during the exuberant growth period of wheat. In 2010s, the areas of sunflower and corn accounted for a larger proportion, and the peak value of ET appeared in July and August, which was consistent with the exuberant growth periods of sunflower and corn.

Crop growth consumes water. The rainy seasons in the HID are between July and August, and the precipitation in the HID is low (Fig. 5e, f). Therefore, the precipitation cannot provide enough water for crop growth, and irrigation must be applied to the crops based on the crop characteristics (Kannan et al. 2011). In 1995s, the proportion of wheat was high, and the irrigation quantity of the

HID was also larger in May. In 2010s, compared with 1995s, the proportions of sunflower and corn were high; the irrigation quantity of the HID decreased in May, but it increased in July and August. Irrigation amplifies the ET quantity (Jarsjö et al. 2012), but this effect does not occur immediately, as it needs to be converted through ET in crops. Figure 5e and f show that the ET peak is consistent with the exuberant crop growth period, but it does not coincide with the period of maximum irrigation quantity; the ET increased in the crop growth period (Wang et al. 2014). Increasing ET will reduce the regional discharge (He et al. 2008). The ET water source and discharge in the HID mainly come from irrigation water (Fig. 5e, f). The irrigation quantity in May of 1995s was more than that in the same period in 2010s, i.e., 7.1×10^8 m^3 and 5.1×10^8 m^3, respectively; however, the discharge values in May of both 1995s and 2010s were equal (Fig. 5d), which may be due to the ET in May of 1995s being greater than that during the same period in 2010s (Fig. 4d). The larger ET decreased the soil water, thus reducing discharge. Similarly, the irrigation values in July and August of 1995s were less than those during the same periods in 2010s (Fig. 5e, f), but the ET values in July and August of 2010s were greater than those during the same periods in 1995s (Fig. 4d). This may explain why the discharge values in July and August of 2010s were less than those during the same periods in 1995s (Fig. 5d).

The precipitation in the HID is low; therefore, the water needed for crop growth mainly comes from irrigation, which is diverted from the Yellow River. However, due to the differing crop characteristics in water consumption, in 1995s, the area of wheat was largest, the diversion quantity in May was the highest; but in 2010s, the area of sunflower and corn was larger than that of wheat, which reduced the diversion quantity in May and increased it in July and August. However, the Yellow River runoff in May was low, large amounts of diverted water will reduce the water supply availability in the downstream region, and it will have a disadvantageous impact on the ecological environment of the river and the downstream region, especially if the downstream region is an arid region (Fig. 6). Therefore, the reasonable planning of river flow allocation is needed to establish a regulation mechanism for ecological river water flow (Petts 1996).

5 Conclusions

SWAT proved to be a useful tool to simulate the effect of land use change on hydrologic processes. CN2, ESCO, SOL_AWC, GW_REVAP and ALPHA_BF were the sensitive parameters in the calibration and validation analysis in this study.

Land use change in the HID was critically influenced by human activities; from 1995 to 2010, the area of wheat in the HID decreased by 22.1%, and the areas of sunflower and corn increased by 9.8 and 6.2%, respectively.

Changing the type of land use can lead to changes in the timing and quantity of ET and discharge, with ET dependent on the water consumption characteristics of the crop. The intra-annual variation in total regional ET was consistent with the exuberant crop growth period, which accounted for a large proportion of the total sown area. The change in land use will change the irrigation volume; discharge increased with increasing irrigation volume and gradually decreased after irrigation. In an area lacking in water resources, adjusting the crop planting structure is a feasible way to reduce the pressure on water resources by reducing the planting area of low-water-productivity crops and increasing the acreage of high-water-productivity crops.

Land use changes affect the timing and quantity of diversion in the river ecological environment and the water usage in the downstream region. Land use change has a critical impact on regional hydrologic processes and water resource availability. Understanding these effects is important for improved future land use planning and water resource management for the sustainable development of an irrigation district.

