Impact of human activity on streamflow in the Huaihe River Basin, China: analysis and simulation

CHUANGUO YANG[1], ZHENCHUN HAO[1], ZHONGBO YU[1], ZHAOHUI LIN[2] & SHAOFENG LIU[2]

1 *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China*
cgyang@hhu.edu.cn

2 *International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing100029, China*

Abstract A distributed hydrological model coupled with a coarse grid land surface model is set up to simulate hydrological processes in the Huaihe River Basin, China. Parameters of the land surface model are interpolated from global soil and vegetation data sets. The characteristics of the basin, including topography, river networks and aquifer geology, are derived from a digital elevation model (DEM) and a national geological survey atlas. The NCEP/NCAR re-analysis data set and observed precipitation data are used as meteorological inputs. The coupled model is firstly calibrated and validated by using observed streamflow over the period 1980–1987. A long-term continuous simulation is then carried out for 1980–2003 forced with observed rainfall data. Results indicate that streamflow is over-estimated for dry years since the 1990s when water withdrawal increased substantially due to the growing industrial activities and the development of water projects. Two methods are proposed to study the human dimension in the hydrological cycle. One is to reconstruct the natural streamflow series using local volumes of withdrawals. The simulated results are consistent with the reconstructed hydrographs. The other method is to integrate a designed modular into the coupled model to represent the impact of human activities. This method can significantly improve the model's performance in streamflow simulation. This study shows that the coupling of hydrological and atmospheric models is a powerful tool for studying the human impact on the hydrological cycle.

Key words streamflow; human activity; hydrology model; withdrawal; Huaihe River, China

INTRODUCTION

Hydrology models and land surface models have been used to study the terrestrial water cycles. The basic theories of hydrological systems were developed on the basis of numerous laboratory and *in situ* experiments before the 1950s and 1960s. Thereafter, lumped conceptual hydrological models have been widely used in various climate regions (e.g. Zhao, 1992). In the last few decades, distributed hydrological models, which account for spatial heterogeneities with discretization by grids or representative elemental areas (REA), have been used for better understanding of hydrological processes and water resource policy development (Beven & Kirkby, 1979; Abbott *et al*., 1986; Wood *et al*., 1988; Yu *et al*., 2006). Few of the lumped models and distributed models integrate the human activity dimension. Research on large-scale distributed hydrological models and its coupling with meso-scale meteorological models and global circulation models (GCMs), are attracting more attention than ever (Benoit *et al.*, 2000; Nijssen *et al.*, 2001; Yu *et al.*, 2006). Some parameterization schemes of hydrological processes at fine scales are being introduced into land surface models to improve water flux description (Yang & Niu, 2003; Koster *et al*., 2004).

The human dimension in the hydrological cycle has two major aspects: land-use/land-cover change (LUCC) and direct withdrawals activities (e.g. dams, pumping wells). Globally, large reservoirs have a total storage capacity of 7000 km^3 (ICOLD, 1998), which accounts for three times the annual average water storage in river channels, or one-sixth of the global annual river discharge (Hanasaki *et al*., 2006). This raises the question about how water withdrawals due to human activities alter streamflow in river channels. Human activities such as construction of dams and sluice gates, water withdrawal for agricultural, industrial and urban needs, and land-use/land-cover changes (Isik *et al*., 2008; Yang *et al*., 2008) bring new challenges in the spatio-temporal variation analysis of the water cycle and distributed modelling at the basin scale. Some observed hydrological data, e.g. streamflow and groundwater level, become less representative of natural processes due to such human activities. Not only must hydrological data series be well analysed and reconstructed, but also the structure, parameterization and calibration of hydrological models needs more support from new theories and experiments.

In this study, a fine-grid hydrological model coupled with a coarse-grid land surface model is used to study the impacts of human activity on streamflows in recent years. First, the model structure, parameters, forcing data, and calibration are described. Then the impact of human activity on streamflow is discussed using a long-term continuous simulation. Finally methods of studying human activity impacts are proposed.

