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Examination of the water budget in upstream and midstream regions of the Yellow River, China

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Abstract:

The Yellow River, the main source of water for the North and Northwest China, showed a marked decrease in runoff during the 1990s compared to that in the 1980s. Since the basin is extensive, covering many different climatic zones with various land uses, the hydrological processes are very complex. It is necessary to develop and verify a detailed water budget in order to understand changes in the hydrological processes within the basin. In this paper, we describe a hydrological model that considers five categories of land use. The calibration and verification of the model were carried out at two independent watersheds (Tangnaihai, 120 000 km^2 and Lushi, 6400 km^2). The results from the model represent the hydrographs and annual runoffs at two gauge stations over a relatively long-term period (18 years at Tangnaihai and 21 years at Lushi). The model was applied to other watersheds of the Yellow River basin above Huayuankou station, and water budget components in each region were analysed. The results indicate only a small change in evapotranspiration, but a marked decrease in precipitation, which was significant in all of the analysed areas except the Lanzhou-Toudaoguai inter-watershed area. Water use for agricultural irrigation was stable throughout the entire simulation period. A numerical experiment of water conservation for the whole basin above Huayuankou station demonstrated that if the number of irrigation days was reduced by 20, 40 or 60%, the amount of water used could be reduced by 26·6, 52·1 or 80·7%, compared to the current situation.

KEY WORDS Yellow River basin; hydrological model; water budget; land use; water use

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INTRODUCTION

The 5464-km-long Yellow River originates in the Yuegu-zonglie basin, which lies in the north of the Bayankala Mountains on the Qinghai–Tibetan plateau. It is the second largest river in China, flowing across nine provinces and autonomous regions, as well as supplying water to about 130 million people, mostly farmers and rural residents (Campos *et al.*, 2003). The basin is located between 32–42 °N and 96–119 °E, with a drainage area of 0·752 million km^2 (Figure 1).

The Yellow River is the main source of water for the North and Northwest China. According to a report by the Yellow River Conservancy Commission (YRCC, http://www.yellowriver.gov.cn/), the annual runoff of the Yellow River measures 58 billion m^3, based on 56 years of data recorded from 1919 to 1975. This figure includes 96% of the entire river flow at Huayuankou and 56% of that at Lanzhou. Water comes chiefly from two regions, the upper reaches above Lanzhou and the middle reaches between Longmen and Sanmenxia, which together account for 75% of the flow of the entire river.

Statistical records show that the current state of water diversion and usage of the available river runoff is 39·5 billion m^3 and water consumption is 30·7 billion m^3. Agricultural irrigation is the main use, with an annual diverted water volume of 36·2 billion m^3 and consumption of 28·4 billion m^3, which accounts for 92% of the total water consumption. However, the water resources of the Yellow River have been decreasing over the last 30 years, resulting in frequent periods of no flow in the downstream region of the river between 1970 and 1999 (Yang *et al.*, 2004).

Reports have described the climatic, hydrological, and hydrochemical changes in the characteristics of the Yellow River basin based on historical data (Chen *et al.*, 2003; Liu and Zheng, 2004; Xia *et al.*, 2004). However,

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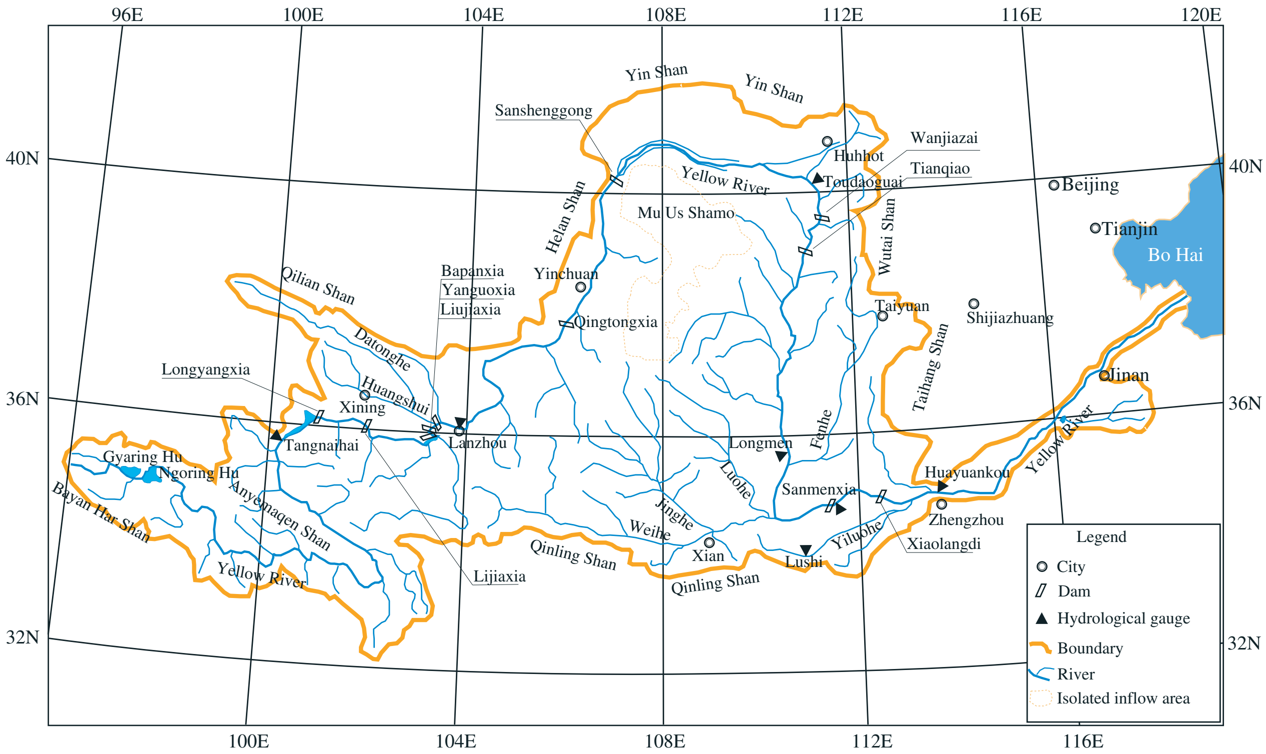

Figure 1. Map of the Yellow River basin showing the locations of cities, dams, and hydrological gauging stations