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References

Abbaspour KC (2012) SWAT-CUP 2012: SWAT calibration and uncertainty programs - a user manual. Swiss Federal Institute Science and Technology, Eawag

Abbaspour KC, Vejdani M, Haghighat S (2007) SWAT-CUP calibration anduncertainty programs for SWAT. Modsim 2007: international congress on modelling and simulation: land, water and environmental management: integrated systems for sustainability, Christchurch, New Zealand

AHID (2015) The administration of Hetao irrigation district (AHID), Bayan Nur department of water, inner Mongolia autonomous region, China (http://www.htgq.gov.cn/)

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. J Am Water Resour As 34(1):91–101

Bakker MM, Govers G, Doorn AV, Quetier F, Chouvardas D, Rounsevell M (2008) The response of soil erosion and sediment export to land-use change in four areas of Europe: the importance of landscape pattern. Geomorphology 98(3–4):213–226

Brath A, Montanari A, Moretti G (2006) Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). J Hydrol 324(1–4):141–153

CAS (2009a) Geospatial data cloud site (GSCloud): computer network information center, Chinese academy of sciences (http://www.gscloud.cn)

CAS (2009b) China soil scientific database (CSDB): soil research center, institute of soil science, Chinese academy of sciences (http://www.soil.csdb.cn/)

CAS (2010) Data center for resources and environmental sciences (RESDC): Chinese academy of sciences (http://www.resdc.cn)

Chaplot V (2007) Water and soil resources response to rising levels of atmospheric CO2 concentration and to changes in precipitation and air temperature. J Hydrol 337(1–2):159–171

Chiang L, Chaubey I, Gitau MW, Arnold JG (2010) Differentiating impacts of land use changes from pasture management in a CEAP watershed using the SWAT model. Trans ASABE 53(5):1569–1584

Chien H, Yeh PJF, Knouft JH (2013) Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. J Hydrol 491:73–88

Cho J, Barone VA, Mostaghimi S (2009) Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed. Agric Water Manag 96(1):1–11

Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The importance of land-cover change in simulating future climates. Science 310(5754):1674–1678

Ficklin DL, Maxwell JT, Letsinger SL, Gholizadeh H (2015) A climatic deconstruction of recent drought trends in the United States. Environ Res Lett 10(4):44009–44018

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin ST, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574

Gupta HV, Sorooshian S, Yapo PO, Gupta HV, Yapo PO (1999) Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J Hydrol Eng 4(2):135–143

Haverkamp S, Srinivasan R, Frede HG, Santhi C (2002) Subwatershed spatial analysis tool: discretization of a distributed hydrologic model by statistical criteria. J Am Water Resour As 38:1723–1733

He H, Zhou J, Zhang W (2008) Modelling the impacts of environmental changes on hydrological regimes in the Hei River watershed, China. Glob Planet Chang 61:175–193

Heuvelmans G, Garcia-Qujano JF, Muys B, Feyen J, Coppin P (2005) Modelling the water balance with SWAT as part of the land use impact evaluation in a life cycle study of CO2 emission reduction scenarios. Hydrol Process 19(3):729–748

Jarsjö J, Asokan SM, Prieto C, Bring A, Destouni G (2012) Hydrological responses to climate change conditioned by historic alterations of land-use and water-use. Hydrol Earth Syst Sci 16:1335–1347

Jordan TE, Correll DL, Weller DE (1997) Relating nutrient discharges from watersheds to land use and streamflow variability. Water Resour Res 33(11):2579–2590

Kannan N, Jeong J, Srinivasan R (2011) Hydrologic modeling of a canal-irrigated agricultural watershed with irrigation best management practices: case study. J Hydrol Eng 16(9):746–757

Krause P, Boyle DP, Se FB (2005) Comparison of different efficiency criteria for hydrological model assessment. J Adv Geosci 5(5):89–97

Li J, Li G, Zhou S, Chen F (2016) Quantifying the effects of land surface change on annual runoff considering precipitation variability by SWAT. Water Resour Manag 30(3):1071–1084

López-Moreno JI, Vicente-Serrano SM, Zabalza J, Beguería S, Lorenzo-Lacruz J, Azorin-Molina C, Morán-Tejeda E (2013) Hydrological response to climate variability at different time scales: a study in the Ebro basin. J Hydrol 477(2):175–188