MODEL AND CALIBRATION

Model descriptions

A coupled coarse land surface model and finer-grid hydrological model (LSX-HMS) (Yu *et al.*, 2006) was used in this study. The single column land surface model (LSX) consists of a six-layer soil module, a two-layer vegetation module (trees and grass) and a three-layer snow module. River/lake and groundwater are explicitly predicted with the components of HMS. The volume of groundwater in an assumed single-layer aquifer is described in the two-dimensional (2-D) Boussinesq equation with Darcy's law representing groundwater flow between grid cells. In each hydrological grid cell, there exists one major river channel conceptualized with a rectangular cross-section. Surface water flow, including river and lake flow, is resolved as 2-D diffusion waves with eight probable orientations, and the flow velocity is parameterized with the Manning equation. 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.

Parameters and forcing data

The LSX-HMS has been used in the Asia continent (Yang *et al.*, 2010). The parameters of the land surface model include soil texture and vegetation type. The spatial distribution and physical attribution of vegetation types are as prescribed in Dorman & Sellers (1989). Soil textures for the upper six layers (~4.25 m) are interpolated into global T62 (~1.9°) grid resolution using a bilinear method from an initial global data set. The coupled model system employs 10 × 10 km hydrological grids. The USGS HYDRO1K DEM data set (1 × 1 km) is used to derive the parameters of the hydrological model required for the description of basin characteristics with a newly developed DEM algorithm. River banks and width are determined with the DEM algorithm and some empirical relationships. The China national 1:4 000 000 geological survey data set is gridded to the hydrological grids using ArcGIS software. Hydrogeological parameters of the single-layer aquifer are then obtained for each lithological type with a look-up table method.

The 6-hour NCEP/NCAR re-analysis data are the basic meteorological forcing data for the coupled model system. Daily precipitation gauge data from 833 meteorological stations across China for the period 1951–2006 are gridded with a revised method described by Xia (2008) which accounts for the topographic effects on rainfall. The gridded observed daily precipitation is disaggregated into hourly values according to a random statistical function.

Model calibration

The model was calibrated over a three-year period (1980–1982) and validated for a five-year period (1983–1987) by comparing the simulated and observed streamflows at Wangjiaba (drainage area of 29 844 km^2), Lutaizi (88 630 km^2) and Bengbu (132 220 km^2) in the Huaihe River basin. Three hydrogeological parameters, i.e. aquifer thickness, hydraulic conductivity and porosity of one assumed aquifer were calibrated by a set of sensitivity analysis experiments (Yang *et al.*, 2010). Monthly simulated streamflow series are compared with the observed hydrographs of the three stations in both the calibration period and validation period in Fig. 1. Both high and low values of the simulated river flow are consistent with the observed values. For the monthly

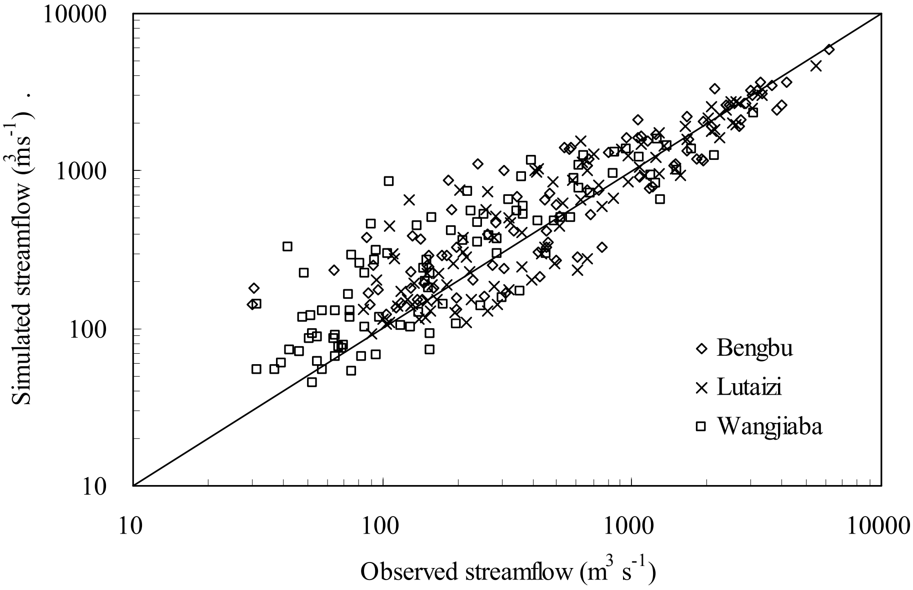

Fig. 1 Monthly streamflow at the Bengbu, Lutaizi and Wangjiaba stations from 1980 to 1987: the observed *versus* the simulated.

