Analysis and Simulation of Human Activity Impact on Streamflow in the Huaihe River Basin with a Large-Scale Hydrologic Model

CHUANGUO YANG

State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, and International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ZHAOHUI LIN

International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ZHONGBO YU

State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China, and Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, Nevada

ZHENCHUN HAO

State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China

SHAOFENG LIU

International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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ABSTRACT

A hydrologic model coupled with a land surface model is applied to simulate the hydrologic processes in the Huaihe River basin, China. Parameters of the land surface model are interpolated from global soil and vegetation datasets. The characteristics of the basin are derived from digital elevation models (DEMs) and a national geological survey atlas using newly developed algorithms. The NCEP–NCAR reanalysis dataset and observed precipitation data are used as meteorological inputs for simulating the hydrologic processes in the basin. The coupled model is first calibrated and validated by using observed streamflow over the period of 1980–87. A long-term continuous simulation is then carried out for 1980–2003, forced with observed rainfall data. Results show that the model behavior is reasonable for flood years, whereas streamflows are sometimes overestimated for dry years since the 1990s when water withdrawal increased substantially because of the growing industrial activities and the development of water projects. Observed streamflow and water withdrawal data showed that human activities have obviously affected the surface rainfall–runoff process, especially in dry years. Two methods are proposed to study the human dimension in the hydrologic cycle. One method is to reconstruct the natural streamflow series using local volumes of withdrawals. The simulated results are more consistent with the reconstructed hydrograph than the initially observed hydrograph. The other method is to integrate a designated module into the coupled model system to represent the effect of human activities. This method can significantly improve the model performance in terms of streamflow simulation.
1. Introduction

The basic theories of hydrologic systems—for example, Darcy’s law and Horton runoff scheme—were developed on the basis of multitudinous laboratory and in situ experiments. Since the 1950s, lumped conceptual hydrologic models (e.g., Burnash et al. 1973; Zhao 1992) have been widely used for many basins. Up to the present time, such models still play important roles in the study and application of rainfall–runoff calculation, hydraulic engineering design, and basin-scale simulation and forecasting. In the last few decades, physically based distributed hydrologic models, which account for spatial heterogeneities with discretization by grids or representative elemental areas (REAs), have been used for better understanding hydrologic processes and water resource policy development (Beven and Kirkby 1979; Abbott et al. 1986; Wood et al. 1988; Yu 2000; Yu et al. 2006).

In recent years, because of issues on global changes and water resources management, research on distributed hydrologic models and their coupling with regional climate models (RCMs) and general circulation models (GCMs), needs more attention than ever (Yates 1997; Benoit et al. 2000; Nijssen et al. 2001a,b; Yu et al. 1999a,b, 2006; Cao et al. 2007). Current atmospheric models typically have a grid resolution of 25–250 km (Pietroniro and Soulis 2003). As a consequence, the variability of finer hydrologic elements is not explicitly represented in the water balance computation of the land surface models integrated in such atmospheric models. Some parameterization schemes of hydrologic processes at finescale are being introduced into land surface models to improve the description of the water cycle at land surface (Findell and Eltahir 1997; Jolley and Wheater 1997; Liang and Xie 2001; Yang and Niu 2003; Zhang et al. 2003; Koster et al. 2004; Gao et al. 2006).

However, the complicated synergetic effect of modules and simple parameterization increase the model uncertainties. Meanwhile, climate variations, human activities such as the construction of dams and sluice gates, water withdrawal for agricultural, industrial and urban needs, and land use–land cover changes (Ye et al. 2003; Isik et al. 2008) bring new challenges in the spatiotemporal variation analysis of the water cycle and distributed modeling at the basin scale (Xia and Zhang 2008). Some observed hydrologic data—for example, streamflow and water table—become less representative to natural processes as a result of such human activities. Not only must hydrologic data series be well analyzed and reconstructed, but the structure, parameterization, and calibration of hydrologic models need more support of new theories and experiments.