Luan X, Wu P, Sun S, Wang Y, Gao X (2018) Quantitative study of the crop production water footprint using the swat model. Ecol Indic 89:1–10

Moriasi DN, Arnold JG, Liew MWV, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 50(3):885–900

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I - a discussion of principles. J Hydrol 10:282–290

Neupane RP, Kumar S (2015) Estimating the effects of potential climate and land use changes on hydrologic processes of a large agriculture dominated watershed. J Hydrol 529:418–429

Nie W, Yuan Y, Kepner W, Nash MS, Jackson M, Erickson C (2011) Assessing impacts of landuse and landcover changes on hydrology for the upper San Pedro watershed. J Hydrol 407(1–4):105–114

Niu G, Li YP, Huang GH, Liu J, Fan YR (2016) Crop planning and water resource allocation for sustainable development of an irrigation region in China under multiple uncertainties. Agric Water Manag 166:53–69

NMIC (2015) China meteorological data network (CMA), national meteorological information center, China (http://data.cma.cn/)

Petts GE (1996) Water allocation to protect river ecosystems. River Res Appl 12(4–5):353–365

Poff LR, Allan JD, Palmer MA, Hart DD, Richter BD, Arthington AH (2003) River flows and water wars: emerging science for environmental decision making. Front Ecol Environ 1(6):298–306

Shibuo Y, Jarsjö J, Destouni G (2007) Hydrological responses to climate change and irrigation in the Aral Sea drainage basin. Geophys Res Lett 34(21):91–99

Simonovic SP, Li L (2004) Sensitivity of the Red River basin flood protection system to climate variability and change. Water Resour Manag 18:89–110

Siriwardena L, Finlayson BL, Mcmahon TA (2006) The impact of land use change on catchment hydrology in large catchments: the comet river, Central Queensland, Australia. J Hydrol 326(1–4):199–214

Sriwongsitanon N, Taesombat W (2011) Effects of land cover on runoff coefficient. J Hydrol 410(3–4):226–238

Stonestrom DA, Scanlon BR, Zhang L (2009) Introduction to special section on impacts of land use change on water resources. Water Resour Res 45(7):160–169

Sun L, Lu W, Yang Q, Martín JD, Li D (2013a) Ecological compensation estimation of soil and water conservation based on cost-benefit analysis. Water Resour Manag 27(8):2709–2727

Sun SK, Wu PT, Wang YB, Zhao XN, Liu J, Zhang XH (2013b) The impacts of interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. Sci Total Environ 444:498–507

Sun SK, Wang YB, Liu J, Wu PT, Cai HJ (2016) Sustainability assessment of regional water resources under the DPSIR framework. J Hydrol 532:140–148

Turner RE, Rabalais NN (2013) Linking landscape and water quality in the Mississippi river basin for 200 years. Bioscience 53:563–572

Vedula S, Jairaj PG (2014) Modeling reservoir irrigation in uncertain hydrologic environment. J Irrig Drain Eng 129(3):164–172

Wang XM, Liu HJ, Zhang LW, Zhang RH (2014) Climate change trend and its effects on reference evapotranspiration at Linhe station, Hetao Irrigation District. Water Sci Eng 7(3):250–266

Yan B, Fang NF, Zhang PC, Shi ZH (2013) Impacts of land use change on watershed streamflow and sediment yield: an assessment using hydrologic modelling and partial least squares regression. J Hydrol 484:26–37

Zhang L, Dawes WR, Walker GR (2001) Response of mean annual ET to vegetation changes at catchment scale. Water Resour Res 37(3):701–708

Zhang Y, Su F, Hao Z, Xu C, Yu Z, Wang L, Tong K (2015) Impact of projected climate change on the hydrology in the headwaters of the Yellow River basin. Hydrol Process 29(20):4379–4397

Zierl B, Bugmann H (2005) Global change impacts on hydrological processes in alpine catchments. Water Resour Res 41(2):851–854