streamflow series, water balance index (WBI), Pearson's product moment correlation coefficient (PMC) and the Nash-Sutcliffe coefficient of efficiency (NSI) are 1.046, 0.952 and 0.902 at the Bengbu Station, respectively, 1.029, 0.968 and 0.926 at Lutaizi Station, and 1.048, 0.910 and 0.817 at Wangjiaba Station in the calibration period. For the validation period, WBI, PMC and NSI are 1.026, 0.921 and 0.848 at Bengbu Station, 1.020, 0.922 and 0.849 at Lutaizi Station, and 1.082, 0.845 and 0.640 at Wangjiaba Station, respectively.

Snow simulation

The basin has an average temperature of 14.9°C, with a trend of temperature increase at a rate of 0.23°C per ten years since 1951. Flat plain accounts for 2/3 of the basin area. There exist small volumes of snow mainly in the winter season, i.e. December, January and February, and there was no snow coverage from May to October (Fig. 2). The maximum of daily average snow depth is 0.8 mm from 1980 to 1987. Due to the Asian monsoon climate characteristics, floods occur in the wet season of July, August and September. The contribution of snow melt is limited to river flows of the basin.

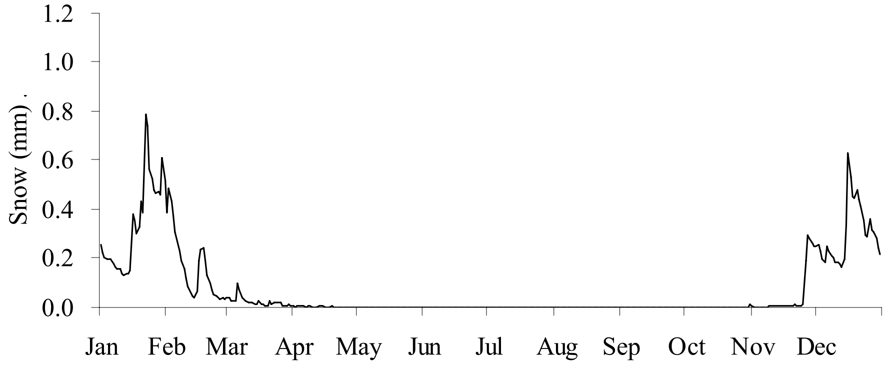

Fig. 2 Daily snow depth in the basin, average from 1980 to 1987.

ANALYSIS OF HUMAN ACTIVITY IMPACT

Comparison with the observed streamflow

In the Huaihe River Basin, agriculture and industry have developed rapidly since the 1980s. Frequent droughts and floods spurred on the new construction of water supply and management projects, and the full use of the existing projects, including more than 5700 reservoirs and 5000 sluice gates. A long-term continuous simulation from 1980 to 2003 was conducted with the coupled model system forced by the gauged rainfall data. Long-term monthly simulated and observed streamflows at the Bengbu Station are compared in Fig. 3. The annual and seasonal variations of the simulated streamflows are generally consistent with the observations. However, there is a remarkably high estimation for the low flows in dry seasons and dry years. The intercept of the fitting linear line is 362.77 $m^3 s^{-1}$.

Results for different periods, including the periods of 1980–1989, 1990–2003, 13 wet years and 11 dry years, indicate that the model has a good performance in the 1980s and in the wet years, and high estimates of streamflows in the years (1990–2003) and in the dry years (Yang *et al.*, 2010). Modelling of the dry years becomes more complicated due to various uncertainties. Small fluctuations of the forcing data may result in a relatively large bias of surface runoff in dry years; meanwhile more surface water is used at the developed basin in the dry seasons.

Trend analysis

Surface water supplies and changes due to human activities are regarded as important error sources for the coupled hydrological 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, e.g. no streamflow in wet seasons (June and July) of 2001. According to the analysis of precipitation and streamflows (Yang *et al.*, 2010), rainfall has a slightly increasing trend in the period, while 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 can not be negligible for the dry years after 1990.

