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Impacts of human activity on long-term water balance in the middle-reaches of the Yellow River basin

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Abstract To clarify the influences of climate change and human activities on river discharge, the long-term (1960–2000) water balance in the middle reaches of the Yellow River basin was analysed using a hydrological model. To estimate evapotranspiration from various land-use types, a high resolution land surface classification map in 2000 was used. When we applied the same land-use parameter of 2000 during the past 40 years, the results estimated by the model underestimated the river discharge. Then we modified the parameter to decrease evapotranspiration by reducing the vegetation cover. After that, the observed discharge was reasonably captured by the model. Consequently it was found that the massive land-use change and rapid decrease of available water resources in the middle reaches of the Yellow River basin will affect the water shortage in the lower reaches of the Yellow River basin.

Key words climate change; human activity; hydrological model s; long-term land-use change; water balance; Yellow River

INTRODUCTION

The Yellow River is the second largest river basin in China. In recent years, the river discharge has been decreasing rapidly, particularly in the lower reaches because of dry climate conditions and heavy water demands. To mitigate the water shortage in the lower reaches of the Yellow River basin, it seems to be important to manage the limited water resources appropriately. In order to clarify the long-term changes of the water balance, a hydrological model can be used. However, it is difficult to apply existing hydrological models directly to the Yellow River basin because the basin includes various artificial factors. Particularly, in the middle reaches of the Yellow River basin, the long-term water balance could be influenced by the massive land-use change due to the soil and water conservation at the Loess Plateau. Thus, in the present study, we attempt to develop a new hydrological model applicable to the middle reaches of the Yellow River basin.

METHODS

Study area

We focused on the middle reaches of the Yellow River basin between Toudaoguai (40.16°N, 111.04°E) and Sanmenxia (34.49°N, 111.22°E) hydrological station. The catchment area is 306 780 km^2, and most of the region is located in the Loess Plateau. With the increase of population, most forests and grasslands had been over-exploited, and the deteriorating vegetation induced severe soil erosions. Thus, immediate attention and action are required in this area.

Data

The observed monthly discharge and daily meteorological data of 1960–2000 were obtained from the Yellow River Conservancy Commission (YRCC) and China Meteorological Administration as the input parameter for the hydrological model. The land surface was classified into five types (TYPE1: Bare, TYPE2: Crop and Grassland, TYPE3: Forest, TYPE4: Irrigated area, and TYPE5: Water surface) using a high-resolution land-use map over the Yellow River domain for 2000 developed by Matsuoka *et al*. (2005). The seasonal change of leaf area index (LAI) in the vegetated areas was derived from the normalized difference vegetation index (NDVI) created from NOAA-Advanced Very High Resolution Radiometer (AVHRR) images in 2000 using the formulas of Biftu & Gan (2000). The elevation data were derived from the US Geological Survey's GTOPO-30 data set. All the data set mentioned above were interpolated into a 0.1° × 0.1° grid scale over the Yellow River basin using the method proposed by Ma *et al*. (2000). To simulate streamflow, the stream channels in a grid cell were lumped into a single channel which flows in the direction of the steepest slope among the surrounding eight grid points. To simplify flow estimates for a river network, the velocity of river flow was set as a constant (= 0.6 m s^{-1}) empirically.

Model structure

The heat and water balance in each grid cell were calculated using the SVAT-HYCY model. The model has two components: one-dimensional soil–vegetation–atmosphere transfer (SVAT) model (Ma *et al*., 1999) and runoff–formation model (HYCYMODEL) developed by Fukushima (1988). To estimate the river flow from upstream to downstream, the Muskingum method, a linear flood routing method, was used (Ma *et al*., 2003). In the present study, we modified the original SVAT-HYCY model to apply it to the middle reaches of the Yellow River basin. At first we applied the potential evaporation *Ep* defined by Xu *et al*. (2005). Then, the evapotranspiration from each vegetated surface *Evt* without soil water deficit were estimated by the formula of Kondo (1998).