In this study, we apply a fine-grid hydrologic model coupled with a coarse-grid land surface model (Yu et al. 2006) to the Huaihe River basin in China to explicitly simulate terrestrial hydrology, groundwater hydrology, and river–lake–groundwater interaction. Effects of human activities on hydrologic simulations are analyzed in the simulation of recent years. Section 2 provides a description of the model setup in large-scale research regions, including model structure, model parameters, and meteorological forcing data. Section 3 describes the simulation experiment design and spinup process conducted for the Huaihe River basin and lists five model performance indices. Model calibration and validation are presented in section 4. Spatial distributions of simulated variables are also analyzed in this section. Section 5 discusses the effects of human activities on long-term hydrologic simulations and the research methods. Section 6 provides the main conclusions of this study.

2. Model and dataset

a. Model description

Using a coupling method based on predicted soil moisture and surface water depth, a fine-grid hydrologic model system (HMS; Yu 2000; Yu et al. 2006) was coupled with a coarse-grid land surface transfer scheme (LSX; Pollard and Thompson 1995; Thompson and Pollard 1997). The single-column land surface model consisting of a six-layer soil module, a two-layer vegetation module (trees and grass), and a three-layer snow module calculates the turbulent transfer of heat, moisture, and momentum in the land–atmosphere interaction for each coarse grid. Runoff, evaporation, and infiltration are disaggregated from coarse LSX grids (global T62 grid, about 1.9°) to fine hydrologic grids at each time step according to a coupling method described in Yu et al. (2006).

Major hydrologic processes are explicitly predicted with the components of HMS. The volume of groundwater in an assumed one-layer aquifer is described in the two-dimensional Boussinesq equation with Darcy’s law representing groundwater flow between the grid cells. Downward drainage as a result of gravity and upward vertical diffusion determined the equilibrium soil moisture profile in the vadose zone with a one-dimensional Richards equation (Clapp and Hornberger 1978). In each hydrologic grid cell, there existed one major river channel conceptualized with a rectangular cross section, which was characterized by bank depth and width derived from a digital elevation model (DEM) dataset. With the predicted elevation of surface water and the groundwater table, water fluxes between the river, lake, and groundwater or the vadose zone are calculated using Darcy’s law. Surface water flow, including river and lake
flow, is resolved as two-dimensional diffusion waves with eight probable orientations, and the flow velocity is parameterized with the Manning equation.

This coupled model system (LSX–HMS) has a good interface with atmospheric models and can be used to investigate various land surface and hydrology processes, and their responses to long-term global climate change and feedbacks.

b. Model parameters

The coupled model system employs a 100-km² hydrologic grid for the Asian continent (Fig. 1). Parameter datasets are constructed for both the land surface model at the global scale and the hydrologic model at the continental scale.

The U.S. Geological Survey (USGS) HYDRO1K DEM dataset (1 km × 1 km), a hydrologically consistent global coverage of topographically data sets developed from USGS 30 arc-second DEM, is used to derive the required parameters of the hydrologic model for the description of basin characteristics with a newly developed DEM algorithm (Yu et al. 2006; Yang et al. 2007) that decreased the amount of effective loss of geographical information in the DEM aggregation process. The original Lambert azimuthal projection is retained for the 100-km² grids centered at 45°N, 100°E. For existing spurious basins and drainage lines, HYDRO1K topography is calibrated with the Shuttle Radar Topography Mission (SRTM) 3° DEM dataset (Rabus et al. 2003) and natural river lines. River banks and width are determined with the DEM algorithm and some empirical relationship equations.

The China national 1:4 000 000 geologic survey dataset covering the entirety of China is gridded to the hydrologic grids using the ArcGIS software. Hydrogeologic parameters—that is, aquifer thickness (At), hydraulic conductivity (K), and porosity (P)—of the one-layer aquifer are then obtained accordingly for each lithologic type with a lookup table method. A calibration process, as described in section 4a, is conducted to refine the geologic parameters for hydrologic simulations of the Huaihe River basin (Fig. 1).