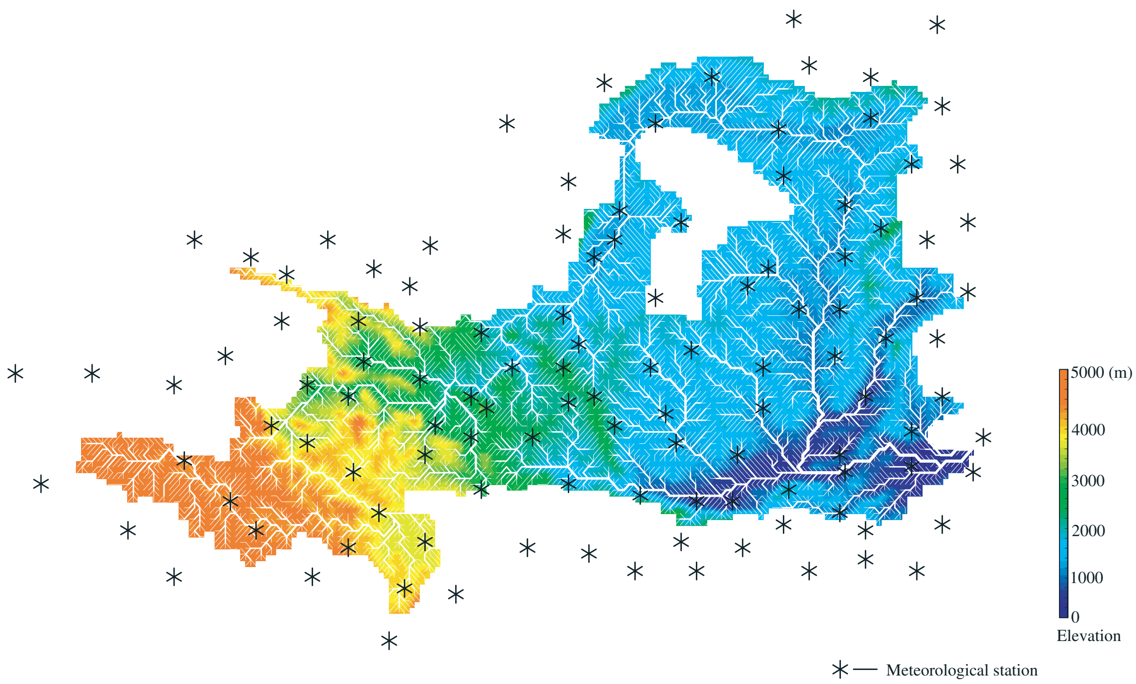

Figure 2. River network system above Huayuankou in the Yellow River basin (0·1° grid) derived from the GTOPO30 data set, and the locations of the 117 meteorological gauges used

no previous report has provided detailed analysis of the water budget of the Yellow River. For sustainable socioeconomic development in the Yellow River basin, hydrological processes including runoff generation and water use within the basin, must be understood. Here, we focus on a water budget analysis using a hydrological model system in which various types of land use in the basin, as determined from satellite-derived data, are considered. The next section provides information on the study area. Section 3 describes the data set and hydrological model used. Section 4 presents the results of the model and hydrological analyses from 1980 to 2001 for the upper and middle reaches of the river. The final section presents conclusions.

Table I. Basic information for each watershed of the Yellow River basin

Region	Area (km^2)		Annual precipitation (mm)	Main land use	Large dams and projects
	Published	Calculated			
W1	122 000	122 012	550	Grassland	No
W2	100 551	100 636	470	Grassland	5
W3	163 415	166 834	270	Shrubland	2
W4	302 455	306 775	500	Grassland	3
W5	41 616	42 575	630	Grassland	1

Watershed area as published by YRCC and calculated from this study.
W1, Tangnaihai watershed; W2, the inter-watershed area between the Tangnaihai and Lanzhou hydrological gauging stations; W3, the inter-watershed area between the Lanzhou and Toudaoguai hydrological gauging stations; W4, the inter-watershed area between the Toudaoguai and Sanmenxia hydrological gauging stations; W5, the inter-watershed area between the Sanmenxia and Huayuankou hydrological gauging stations.

STUDY AREA

The YRCC has divided the river into three reaches: the upper (above Toudaoguai gauging station), middle (from Toudaoguai to Huayuankou), and lower reaches (downstream from Huayuankou). There are many different factors, including climate, land cover, and cultivation, in each of these regions. We divided the river basin into five catchment regions above the Huayuankou station. The first catchment region is the Tangnaihai watershed, the principal source region of the Yellow River. This region is over 3000 m in altitude and has an area of approximately 122 000 km^2. The Tangnaihai watershed is largely undisturbed, with minimal anthropogenic influences. The major type of land cover is grassland, with only a small area of irrigated farmland. The area south of 34 °N is sub-humid and is the principal source of water in the region. The annual precipitation between 1980 and 2001 was approximately 550 mm.

The second catchment region is the inter-watershed area between the Tangnaihai and Lanzhou hydrological gauging stations (100 551 km^2). The measured discharge is influenced by several dam controls at the Lanzhou gauging point. There are two multipurpose dams, Longyangxia and Liujiaxia, on the main river; these provide gravity irrigation mainly along the Huangshui River between Xining and Lanzhou. Grassland is the major type of land cover, and the annual precipitation is low, ranging from 395 to 540 mm, which is indicative of a semiarid climate.

The third catchment region is a relatively flat area between the Lanzhou and Toudaoguai gauging stations (163 415 km^2). The Qingtongxia and Sanshenggong dams are located on the main river, and these major diversion points supply river water to two large irrigation districts, the Qingtongxia Irrigation District and the Hetao Irrigation District. This is an arid region, with low precipitation (270 mm on average) and high potential evaporation (2400 mm, YRCC), resulting in a very low proportion of runoff. Moreover, the total runoff is further reduced because water is taken directly from the river.

The fourth catchment region is the inter-watershed area between Toudaoguai and Sanmenxia (302 455 km^2), which belongs to the Loess Plateau area. Most of the sediment in the Yellow River comes from this region. Annual precipitation increases toward the south and is higher than in the third region, ranging from 350 to 625 mm. The Yellow River is fed by four main tributaries: the Fenhe, Luohe, Jinghe, and Weihe rivers. There are two main dams, which are located at Wanjiazai and Sanmenxia.

The fifth catchment region is the smallest, occupying the area between Sanmenxia and Huayuankou (approximately 42 000 km^2). The Xiaolangdi dam, used for sediment storage, is the dam that is located the farthest downstream on the Yellow River. The main tributary is the Yiluohe River. The average annual precipitation is 630 mm. The Lushi basin (4600 km^2), which was selected to check the performance of the model, is the regional source of the Yiluohe River and has been developed as a re-vegetation model area in China. Figure 2 shows a digital elevation map of the basin with a 0·1° grid resolution derived from the GTOPO30 data set (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html). Table I provides basic information on each watershed, and large dams and projects on the Yellow River are listed in Table II.

DATA AND METHODS

To examine recent changes in the hydrological regime of the basin, we compiled the following hydrological and

Table II. Completed dams and other projects on the Yellow River

Name	Gross reservoir capacity ($10^8 m^3$)	Operation beginning
Longyangxia	247	Sep 1987
Lijiaxia	16·5	Feb 1997
Liujiaxia	60·9	Apr 1969
Yanguoxia	2·2	Nov 1961
Bapanxia	0·49	Jan 1975
Qingtongxia	6·06	Dec 1967
Sanshenggong	0·8	Jan 1961
Wanjiazai	8·96	Nov 1998
Tianqiao	0·67	Feb 1977
Sanmenxia	162	Feb 1973
Xiaolangdi	126·5	Jan 2000

meteorological data. Monthly discharges were measured by the YRCC during the period of 1980–1997. Five gauging stations along the main river were selected: Tangnaihai, Lanzhou (where the period extended up to 2000), Toudaoguai, Sanmenxia, and Huayuankou. In addition, daily discharge data for Lushi from 1980 to 2000 were used. There are 117 meteorological stations within or nearby the study area. Routine daily data measured by the China Meteorological Administration were used for the period 1980–2001. Figure 2 shows the locations and recorded data for these stations.

Land use in the Yellow River basin (derived from Matsuoka *et al.*, 2005) was classified into 15 categories using land-surface reflectance data (250-m resolution) and snow-cover data (500-m resolution) from resolution Imaging Spectroradiometer (MODIS) and the Defense Meteorological Satellite Program human settlements product (1-km resolution) obtained in 2000. Table III provides detailed information on the land-use data. The major land cover is grassland, with the exception of region W3, and the single-crop area is limited to regions W1 and W2. Intercropping or multiple-cropping areas are widely distributed over the other regions.