$$Evt/Ep = 0.45 + 0.4\,\{1 - \exp(-1.5 \cdot \mathrm{LAI})\} \quad (1)$$

At the water surface and irrigated area during the irrigation period, the evapotranspiration rate was set as equal to *Ep*. When the *Ep* exceeded precipitation in the irrigation area, the deficit was supplied from the nearest river channel. The irrigation period (DOY: 90–300) was determined by the seasonal change patterns of NDVI. The evaporation ratio during the non-irrigated period was calculated by equation (1) assuming bare surface (LAI = 0). Finally, the actual evapotranspiration *Ea* was estimated by the following equations:

$$Ea = Evt \quad (S_t \geq S_{max}) \tag{2}$$

$$Ea = (S_t/S_{max}) \cdot Evt \quad (S_{min} < S_t < S_{max}) \tag{3}$$

$$Ea = 0 \quad (S_t \leq S_{min}) \tag{4}$$

where S_t is the total soil water content derived from $S_u + S_b$ in the HYCYMODEL. S_{max} and S_{min} are parameters to regulate *Ea*. The model parameters used in this study are summarized in Table 1. Other parameters were set the same as the original models.

Table 1 List of model parameters used in this study.

Symbol	Notation	Value	Unit
S_{max}	Constant for Ea	560.0	mm
S_{min}	Constant for Ea	450.0	mm
D50	Effective soil depth	200.0	mm
Dsig	SD of soil depth	5.0	–

RESULTS AND DISCUSSION

Impacts of the climate change

Figure 1(a) shows annual variations of the discharge observed at Sanmenxia, *Qobs*. The *Qobs* has decreased (–21.0 billion m^3) over the past 40 years. The annual precipitation *P* (Fig. 1(b)) has also decreased (–25.9 billion m^3), and the decrease was concentrated particularly in the middle reaches of the Yellow River basin (Fig. 1(d)). The annual mean air temperature T_{ave} rose in the 1990s (Fig. 1(c)), however, the rise mainly occurred in the arid northwestern areas (Fig. 1(e)). Thus, the increase of evapotranspiration with the air temperature might be restricted by the soil moisture deficit. The ratio of the *Qobs*/*P* decreased from 26.5% to 16.7% in the past 40 years. These results suggest that the available water resources in the middle reaches of the river have been significantly decreasing in this period.

Figure 2 shows the comparison between calculated *Qcal* and observed *Qobs* annual discharge at Sanmenxia. In the present study, we used a vegetation cover ratio (VCR) to evaluate the impact of long-term land-use change. The VCR is based on non-irrigated vegetation area (TYPE2: Crop and Grassland + TYPE3: Forest) in 2000. When we applied constant VCR (=100%) to all the study period, the model underestimated annual discharges (Fig. 2(a)). The following index was used to validate our model performance:

$$TWBE = (|\sum Qcal - \sum Qobs| \,/\, \sum Qobs) \cdot 100(\%) \tag{5}$$

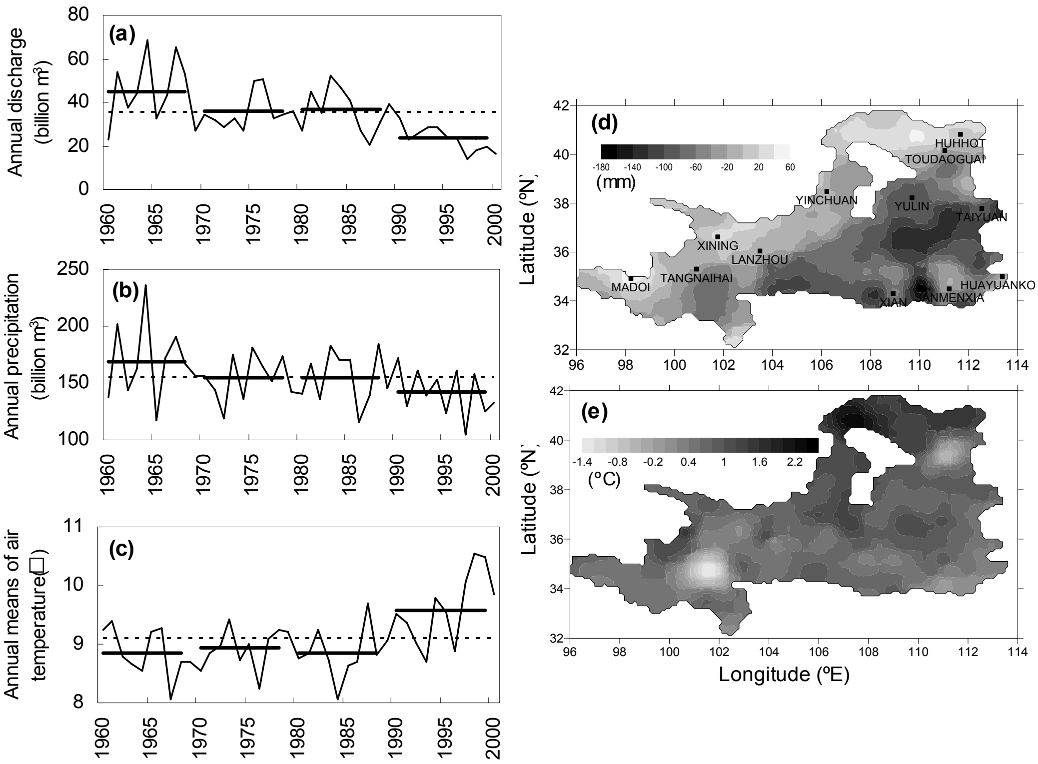

Fig. 1 Annual variations in (a) observed discharge; (b) precipitation; (c) air temperature in the middle reaches of the Yellow River basin from 1960 to 2000, and spatial distribution of change in (d) precipitation and (e) temperature between the 1960s and 1990s. The broken line and bold lines in (a)–(c) indicate the mean and 10-years average, respectively.