The parameters of the land surface model consist of soil texture and vegetation type. The spatial distribution and physical attribution of the vegetation types are as prescribed in Dorman and Sellers (1989). Soil textures for the upper six layers (∼4.25 m) are interpolated into global T62 grid resolution using a bilinear method from an initial global dataset of the Global Environmental and Ecological Simulation of Interactive Systems (GENESIS) GCM (Pollard and Thompson 1995).

c. Meteorological input dataset

The 6-h National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) near the land surface are the basic meteorological forcing data for the coupled model system. Observed precipitation has not been assimilated into the NCEP–NCAR reanalysis system, thus the precipitation estimates of the reanalysis data are inaccurate for some regions. To overcome this problem, daily rain gauge data from 833 meteorological stations across China for the period of 1951–2006 are gridded.

FIG. 1. Drainage basin boundaries of Asian continent and topography of the Huaihe River basin (100-km² grids). The observed streamflows at three stations—Wangjiaba, 29 844 km²; Lutaizi, 88 630 km², and Bengbu, 132 220 km²—are used to validate the coupled model.
with the method described in Milly and Dunne (2002) and Xia (2008), which accounts for the topographic effects on rainfall. For each grid cell, if three or more rain gauges exist, the value of precipitation for that cell is interpolated only with rain gauge data in the cell; otherwise, the three nearest rain gauges are chosen to estimate the grid precipitation. The weight of spatial interpolation for each rain gauge is determined by the inverse distance method using an inverse index of value 2. Because of the development of the observed station network, the maximum number of used gauges is ensured with a developed auto-searching method based on the observing period of gauges for making the best use of observed data sources (Fig. 2). The simulation of land surface processes requires the model to operate at subdaily time steps and to utilize the diurnal variation of precipitation forcing (Waichler and Wigmosta 2003). The gridded observed daily precipitation is disaggregated into hourly values according to a random statistical function.

3. Hydrologic simulation

a. Simulation experiment design

The performance of HMS was first calibrated over a 3-yr period (1980–82) and evaluated for a 4-yr period (1983–87) by comparing the simulated and observed streamflows at Wangjiaba (29 844), Lutaizi (88 630), and Bengbu (132 220 km²) in the Huaihe River basin. To evaluate the capability of HMS for long-term hydrologic modeling, a continuous simulation was conducted with the calibrated hydrogeologic parameters for the basin between 1980 and 2003. The International Satellite Land Surface Climatology Project (ISLSCP) Initiative II dataset (Hall et al. 2005) indicated that there were no obvious land use/land cover changes in the basin since the 1970s. Vegetation type and soil texture were thus kept constant for the entire simulation period.

b. Spinup process

The initial conditions of the coupled model system included the state variables for groundwater and the vadose zone, which were determined by the spinup processes described in Yu et al. (2006). With the coupled model system, a 24-yr simulation, tricycling from 1980 to 1987, was conducted for the calibration and validation period. The analysis described later is based on the most recent 8-yr simulation. In the tricycling simulation for the period 1980–2003, the same initial condition file was used, and similarly the most recent cycling provides the hydrologic simulation results in this study.

c. Performance indices

Five performance indices—water balance index (WBI), Pearson product–moment correlation coefficient (PMC), Nash–Sutcliffe coefficient of efficiency index NSI; Nash and Sutcliffe 1970), index of agreement (IOA), and a reformed normalized root-mean-square error (RNRM)—are used to evaluate how well the streamflows simulated with the coupled model system compare to the observed. The evaluation criteria are defined as

\[
WBI = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} O_i},
\]

\[
PMC = \frac{\frac{\sum_{i=1}^{N} (P_i - \bar{P})(O_i - \bar{O})}{\left[\sum_{i=1}^{N} (P_i - \bar{P})^2\right]^{0.5} \left[\sum_{i=1}^{N} (O_i - \bar{O})^2\right]^{0.5}}}{\sum_{i=1}^{N} (P_i - \bar{P})^2}
\]

\[
NSI = 1.0 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2},
\]

\[
IOA = 1.0 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left([O_i - \bar{O}] + |P_i - \bar{O}|\right)^2}
\]

\[
RNRM = 1.0 - \sqrt{\frac{1}{N} \sum_{i=1}^{N} \frac{(P_i - O_i)^2}{\bar{O}^2}}
\]

where \(P_i\) and \(O_i\) are the simulated and observed values at the \(i\)th time step, respectively; \(N\) is the total number of
samples; $\bar{P}$ and $\bar{O}$ denote the mean values of $P_i$ and $O_i$; and RNRM, which measures consistency between the simulated and observed values.