Because only limited past satellite data were available, land-use changes occurring between 1980 and 2001 were not considered. In addition, the total area irrigated in the upper and middle reaches has changed little since the 1980s (Li, 2003).

The hydrological model system used was a combined model based on that of Ma *et al.* (2000). The interaction between the atmosphere and the land surface was described using a one-dimensional soil–vegetation–atmosphere transfer (SVAT) scheme. Vegetation activity was detailed on a 'big-leaf' basis, and water phase changes and temperature calculations were made for a soil layer 6-m deep. The Penman–Monteith method (Monteith, 1965) was used to describe the heat fluxes between the land surface and the atmosphere:

$$\ell E = \frac{\Delta(R_n - G) + \rho_a c_a \delta q / r_a}{\Delta + \gamma(1 + r_s/r_a)} \quad (1)$$

$$H = \frac{(R_n - G)\gamma(1 + r_s/r_a) - \rho_a c_a \delta q / r_a}{\Delta + \gamma(1 + r_s/r_a)} \quad (2)$$

where G is the heat flux into the soil or snow layer, Δ the slope of the saturated vapor pressure curve at air temperature T_a, γ the psychrometric constant, c_a the specific heat of the air, ρ_a the density of air, δq the specific humidity deficit, r_a the aerodynamic resistance, and r_s the surface resistance. The value of G was determined using the soil temperature profile, and r_a was calculated with logarithmic wind and temperature profile equations based on Monin–Obkuhov similarity theory, as follows:

$$r_a = \frac{1}{ku_*}\left[\ln\left(\frac{z_w - d}{z_{oh}}\right) - \psi_h\left(\frac{z_w - d}{L}\right)\right] \quad (3)$$

where z_w is the measurement height over the canopy, d the displacement height ($d = 0{\cdot}7\ h$, where h is the plant height), z_{oh} the roughness length for scalar variables, L the Obukhov length, k von Karman's constant, and u_* the friction velocity, estimated from the wind speed and the roughness length, as follows:

$$u_* = \frac{ku}{\left[\ln\left(\frac{z_w - d_o}{z_o}\right) - \psi_m\left(\frac{z_w - d_o}{L}\right)\right]} \quad (4)$$

where u is the wind speed at height z_w and z_o is the roughness length for momentum ($z_{oh} = 0{\cdot}1 z_o$). The terms ψ_h and ψ_m in Equation (3) and Equation (4) are the stability correction functions for scalar fluxes and momentum, respectively. These terms of ψ were set to zero (i.e. the atmosphere became neutral) as a simple assumption.

To determine r_s, Blyth and Harding (1995) reported the following simple modification of the method of Jarvis (1976):

$$r_s = r_{smin}\exp(\beta\delta q) \quad (5)$$

where r_{smin} is the minimum surface resistance and β is a constant (dimensionless number; $= 0{\cdot}046$). Ma *et al.* (1999) conducted a detailed study to fit the value of r_{smin}, and found a linear relationship between r_{smin} and the radiation dryness index (*RDI*; the ratio of the annual net radiation to precipitation for a region), and then compared the results derived from different climate regions with different vegetation communities. Accordingly, r_{smin} is given by

$$r_{smin} = \eta \cdot RDI \quad (6)$$

where η is a coefficient (dimensionless number) related to local vegetation conditions and ranges between 100 for forest and 490 for open land (Ma *et al.*, 1999).

The runoff from both surface and base flows for a grid was estimated using a runoff generation system that consisted of linear and nonlinear reservoir systems to represent the relationship of storage and outflow using the HYCY model (Fukushima, 1988). The model input was effective precipitation, which is the total amount of precipitation and snowmelt minus the evapotranspiration calculated using the SVAT model. River flow in the river network was assumed to be linear from upstream to downstream with a constant velocity (v, m/s), which ranged from 0·2 to 0·6 m/s (e.g. Wyss *et al.*, 1990; Naden, 1993; Kite *et al.*, 1994; Miller *et al.*, 1994).

Part of the model system has also been applied to the Lena River basin in Siberia (Ma *et al.*, 2000) and to the Selenge River basin in Mongolia (Ma *et al.*, 2003). The results showed that the model could be used for research on land surface hydrological processes. The model was also used in the Project for Intercomparison of Land-surface Parameterizations Phase 2(e) experiment (Bowling *et al.*, 2003; Nijssen *et al.*, 2003) where it satisfactorily simulated evapotranspiration, surface runoff, and subsurface runoff. For input, the model uses daily standard meteorological data, including air temperature (daily mean, maximum, and minimum) at 2 m above the land surface, precipitation amount, wind speed, relative humidity, air pressure, and sunshine duration.

The 15 land-cover types shown in Table III were grouped into five major categories. Group 1 represents land surfaces with scarce plant cover. Group 2 consists mainly of grassland and non-irrigated cropland. Group 3 is forest, Group 4 is irrigated farmland, and Group 5 is water bodies. The parameters used in the SVAT model were divided into five groups corresponding to the land-use categories. Surface resistance varied with changes in soil water storage, which is influenced by interannual and seasonal variation in the regional climate. Evaporation from water bodies was estimated as equal to potential evaporation using the method of Kondo (2000). Two parameters, η and v are required for the calibration of a basin. The values of several parameters related to plants, the energy budget, and soil layers were based on previous data (e.g. Kondo 1994). Table IV lists the main parameters used in the model. Figure 3 presents the model structure, flowchart of the study, and the five land-use groups considered for the Yellow River basin.

Agricultural irrigation is a very important component of the water budget of the Yellow River basin. The irrigation process in the model was designed to evaluate the volume of water used. Irrigation water use was calculated as the difference in evapotranspiration from irrigated areas between irrigation runs (i.e. G-4 in Table IV), in which evapotransipiration was calculated as potential evaporation by setting the surface resistance to zero during the irrigation period, as well as non-irrigation runs, in which evapotranspiration was controlled by soil water storage (as stated above). In general, farming above Lanzhou is suitable for cold-region single-cropping. Inter-cropping or multiple-cropping occurs in the area between Lanzhou and Huayuankou, including the Qingtongxia and Hetao irrigation districts and the sub-humid region below Toudaoguai. The period of irrigation also varies from region to region. We simplified the irrigation periods based on field investigations conducted four times along the river; the units of irrigation were days. In the region above Lanzhou, the irrigation period was set to 5 days per half-month from May to July (the 1st–5th for the first half of the month and the 16th–20th for the second half of the month) in the model. Below Lanzhou, irrigation was set to 7 days per half-month (1st–7th and 16th–22nd) from April to July and October. Irrigation in October was for winter crops.

Taking into account the complexity of the watershed, the river network of the Yellow River basin (on the basis of a 0·1°-grid elevation; Figure 2) was derived from the GTOPO30 data set. A comparison between the data reported by the YRCC for the watershed area and our calculations is presented in Table I.