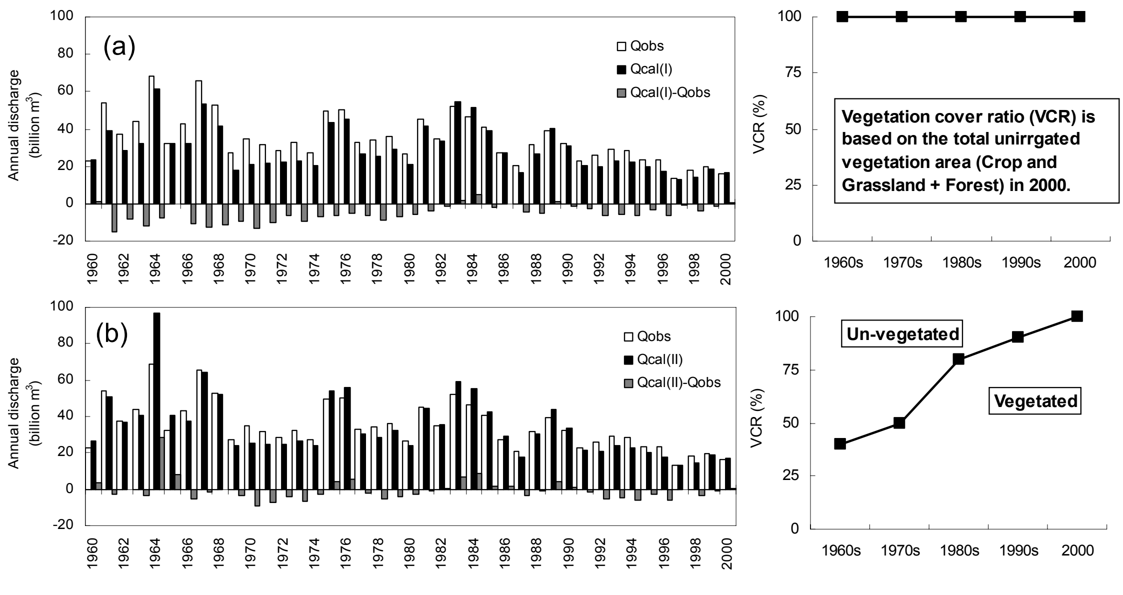

Fig. 2 Comparisons between calculated and observed discharge from the middle reaches of the Yellow River basin (Sanmenxia) from 1960 to 2000. *Qobs* is the observed discharge, *Qcal* is the calculated discharge, and *Qcal* – *Oobs* is the difference between *Qcal* and *Oobs*. *Qcal*(I) in (a) were calculated using constant vegetation cover ratio (VCR) as 100%. *Qcal*(II) in (b) were calculated using variable VCR (1960s: 40%; 1970s: 50%; 1980s: 80%; 1990s: 90%, and 2000: 100%

where *TWBE* is the annual total water balance error (Fukushima, 1988). Although, the value of *TWBE* in 2000 (= 2.4%) seemed in good agreement, it increased more than 10.6% during the period from the 1980s to the 1990s. Furthermore, it rose up to 20.9% during the period from the 1960s to the 1970s. This implies that our initial model could not simulate the long-term water balance in the middle reaches of the Yellow River basin using the same VCR which can simulate the water balance in 2000. This result also indicates that our initial model overestimated the amount of evapotranspiration during the past 40 years.

Then, to reduce evapotranspiration, we attempt to modify the parameters of soil properties (i.e. effective soil depth, infiltration ratio, water storage capacity, and wilting point). However, we could not only reduce the amount of evapotranspiration by modifying the parameters of soil properties. Then, we modified the VCR in the 1960s to 40% and gradually increased it up to 100% in 2000 by the trial-and-error method. When we applied the modified VCR, the annual water balance was reasonably in agreement with the observed data (Fig. 2(b)). The value of TWBE decreased to 3.1% (from the 1960s to the 1970s) and 5.0% (from the 1980s to the 1990s), respectively, by using modified VCR. These results suggest that the long-term water balance in the middle reaches of the Yellow River basin could be influenced by massive land-use changes in the past 40 years. The vegetation recovery by the soil and water conservation project conducted in the Loess Plateau might increase evapotranspiration loss and it could contribute to reduce the discharge in the middle reaches of the Yellow River basin. The extreme overestimation in 1964 could be influenced by an unexpected artificial reservoir operation by the Sanmenxia dam.

Long-term water balances in the middle reaches of the Yellow River basin

Figure 3 summarizes the long-term water balance in the middle reaches of the Yellow River basin. The total water supply *WS* is defined as the sum of inflow from the upstream *Qin* (observed discharge at Toudaoguai) and the amount of precipitation *P*. The *WS* was decreased (–36.8 billion m^3) in the past 40 years (Fig. 3(a)). The observed evapotranspiration *Eobs* indicated in Fig. 3(b) was derived from the water balance equation (*Eobs* = *WS* – *Qobs*) assuming no significant change in the soil moisture storage. In spite of the rise in air temperature, the *Eobs* decreased (–15.7 billion m^3) from the 1960s to the 1990s. The *Ea* estimated by the model corresponded well with the *Eobs* (Fig. 3(b)). Thus, we confirmed that the variable VCR applied in this study can be appropriate for simulating the long-term land-use change of the middle reaches of the Yellow River basin. According to Xu *et al*., (2006), a significant decrease trend in the evapotranspiration during 1960–2000 was also detected in the humid Changjiang (Yangtze River) catchment. They conclude that the decrease was mainly caused by a significant decrease in the net total radiation and wind speed over the catchment. However, from Fig. 3, we confirmed that the decrease of *Ea* in the arid middle reaches of the Yellow River basin was mainly restricted by the soil water deficit with the rapid decrease of *WS*. These results imply that the factors which regulate the amount of evapotranspiration may change with the climate (humid or arid) conditions. Finally, we analysed the long-term changes of available water resources