4. Calibration and validation

a. Calibration method

Three hydrogeologic parameters of HMS—that is, aquifer thickness, hydraulic conductivity, and porosity of one assumed aquifer—deserve particular attention. The first guesses of these parameters for the Huaihe River basin (as described in section 2b) are aquifer thickness, 20–1100 m; hydraulic conductivity, $10^{-3}$–$10^{-8}$ m s$^{-1}$; and porosity, 0.1–0.4. The whole Huaihe River basin consists of 2690 grids with 100-km$^2$ hydrologic grid resolution. With the given initial values, these parameters were calibrated through a set of sensitivity experiments. Four groups of experiments were designed for the model calibration with a simulation period of the three years from 1980 to 1982. The initially specified hydrogeologic parameters were used in Experiment 0 (Exp0). In Exp1, the initial aquifer thickness was multiplied by different values at each grid and the other two parameters were not changed. In Exp2, the calibrated aquifer thickness from the best case in Exp1 was used; the hydraulic conductivity was allowed to vary by a factor of 0.01 to 100 times; the porosity was remained unchanged. In Exp3, based on the best case in Exp2, porosity was calibrated similarly. The parameters used in these sensitivity experiments are summarized in Table 1.

b. Results

Streamflow is an important variable for evaluating the capability of a hydrologic model. Figure 3 shows the five performance indices derived with the simulated and observed monthly streamflow series at the Bengbu (contribution area of 132 220 km$^2$), Lutaizi (contributing area of 88 630 km$^2$), and Wangjiaba (contributing area of 29 844 km$^2$) stations in the 3-yr calibration period (1980–82). An acceptable simulation (PMC: 0.957, 0.976, 0.890; NSI: 0.819, 0.790, 0.746, for the Bengbu, Lutaizi and Wangjiaba stations, respectively) was obtained with the initial hydrogeologic parameters ($A_0$, $K_0$, and $P_0$), although a high water budget was estimated by Exp0 (Fig. 3).

Aquifer thickness is a major factor in determining the water volume of the one-layer aquifer in the model. Forced by the same precipitation input, the simulated underground water level becomes lower with a thick aquifer that has a larger water volume. Thereby, less groundwater, the main water source of low flow, flows into the river channel in the case Exp1–2 (WBI = 1.108, PMC = 0.944, NSI = 0.877, IOA = 0.963, RNRM = 0.495 for the Bengbu station) when $A_0$ was multiplied by 1.5 for each 100-km$^2$ grid. Similarly, hydraulic conductivity and porosity were calibrated with the sensitivity analysis in Exp2 and Exp3 separately. Performance indices in Fig. 3 show that better simulations were obtained with $K_0 \times 0.1$ and $P_0 \times 1.2$ in the cases Exp2–1 and Exp3–2. After these four groups of simulation experiments, the hydrologic model parameters were calibrated to be 1.5, 0.1, and 1.2 times the respective initial values.

With the calibrated parameters, PMC and NSI equal to 0.952 and 0.902, respectively, at Bengbu station in the calibration period—consisting of two flood years and one drought year—a good hydrograph process (PMC = 0.921, NSI = 0.848) was simulated at Bengbu station in

| Table 1. Values of hydrogeological parameters in sensitivity experiments for calibration in the Huaihe River basin (see section 2b). |
|---|---|---|---|
| Exp0 | $A_0$ | $K_0$ | $P_0$ |
| Exp1–1 | $A_0 \times 0.7$ | $K_0$ | $P_0$ |
| Exp1–2 | $A_0 \times 1.5$ | $K_0$ | $P_0$ |
| Exp2–1 | $A_0 \times 1.5$ | $K_0 \times 0.1$ | $P_0$ |
| Exp2–2 | $A_0 \times 1.5$ | $K_0 \times 10.0$ | $P_0$ |
| Exp3–1 | $A_0 \times 1.5$ | $K_0 \times 0.1$ | $P_0 \times 0.8$ |
| Exp3–2 | $A_0 \times 1.5$ | $K_0 \times 0.1$ | $P_0 \times 1.2$ |
the 5-yr validation period from 1983 to 1987. More details are listed in Table 2.