A model run on a whole-basin scale was generated in two steps to save computing time. The first step was to calculate runoff on a 1°-grid using daily meteorological data as the model input. Second, runoff for each grid element was redistributed onto a 0·1°-grid (the same grid size used for the Yellow River network); the river routing

Table III. Land-use distribution in the Yellow River basin

Watershed	Land use type	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12	T-13	T-14	T-15
All basin	Area (km^2)	43 823	24 194	25 408	17 067	5 369	1 654	52 822	464	326	416 214	39 730	107 929	163	956	2724
	Percentage	5·9	3·3	3·4	2·3	0·7	0·2	7·1	0·1	0·0	56·3	5·4	14·6	0·0	0·1	0·4
W1	Area (km^2)	614	228	949	25	82	8	341	35	19	105 330	7951	4944	103	0	1 385
	Percentage	0·5	0·2	0·8	0·0	0·1	0·0	0·3	0·0	0·0	86·3	6·5	4·1	0·1	0·0	1·1
W2	Area (km^2)	2 343	2 097	4 619	1 563	824	43	380	131	118	73 797	5 742	8 283	60	129	507
	Percentage	2·3	2·1	4·6	1·6	0·8	0·0	0·4	0·1	0·1	73·3	5·7	8·2	0·1	0·1	0·5
W3	Area (km^2)	38 863	116	602	37	40	19	1 119	0	16	45 736	16 513	63 103	0	267	404
	Percentage	23·3	0·1	0·4	0·0	0·0	0·0	0·7	0·0	0·0	27·4	9·9	37·8	0·0	0·2	0·2
W4	Area (km^2)	2 001	15 228	15 896	12 112	2 928	156	39 490	291	158	176 758	9 423	31 558	0	496	287
	Percentage	0·7	5·0	5·2	3·9	1·0	0·1	12·9	0·1	0·1	57·6	3·1	10·3	0·0	0·2	0·1
W5	Area (km^2)	1	6 525	3 343	3 330	1 497	1 428	11 492	7	15	14 593	102	42	0	63	141
	Percentage	0·0	15·3	7·9	7·8	3·5	3·4	27·0	0·0	0·0	34·3	0·2	0·1	0·0	0·1	0·3

Land use classified by Matsuoka *et al.* (2005).
T-1, Barren; T-2, Croplands (including paddy); T-3, Croplands (non-paddy); T-4, Deciduous broadleaf forests; T-5, Deciduous needleleaf forests; T-6, Double cropping fields (including paddy); T-7, Double-cropping fields (non-paddy); T-8, Evergreen broadleaf forests; T-9, Evergreen needleleaf forests; T-10, Grasslands; T-11, Irrigated fields; T-12, Open shrublands; T-13, Snow and ice bodies; T-14, Urban and built-up lands; T-15, Water bodies.

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Table IV. Main parameters used

Group in the study	Land use category	Symbol	h plant height (m)	d displacement height (m)	z0 roughness length (m)
G-1	Barren	T-1	0·1	0·07	0·01
	Urban & built-up lands	T-14			
	Croplands (non-paddy)	T-3	1	0·7	0·3
G-2	Double-cropping fields (non-paddy)	T-7			
	Grasslands	T-10			
	Open shrublands	T-12			
	Deciduous broadleaf forests	T-4	10	7	1
G-3	Deciduous needleleaf forests	T-5			
	Evergreen broadleaf forests	T-8			
	Evergreen needleleaf forests	T-9			
	Croplands (including paddy)	T-2	1	0·7	0·3
G-4	Double cropping fields (including paddy)	T-6			
	Irrigated fields	T-11			
G-5	Snow and ice bodies	T-13	—	—	—
	Water bodies	T-15			

was conducted from upstream to downstream. The model run in the Lushi basin used the same 0·1°-grid in both steps because the area to be covered was small.

RESULTS AND DISCUSSION

Model calibration was conducted using the Tangnaihai watershed, in which some water control influences

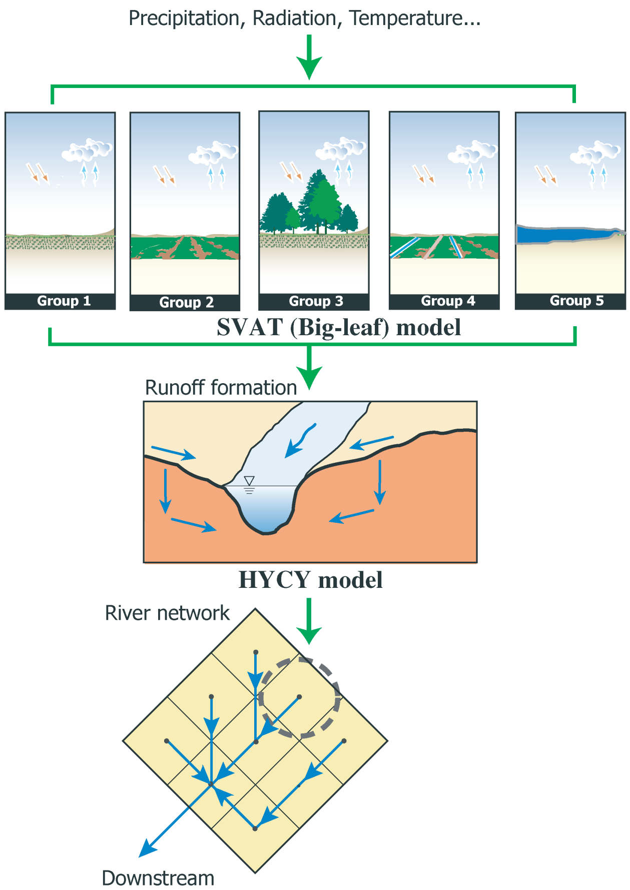

Figure 3. Structure and flowchart of the hydrological model system

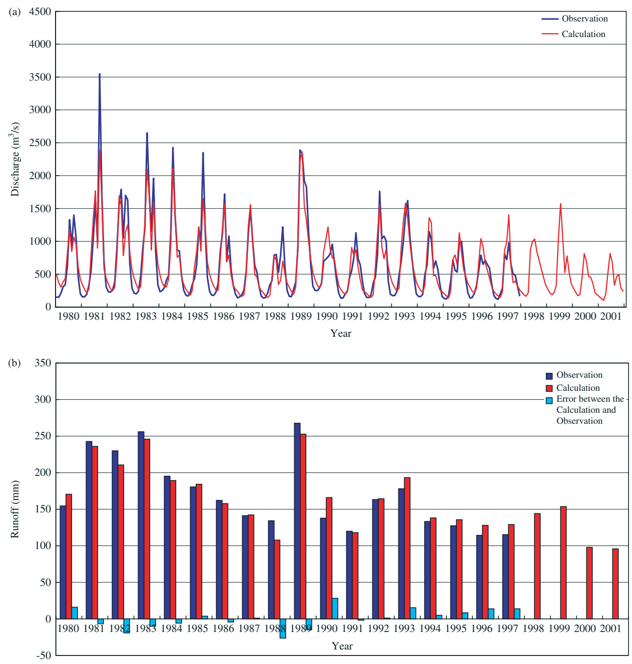

Figure 4. Monthly hydrographs (a) and annual runoff (b) at Tangnaihai for the period 1980–2001

could be omitted. Figure 4a shows a comparison of the calculated and observed monthly discharge data, and variation in the hydrograph can be presented on both an interannual and seasonal basis. The simulated maximum values roughly coincided with observed values, except for the first 6 years (1980–1985), when the model values were underestimated relative to observations from 1980 to 1997; (e.g. the measured annual runoff averaged 169·6 mm, and the calculated value was 170·5 mm during the period 1980–1997). The differences between the observed and the calculated values are shown in Figure 4b. The average error was 1·8 mm and ranged from −28·9 to +25·8 mm.