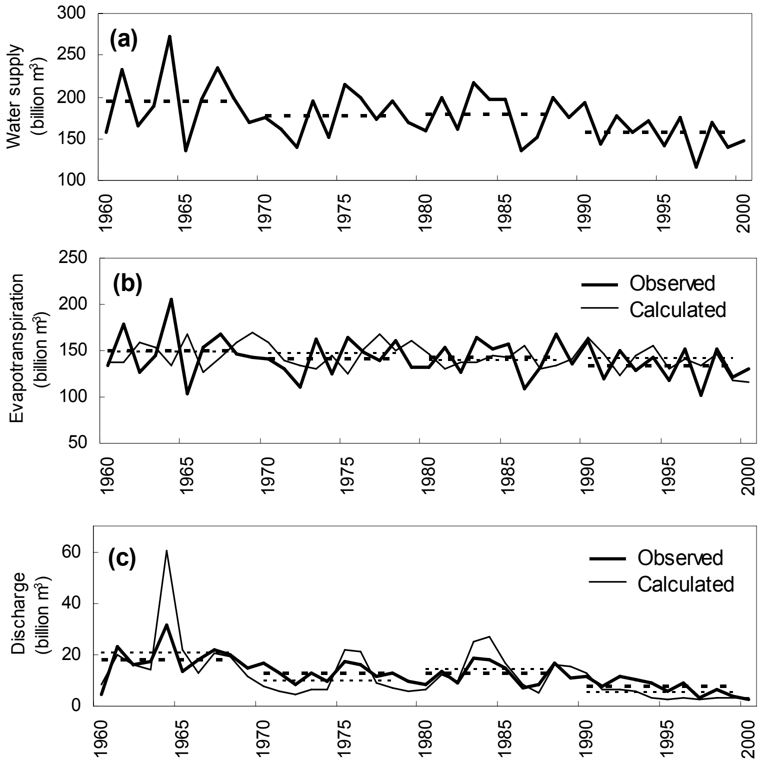

Fig. 3 Annual variations in (a) water supply, (b) evapotranspiration, and (c) discharge of the middle reaches of the Yellow River basin from 1960 to 2000. The broken lines indicate the 10-years average. The amount of water supply (*WS*) in (a) is the sum of inflow was Toudaoguai (*Qin*) and precipitation. The value of *WS* minus *Qobs* is used as observed evapotranspiration in (b). The discharge from the middle reaches in (c) is derived as *Qin* minus *Qobs*.

generated in the middle reaches of the Yellow River basin. In the present study, we defined the available water resources as the amount of tributary discharge *Qtrb* from the middle reaches of the Yellow River basin, which supplies surface water resources to the downstream. The *Qtrb* was calculated as *Qin* – *Qobs*. According to Fig. 3(c), it was found that the *Qtrb* decreased from 18.1 billion m^3 to 7.9 billion m^3 over the past 40 years and almost dried up during the recent few years.

CONCLUSIONS

The results obtained in this study are summarized in Table 2. The rapid decrease in observed river discharge *Qobs* could be caused by the decrease in precipitation *P* and inflow from the upstream *Qin*. The discrepancy between calculated and observed discharge was reduced by increasing the vegetation cover ratio (see Fig. 2). However, the evapotranspiration loss *Eobs* was decreased. It implies that the deficit of soil moisture was restricting the evapotranspiration. The available water resources *WR* in the middle reaches of the Yellow River basin have been almost depleted in recent years. This will severely affect the water shortage in the lower reaches of the Yellow River basin.

Table 2 Change of hydrological and climate factors in the middle reaches of the Yellow River basin.

	Qobs (billion m^3)	*Qin* (billion m^3)	*P* (billion m^3)	*Eobs* (billion m^3)	*VCR* (%)	*WR* (billion m^3)
1960s	44.7	26.7	168.5	150.4	40	18.1
1990s	23.7	15.7	142.7	134.7	90	7.9
Change	–21.0	–11.0	–25.8	–15.7	50	–10.2

Qobs, discharge observed at Sanmenxia; *Qin*, inflow from upstream (Toudaoguai); *P*, precipitation; *Eobs*, evapotranspiration loss (= *Qin* + *P* – *Qobs*); *VCR*, vegetation cover ratio; *WR*, available water resources (= *Qobs* – *Qin*).

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