In Fig. 4, monthly simulated streamflow series are compared with the observed hydrographs of the three stations for both the calibration period and the validation period. Both high and low values of the simulated river flow are consistent with the observed. According to the performance indices in Table 2, we find that the accuracy of the simulation is somewhat lower for the validation period than that for the calibration period, probably because the period of 1983–87 was relatively dry. The simulated and observed daily streamflows at the Bengbu station are showed in Fig. 5. Most simulated peaks coincide well with the observed peaks (PMC = 0.899, NSI = 0.807) from 1980 to 1987, indicating that the coupled model system has the capability of continuous daily hydrologic simulation for the basin.

c. Spatial simulations

Spatial distributions of hydrologic variables at 100-km² grid resolution annually averaged for the year 1984 are shown in Fig. 6. As an important input factor of the coupled model system, precipitation reduced from >1000 mm at the southern part to <800 mm at the northeastern part (Fig. 6a). Streamflow was computed for each grid according to the routing of surface runoff and channel–groundwater flux. The simulation of river networks accounts for real spatial distribution and flow magnitude (Fig. 6b). The spatial patterns of soil moisture in Fig. 6c, the dryness in the north and southwest regions, and the wetness in the central and southeastern regions are in agreement with the distributions interpolated from gauged data (available online at http://www.cma.gov.cn/tqyb/product/QH/HLJC_OYGHC/1.html). A reasonable shallow groundwater distribution (depth <5 m) existing in the low plains areas (Fig. 6d) has been validated by the contour lines of observed groundwater depth (available online at http://sqqx.hydroinfo.gov.cn/shuiziyuan/index.aspx#).

5. Analysis of long-term simulation

a. Precipitation and simulated streamflow

The capability of the calibrated model system has been demonstrated with spatiotemporal simulations shown in section 4. Simulations in this section were conducted

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<th>Calibration period (1980–82)</th>
<th>Validation period (1983–87)</th>
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<tbody>
<tr>
<td></td>
<td>Bengbu</td>
<td>Lutaizi</td>
</tr>
<tr>
<td>WBI</td>
<td>1.046</td>
<td>1.029</td>
</tr>
<tr>
<td>PMC</td>
<td>0.952</td>
<td>0.968</td>
</tr>
<tr>
<td>NSI</td>
<td>0.902</td>
<td>0.926</td>
</tr>
<tr>
<td>IOA</td>
<td>0.972</td>
<td>0.978</td>
</tr>
<tr>
<td>RNRM</td>
<td>0.550</td>
<td>0.598</td>
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Fig. 4. Monthly simulated and observed streamflows at (a) Wangjiaba, (b) Lutaizi, and (c) Bengbu stations in the Huaihe River basin.
using the coupled model system at a 100-km² grid scale. Long-term monthly simulated and observed streamflows at the Bengbu station from 1980 to 2003 are shown in Fig. 7 together with the observed monthly mean of the observed precipitation at 12 rain gauges upstream from the Bengbu hydrologic station. The annual and seasonal variations of the simulated streamflows are generally consistent with the observations. Figure 8 presents the performance of the modeling of different periods, including the periods of 1980–89, 1990–2003, 13 wet years, and 11 dry years. Generally, an overestimation of streamflow, with a WBI value of 1.3, exists for the basin, which is mainly contributed by the results in the period of 1990–2003 (WBI: 1.5) and in dry years (WBI: 2.2). The model performed better for the simulations in the 1980s (PMC: 0.93, NSI: 0.86) and in wet years (PMC: 0.93, NSI: 0.87). Modeling dry years becomes more complicated with various uncertainties. Small fluctuations of forcing data may result in a relatively large bias of surface runoff in dry years. More surface water is used at a developed basin in dry seasons (for a discussion, see the next section).

b. Effects of human activities

According to the analysis of precipitation and streamflows shown in Fig. 9, rainfall has a slightly increasing trend in the period, whereas observed streamflow shows a remarkable decreasing trend. The model-simulated streamflow provides a hydrograph with a similar trend compared to the rainfall series. The difference between the observed and simulated streamflows cannot be negligible for the dry years after 1990.