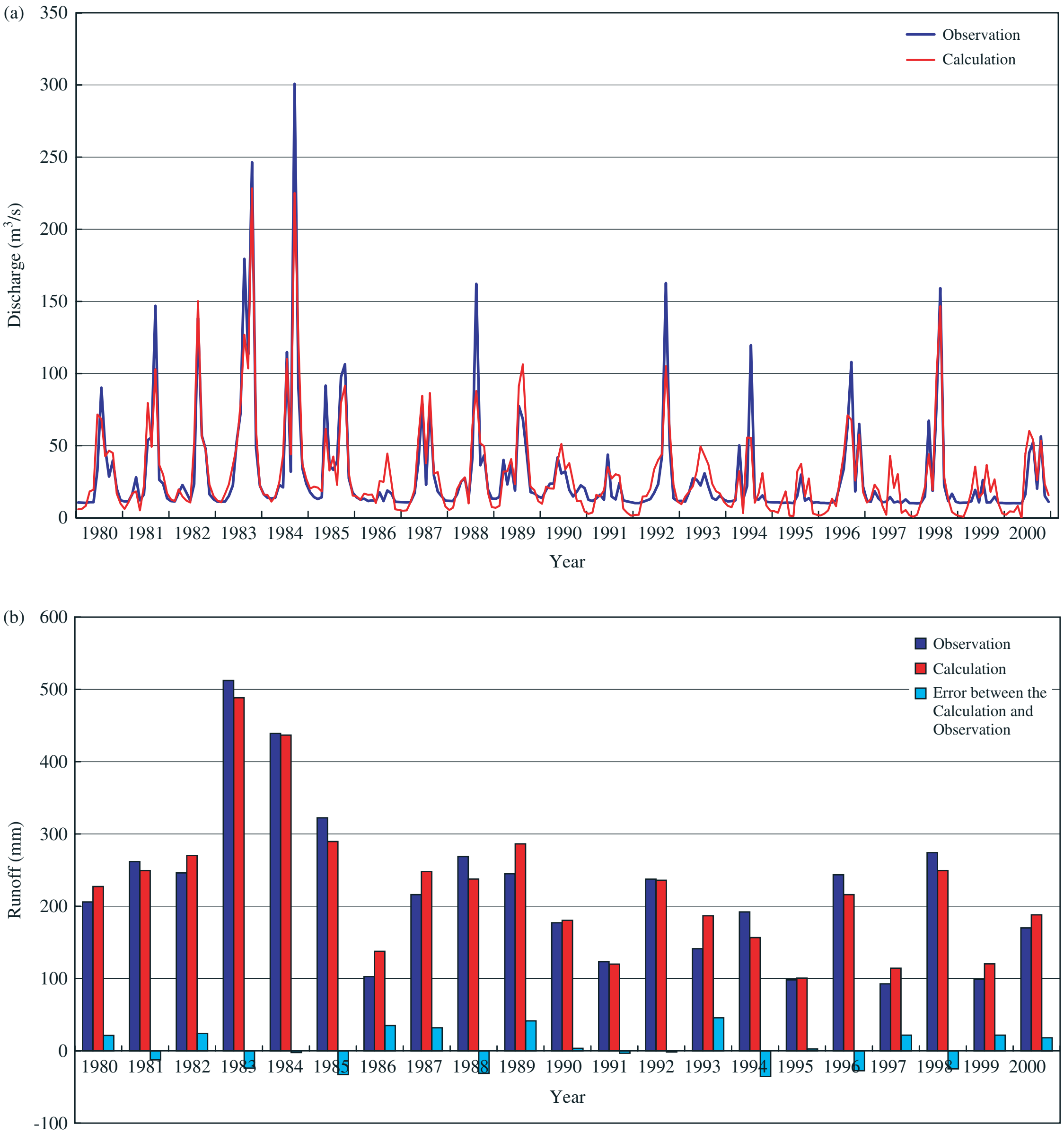

Figure 5. Monthly hydrographs (a) and annual runoff (b) at Lushi for the period 1980–2000

The model was verified using the Lushi watershed data. Daily discharge at the Lushi gauge was obtained between 1980 and 2000. Figure 5a shows the calculated hydrograph, which is very consistent with observations throughout the period. The average annual runoff at Lushi was 222·3 mm, and the error between calculated and observed values averaged 3·4 mm, with a range of −35·6 to +45·7 mm (Figure 5b).

The results indicate that the model system has sufficient accuracy for hydrological studies of the Yellow River basin. The values of η and v were fixed, with η at 135 for land-use Group 3,220 for Group 2 and Group 4, and 350 for Group 1, and v at 0·6 m/s. The results obtained from other regions are described below.

Figure 6a shows the monthly hydrographs at Lanzhou, but only up to 1986; subsequently, some external influence clearly affected the data. This may have been the Longyanxia dam, the largest capacity dam in the upper region of the Yellow River, which began operations in 1987 (Table II). In general, this reservoir retains some of the floodwater in the rainy season and then releases it during other seasons. As a result, the flood peak declined and discharge in low flow periods increased. The total runoff volume changed very little, and Figure 6b shows the calculated annual runoff compared with observations from 1980 to 2000 at Lanzhou. The calculated annual runoff adequately reproduced interannual variation, and the calculated annual average was 139·9 mm (1980–2000), an overestimation compared to the measured 133·4 mm.

Below Lanzhou, water flows into the Qintongxia and Hetao irrigation districts, and the water used for irrigation, is supplied by the Qintongxia multipurpose dam and the Sanshenggong water project. Figure 7a shows the annual runoff from 1980 to 2001 at the Toudaoguai gauging station below the two irrigation districts. The measured annual runoff decreased to 52·5 mm

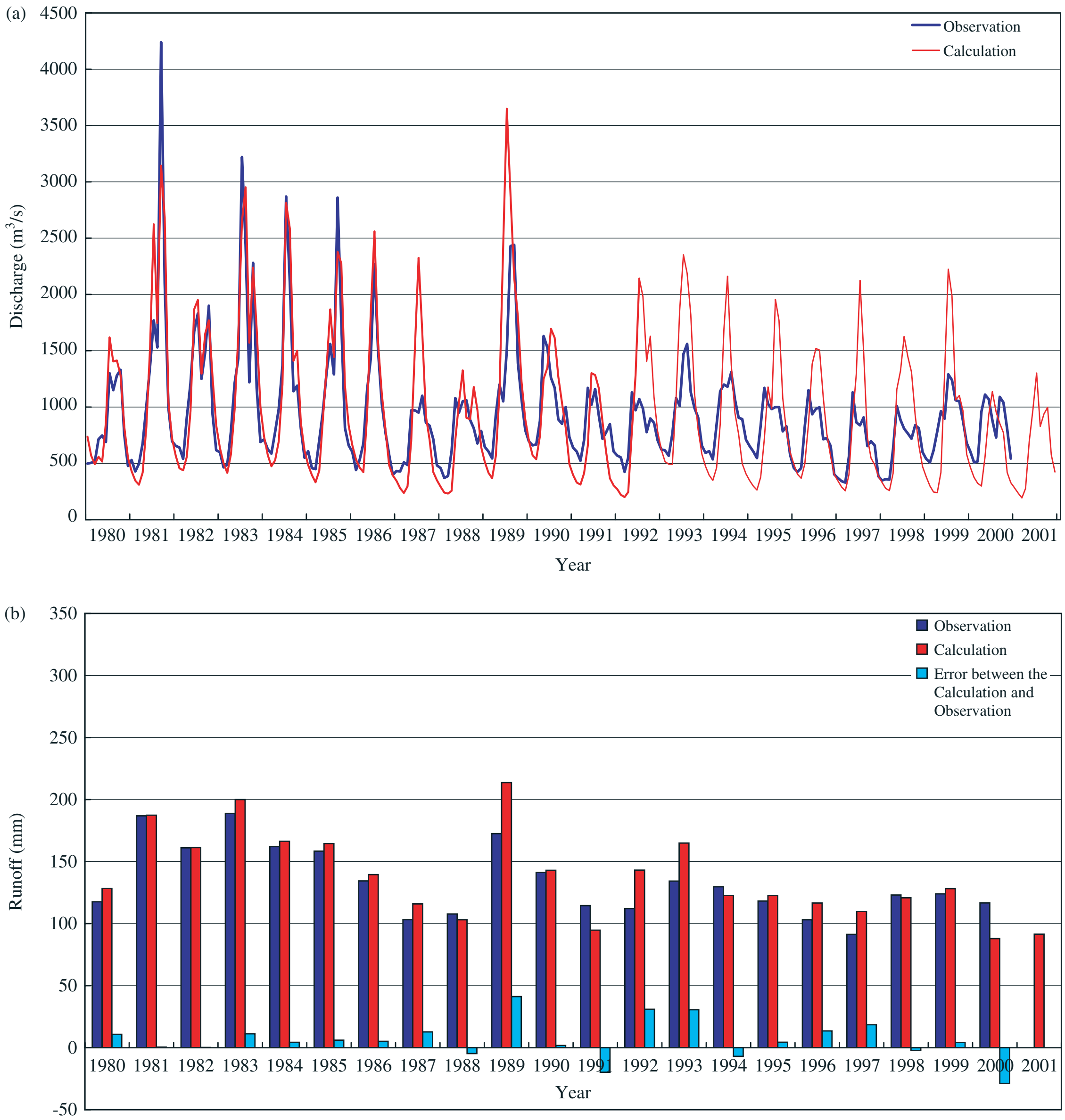

Figure 6. Monthly hydrographs (a) and annual runoff (b) at Lanzhou for the period 1980–2001

on average, and the average error between the calculated and observed values was −2·4 mm during the period 1980–1997. Model performance was also confirmed at the Sanmenxia (Figure 7b) and Huayuankou (Figure 7c) gauging stations. Table V presents the results from six hydrological gauging stations.

These results highlight that river runoff markedly decreased after the latter half of the 1980s. To determine the mechanism driving this pattern, we conducted a long-term analysis of the regional average precipitation for the period 1960–2001 (Figure 8a). The changes in precipitation differed among the five regions, and 5-year anomaly averages from 1963 to 1999 were noted for each region (Figure 8b). Since 1983, the precipitation values tended to decrease, except in the Lanzhou–Toudaoguai inter-watershed. The difference in annual average precipitation between the period 1961–1985 and 1986–2001 was 13·5 mm (a decrease of 0·6 mm/year on average from 1961 to 2001) in the Tangnaihai watershed, 29·3 mm (a decrease of 1·5 mm/year) in the Tangnaihai–Lanzhou inter-watershed, 42·4 mm (a decrease of 2·7 mm/year) in Toudaoguai–Sanmenxia, and 42·6 mm (a decrease of 2·7 mm/year) in Sanmenxia–Huayuankou. The decreases were greater in the middle reaches of the river than in the upper area.

In addition, the main components of the water budget were examined from the model output. Figure 9 shows the annual precipitation, evapotranspiration, and irrigation water use for the five regions from 1980 to 2001. Changes in precipitation and evapotranspiration occurred over this period, with precipitation noticeably decreasing, with the exception of the Lanzhou–Toudaoguai inter-watershed area. The annual mean precipitation from 1980 to 1989 was 583·1 mm in the Tangnaihai watershed, 481·9 mm in the Tangnaihai–Lanzhou inter-watershed, 525·2 mm in Toudaoguai–Sanmenxia, and 666·6 mm in Sanmenxia–Huayuankou. The corresponding values for 1990 to 2001 were 523·4, 459·8, 480·5, and 602·3 mm,

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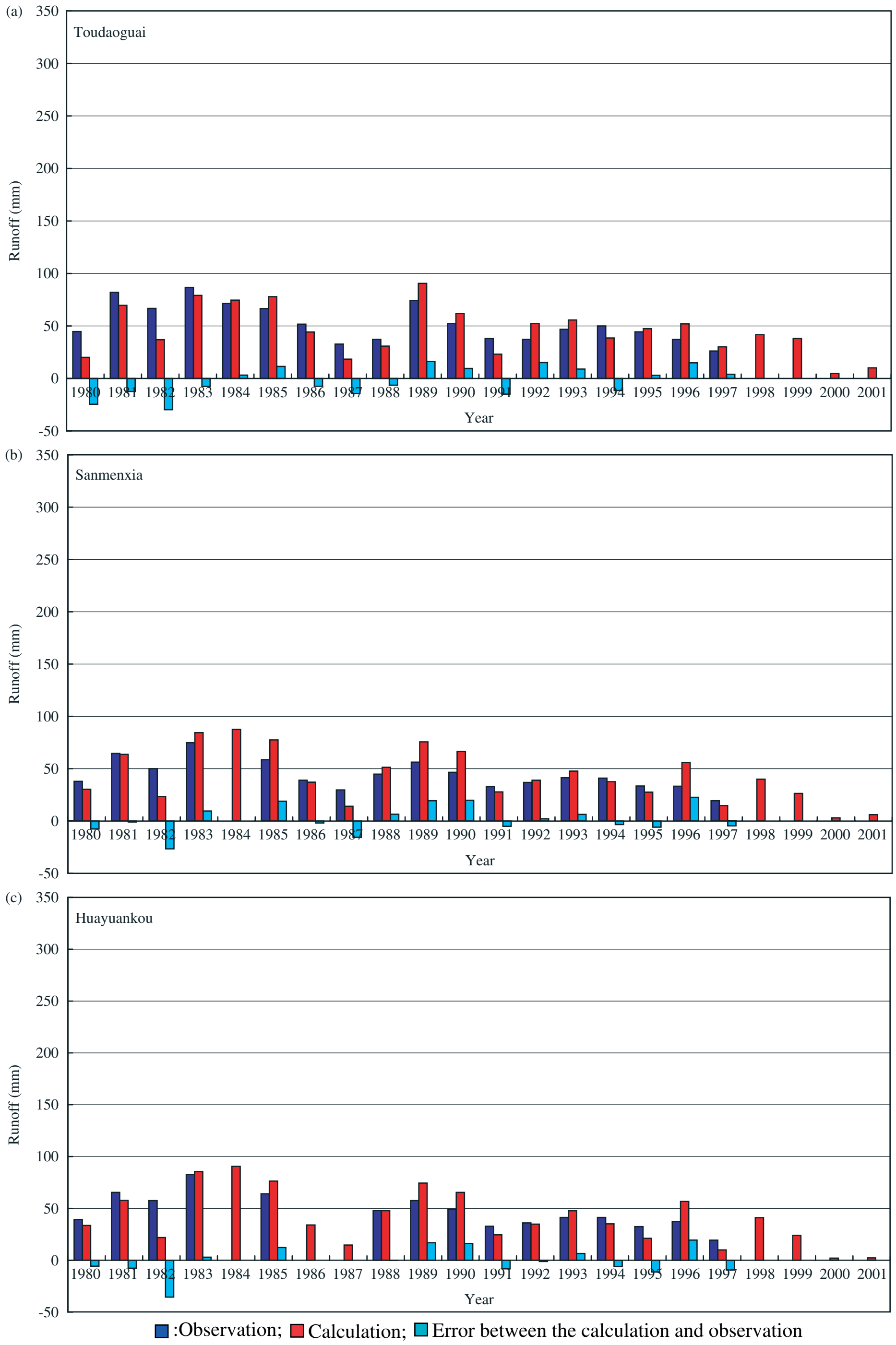