In Huaihe River basin, the rapid development of agriculture and industry began in the 1980s. Frequent droughts and floods, such as the heavy flood in 1991, have spurred new construction of water supply and management projects and full use of the existing projects, which include more than 5700 reservoirs and 5000 sluice gates.
gates. Many kinds of surface water supply problems due to human activities are regarded as important error sources for the coupled hydrologic model simulations since the 1980s, which is confirmed by both the trend analysis of streamflow and rainfall, and the monthly observed streamflow with abnormal values in the dry years—for example, no streamflow in the wet seasons (June and July) of 2001 in Fig. 7.

The uses of surface water decrease and redistribute local surface runoff directly and thus affect the basin’s streamflow hydrographs. Figure 10 describes the variability of the water withdrawal in the upstream of the Bengbu station from 1997 to 2003, as provided by the Water Resources Bulletin of the Huaihe River basin (Huaihe River Committee 2007). A huge volume of the annually averaged 12.46 billion cubic meters of surface water was supplied for local agriculture, industry, and urban uses, equaling about 395.2 m$^3$ s$^{-1}$ of streamflow, 109.0% of the observed streamflow of the 11 dry years at the Bengbu station. Compared with the simulated streamflows, less than a quarter of the streamflows were used in the wet years with high floods and less withdrawals—for example, 1993, 2000, and 2003—as shown in Fig. 10. In dry years, more than half of the streamflows were withdrawn because of local human activities, which could have detrimental effects on river ecology and the local environment. It is thus evident that human activities play an important role in the deviation between the simulated and observed streamflows at the Bengbu station in recent years, especially in the dry years.

c. Reconstruction of natural streamflow

As described earlier, remarkably high estimations exist in the summers of the years 1997, 1999, and 2001 at the Bengbu station while there are good simulations for the wet years (Fig. 11), and the WBI equals 1.37 for the entire period. Peaks of simulated streamflows are deemed to be consistent with the real natural hydrograph, such as in the 1980s when the disturbance of human activities could be ignored. Therefore, the difference between the original observed streamflow and the simulated streamflow was used as weights of the water withdrawal to adjust the monthly observed streamflow for each year with the following equation:

$$R_{a_i} = R_{o_i} + \frac{\max(10, R_{S_i} - R_{o_i})}{\sum_{i=1}^{12} \max(10, R_{S_i} - R_{o_i})} \times \frac{WS}{(N_{d_i} \times 24 \times 3600)}$$

where $R_{a_i}$ and $R_{o_i}$ are separately adjusted and original observed streamflows of the $i$th month (m$^3$ s$^{-1}$),
respectively; $R_s$ is the simulated streamflow of the $i$th month ($m^3$ $s^{-1}$); WS is the total annual water withdrawal ($m^3$); and $N_d_i$ is the day number of the $i$th month. Some negative weights in winters were changed to be $10$ $m^3$ $s^{-1}$ in the adjusting process.

The simulated streamflows are in good agreement with the observed streamflows adjusted with the withdrawal (Fig. 11). Performance indices PMC and NSI reach high values of $0.934$ and $0.940$, increasing by $0.075$ and $0.298$ as compared to the original observed values, respectively. A better water balance is obtained with a WBI of $0.948$ when the withdrawal is included. The WBI fell below $1.0$ for the first time in this study, which indicates the probable existence of return flow in the withdrawal, for example, irrigation.

d. Simulation of human activities’ impacts

An alternative way to represent the effect of human activity is to integrate a new module in the coupled model system. In a river basin, parts of surface runoff and channel flow are usually dammed up for local industrial and agricultural water uses. Then their spatio-temporal distribution could be changed—even some sections of the main channel dried up in dry seasons. In the designed human activity module (Fig. 12), a fraction of surface runoff $R$, which is directly affected by human
activities, is dammed by a withdrawal factor $zw$ ($0 \sim 1$) and stored into a fictitious “reservoir.” Because of irrigation and industrial water use, water in the reservoir returns to the natural water cycle as input of precipitation $P$ at the next time steps. In Fig. 12, $E$ stands for evapotranspiration and $I$ for infiltration at the land surface.