Figure 7. Comparison of observed and calculated runoff values at Toudaoguai (a), Sanmenxia (b), and Huayuankou (c) for the period 1980–2001. Data are missing for 1984 for Sanmenxia and Huayuankou and from 1986 to 1987 for Huayuankou

which amounted to differences of 59·7, 22·1, 44·7, and 64·3 mm, respectively. In contrast, changes in evapotranspiration varied across regions. For example, between the two decades, average evapotranspiration decreased by 3·4 mm in the Tangnaihai watershed, increased by 5·9 mm in Tangnaihai–Lanzhou, decreased by 21·9 mm in Toudaoguai–Sanmenxia and decreased by 36·9 mm in Sanmenxia–Huayuankou. The percentage loss (evapotranspiration to precipitation) varied from 64·9% in the first half of the period to 71·7% in the second half of the period for the Tangnaihai watershed, 73·2–78% in the Tangnaihai–Lanzhou region, 86·3–89·8% in Toudaoguai–Sanmenxia, and 89·6–93% in Sanmenxia–Huayuankou. In the Lanzhou–Toudaoguai region, the average annual evapotranspiration was 286·6 mm, which was greater than precipitation (271·2 mm). The estimated annual average water use for irrigation from 1980 to 2001 was $3{\cdot}2 \times 10^8$ m^3 in the Tangnaihai watershed, $4{\cdot}0 \times 10^8$ m^3 in the Tangnaihai–Lanzhou region, $103{\cdot}5 \times 10^8$ m^3 in Lanzhou–Toudaoguai, $74{\cdot}9 \times 10^8$ m^3 in Toudaoguai–Sanmenxia and $19{\cdot}6 \times 10^8$ m^3 in Sanmenxia–Huayuankou. The amount of water used for

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Table V. Comparison of calculated and observed values of annual runoff at six gauging stations (mm)

Name of gauge	Runoff		Error (calculation-observation)		
	Observation (1980–1997)	Calculation (1980–1997)	Average	Maximum overestimation (year)	Maximum underestimation (year)
Tangnaihai	169·6	170·5	0·9	28·2 (1990)	26·4 (1988)
Lanzhou	133·4[a]	139·7	6·4	41·2 (1989)	28·8 (2000)
Toudaoguai	52·5	50·2	−2·4	16·2 (1989)	29·8 (1982)
Sanmenxia	43·6[b]	45·6	2	16·2 (1989)	29·8 (1982)
Huayuankou	46·9[c]	46·2	−0·8	19·4 (1996)	35·6 (1982)
Lushi	222·3[a]	225·7	3·4	45·7 (1993)	35·6 (1994)

[a] Data series from 1980 to 2000.
[b] Data missing for 1984.
[c] Data missing for 1984 and 1986–1987.

Figure 8. Regional mean annual precipitation (a) from October 1960 to September 2001 and its 5-year anomaly (b) from October 1963 to September 1999 over the Yellow River basin

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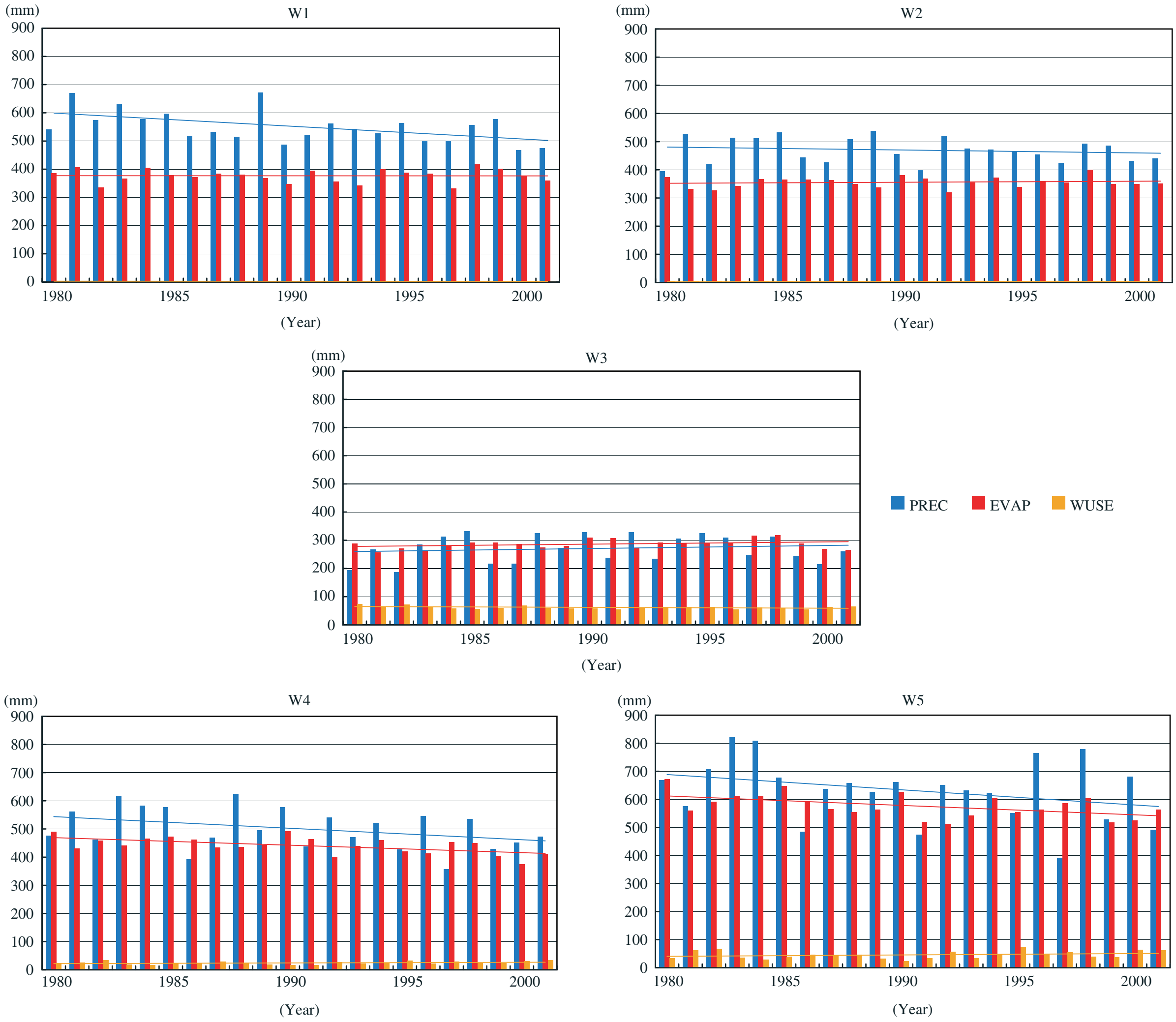

Figure 9. Interannual variation in precipitation (PREC), estimated evapotranspiration (EVAP) and water use (WUSE) in the five regions from 1980 to 2001 (bar graph). The linear regression is indicated in the same color as the bar graph