Considering the complexity and artificiality of water use, the water return rate from the reservoir is determined by a constant factor $WR$ ($100 \text{ kg m}^{-2} \text{ day}^{-1}$) temporally in this study. In wet years, as indicated in the previous sections, a relatively small amount of water withdraw can meet the demands of local industry and agriculture, leaving more substantial surface runoff. Additionally, a WBI of 1.37 is larger than 1 at the Bengbu station in the original simulation. In the simulation considering human activities from 1997 to 2003, the withdrawal factor $zw$ was set as 0.2 in wet years and 0.4 in dry years.

Compared with the original simulated result, monthly streamflow simulated using the model with the human activity module is obviously smaller in dry years. The annually averaged simulated streamflow decreases by 141.1 in 1997 and 106.1 m$^3$ s$^{-1}$ in 2001. The model performance was improved for the last decade (Table 3). The results indicate that the designed module represents well the effect of human activities on the local land water cycle.

6. Conclusions

A coupled land surface and hydrology model system was set up in the Huaihe River basin for long-term continuous hydrologic simulation. In future studies, this model will be coupled with atmospheric models. Based on the physical meaning, parameters for basin characteristics and hydrogeology of finer hydrologic grids were derived from a DEM and a national geological survey.

FIG. 11. Comparisons between the simulated streamflow and the observed hydrograph adjusted with surface water withdrawal at Bengbu station.

FIG. 12. Sketch of human activity module newly introduced in the coupled model.
Table 3. Comparison of model performance indices as a result of the integration of the designed human activity module.

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<th>Original simulation</th>
<th>Simulation with human activity module</th>
<th>Improvement (%)</th>
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<tbody>
<tr>
<td>WBI</td>
<td>1.37</td>
<td>1.23</td>
<td>10.2</td>
</tr>
<tr>
<td>PMC</td>
<td>0.86</td>
<td>0.88</td>
<td>2.3</td>
</tr>
<tr>
<td>NSI</td>
<td>0.64</td>
<td>0.75</td>
<td>17.2</td>
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planning under global changes. Human activity schemes should be integrated into such coupled models.

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atlas. A gridded hourly precipitation dataset covering the whole China was developed as the input to the model, according to the observed daily precipitation data.

In view of structure complexities and intrinsic meanings of parameter for a physically based gridded hydrologic model, hydrogeologic parameters of the hydrologic model in this study were calibrated by means of sensitivity analysis. Monthly simulated streamflow have been found to be consistent with the observed hydrographs at the three stations—both in the calibration period and validation period. The simulated streamflow, soil moisture, and groundwater depth have shown reasonable spatial patterns. An autocalibration method will be developed for the coupled model based on characteristics of the parameters themselves. However, we recognize that an over calibration may conceal some of the deficiencies in model structure, parameterization schemes, and anthropocentric effects on hydrologic processes.

Hydrologic simulation and prediction are facing new challenges because of the expansion of human activities and recent climate changes, which are particularly important in long-term simulations. In this study, how to detect the effects of human activities in the Huaihe River basin has been discussed. Results show that more than half of the natural streamflow was withdrawn for human uses in recent dry years. Reconstruction of the natural streamflow series is necessary for a basin where there exists an over exploitation of water resources, especially for dry years. The reconstruction method of the natural streamflow could be improved if monthly withdrawal data are used. The study in section 5d shows that integrating a human activity module can help improve the performance of the hydrologic model in developed basins. A more physical and functional module to represent human activities is planned for the future study, for example, the water withdrawal factor zw and returning rate WR vary with soil moisture and the annual crops’ growing process. Operation records of local water conservancy projects are also planned to be assimilated into hydrologic models.

Coupling a land surface–hydrologic model is the key step to realize two-way coupling of atmospheric–hydrologic models, which are particularly useful for water resources