Table VI. Annual precipitation, estimated evapotranspiration and water use for each catchment region

Region	Annual precipitation (mm)				Evapotranspiration (mm)				Water use ($10^8 m^3$)		
	1980–2001	1980–1989	1990–2001	diff.	1980–2001	1980–1989	1990–2001	diff.	1980–2001	1980–1989	1990–2001
W1	550·5	583·1	523·4	59·7	376·6	378·5	375·1	3·4	3·2	3·5	3·0
W2	469·9	481·9	459·8	22·1	355·9	352·7	358·6	−5·9	4·0	4·0	3·9
W3	271·2	261·3	279·4	−18·1	286·7	279	293·1	−14·1	103·5	106·4	101·1
W4	500·9	525·2	480·5	44·7	441·3	453·3	431·4	21·9	74·9	71·7	77·5
W5	631·5	666·6	602·3	64·3	576·9	597	560·1	36·9	19·6	18·6	20·4

diff., difference in annual values between the two periods 1990–2001 and 1980–1989.

irrigation changed little from 1980 to 2001. Therefore, the main cause of reduced runoff in the Yellow River was clearly decreasing precipitation. A brief summary of the water budget for each region is shown in Table VI. The estimated water use in the Lanzhou–Toudaoguai region was close to the value of 120×10^8 m^3 reported by the YRCC for the period 1998–2004.

According to our field surveys, extensive irrigation takes place in the Yellow River basin. The irrigation system is composed of earth canals with seven grades from large to small, and flood irrigation methods are still used in most regions. The water efficiency in the canal system was reported to be <0·78 (Ren *et al.*, 2000), indicating that approximately 20% of the water taken from the river leaks from the canals. Moreover, the water use efficiency of flood irrigation in the basin is <0·5. To evaluate the possible effect of water conservation, we conducted a numerical experiment. Here, three plans

Table VII. Changes in annual water use under three water conservation plans

Region	P0	P1			P2			P3		
	Water use	Water use	Water saving		Water use	Water saving		Water use	Water saving	
	($10^8 m^3$)	($10^8 m^3$)	($10^8 m^3$)	(%)	($10^8 m^3$)	($10^8 m^3$)	(%)	($10^8 m^3$)	($10^8 m^3$)	(%)
W1	3·2	2·5	0·7	21·9	1·8	1·4	43·8	1·2	2·0	62·5
W2	4·0	3·5	0·5	12·5	3·0	1·0	25·0	2·2	1·8	45·0
W3	103·5	80·1	23·4	22·6	56·4	47·1	45·5	26·0	77·5	74·9
W4	74·9	51·5	23·4	31·2	29·7	45·2	60·3	7·9	67·0	89·5
W5	19·6	13·0	6·6	33·7	7·4	12·2	62·2	2·3	17·3	88·3
Whole basin	205·2	150·6	54·6	26·6	98·3	106·9	52·1	39·6	165·6	80·7

P0, current state in the period 1980–2001; P1, number of irrigation days decreased by 20%; P2, number of irrigation days decreased by 40%; P3, number of irrigation days decreased by 60%.

were designed with no changes in land-use in the basin. In the first plan (P1), the amount of irrigation days was reduced by 20% compared to the number of irrigation days from 1980 to 2001 (P0), decreasing the number of annual irrigation days in the model by 6 days in the region above Lanzhou and 15 days in other regions. Such a plan is feasible through strengthening of seepage controls and improved maintenance of canals. In the second plan (P2), the number of irrigation days was decreased by 40% compared to the number of irrigation days between 1980 and 2001, decreasing the number of irrigation days in the model by 12 days in the region above Lanzhou and 30 days in other regions. This second plan could be realized through the use of an efficient irrigation method (e.g. drop irrigation) instead of flood irrigation based on Plan 1. In the third plan (P3), the number of irrigation days was reduced by 60% compared to the number of irrigation days between 1980 and 2001, decreasing the number of irrigation days in the model by 18 days in the region above Lanzhou and 49 days in other regions. This plan models a potential change in crop type given the implementation of P2 in the basin.

The results indicate that the amount of water used for irrigation would be reduced by 26·6% ($54·6 \times 10^8$ m^3 in volume) to 80·7% ($165·6 \times 10^8$ m^3) compared to the current basin average (Table VII). The water-saving would be concentrated mainly in the Lanzhou–Huayuankou inter-watershed area, which accounted for 97% of the saving in each plan. In particular, water use in the Lanzhou–Toudaoguai region would be reduced by 22·6% ($23·4 \times 10^8$ m^3), 45·5% ($47·1 \times 10^8$ m^3) and 74·9% ($77·5 \times 10^8$ m^3) for the P1, P2, and P3 scenarios, respectively. The decrease in water use in the Toudaoguai–Sanmenxia inter-watershed area was similarly dramatic, at approximately 31·2% ($23·4 \times 10^8$ m^3), 60·3% ($45·2 \times 10^8$ m^3), and 89·5% ($67·0 \times 10^8$ m^3) for P1, P2, and P3, respectively. Reductions as large as those in P3 may be difficult to achieve, but the P1 and even P2 reductions should be possible.

SUMMARY AND CONCLUSIONS

The hydrological processes in the Yellow River basin are complex and include the development of agriculture and a tendency to overuse water resources. We developed a hydrological model that considered various types of land use to elucidate the composition of the water budget for the Yellow River basin. The model was calibrated and verified at two independent watersheds, Tangnaihai and Lushi, at which water controls such as large dams could be ignored. The monthly hydrograph at Tangnaihai was modeled well for the period 1980–1997, and the average error in annual runoff was 1·8 mm. The calculated hydrograph at Lushi also corresponded with observations from 1980 to 2000. The error between the calculated and observed values averaged 3·4 mm annually. The model was applied to other watersheds of the Yellow River basin, confirming the model performance. Moreover, components of the water budget in each region were analysed from 1980 to 2001, and the results demonstrated a marked decrease in precipitation. The differences in annual precipitations between the period 1980–1989 and 1990–2001 were 59·7 mm in the Tangnaihai watershed, 22·1 mm in the Tangnaihai–Lanzhou inter-watershed, 44·7 mm in Toudaoguai–Sanmenxia, and 64·3 mm in Sanmenxia–Huayuankou. A time series of land-use change was not considered in the model, and there was very little change in the amount of water used for irrigation in the period 1980–2001. Therefore, the reduction of runoff in the Yellow River was caused mainly by decreases in precipitation.

In addition, the effects of less irrigation were examined by decreasing the number of annual irrigation days under the current land-use conditions. The results indicated that the water use would decrease by 26·6% ($54·6 \times 10^8$ m^3) to 80·7% ($165·6 \times 10^8$ m^3) of the basin average. If the number of irrigation days was decreased by 20% (by 6 days in the region above Lanzhou and 15 days in other regions), the amount of water used for irrigation would be reduced by approximately 22·6% ($23·4 \times 10^8$ m^3) and 31·2% ($23·4 \times 10^8$ m^3) in the Lanzhou–Toudaoguai inter-watershed area and in the Toudaoguai–Sanmenxia area, respectively. If the

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number of irrigation days was decreased by 40% (by 12 days in the region above Lanzhou and 30 days in other regions), the amount of water used for irrigation would be reduced by approximately 45·5% ($47{\cdot}1 \times 10^8$ m^3) and 60·3% ($45{\cdot}2 \times 10^8$ m^3), respectively, in the two regions.

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