Surface water withdrawals

The uses of surface water decrease and redistribute local surface runoff directly, and thus affect the basin's streamflow hydrographs. Table 1 gives the annual volumes of surface water withdrawal

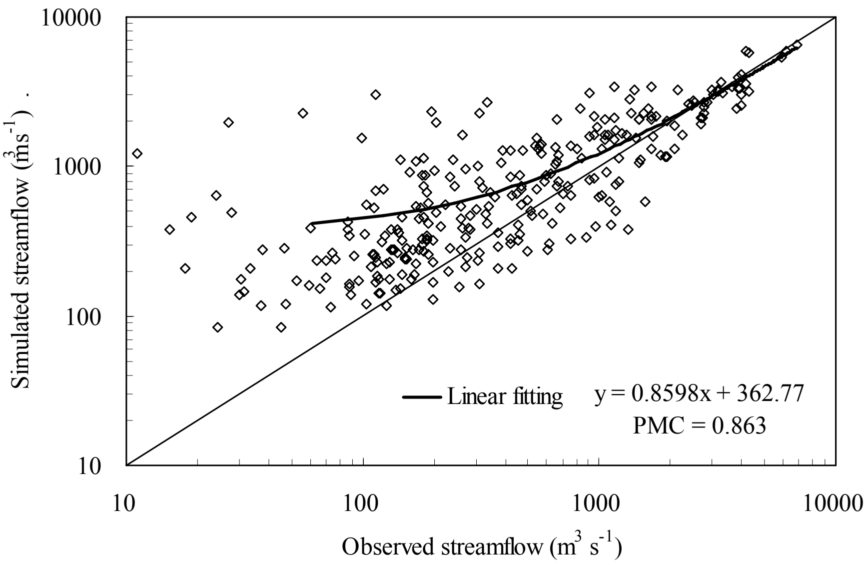

Fig. 3 Monthly observed and simulated streamflows at the Bengbu Station from 1980 to 2003.

Table 1 Annual surface water withdraws in the upstream of Bengbu Station and its percentage of simulated streamflows.

Year	1997	1998	1999	2000	2001	2002	2003
Withdraws ($\times 10^9$ m^3)	14.81	11.87	13.75	11.26	14.16	12.54	9.96
Percentage of simulated streamflow (%)	55.09	24.35	54.75	23.88	64.61	43.25	16.96

upstream of Bengbu station from 1997 to 2003, provided by the Water Resources Bulletin of the Huaihe River Basin (Huaihe River Committee, China). A huge volume of surface water, annual average 12.46×10^9 m^3, was supplied for local agriculture, industry and urban uses, i.e. about 395.2 m^3 s^{-1} of streamflow, or 109.0% of the observed streamflow of the 11 dry years at Bengbu station. Comparing with the simulated streamflow indicates that more than half of the streamflow was withdrawn due to local human activities in the dry years, which could have detrimental effects on the river ecology and the local environment. Human activities play an important role in the deviation between the simulated and observed streamflows in recent years, especially in the dry years.

STUDY METHODS OF HUMAN ACTIVITY IMPACTS

Reconstruction of natural streamflow

According to the above analysis, surface water withdrawals account for high percentages of the streamflows in the Huaihe River Basin. Therefore, it is necessary to reconstruct the natural streamflow with the information on water withdrawals. In this study, the difference between the observed streamflow and the simulated value was used as weights of the annual water withdrawal to adjust the monthly observed streamflow for each year. Some negative weights in winters were changed to be a small weight of 10 m^3 s^{-1} in the adjusting process. The simulated streamflows are in good agreement with the observed streamflows adjusted for the withdrawal. Performance indices PMC and NSI reach high values of 0.934 and 0.940, increasing by 0.075 and 0.298 compared to the original observed values, respectively. A better water balance is obtained with a WBI of 0.948 when the withdrawal is included. WBI fell below 1.0 for the first time in this study, which indicates the probable existence of return flow from the withdrawals.

Simulation of human activity impact

The other method to study the impacts of human activity is to integrate a new module into the coupled model. In the new module (Fig. 4), a fraction of surface runoff (*R*) which is directly affected by human activities is dammed by a withdrawal factor *zw* (0~1), and stored in a fictitious "reservoir". Due to irrigation and industrial water use, water in the reservoir returns to the natural water cycle with a rate of *WR* at the next time step. In Fig. 4, *E* stands for evapotranspiration, and *I*

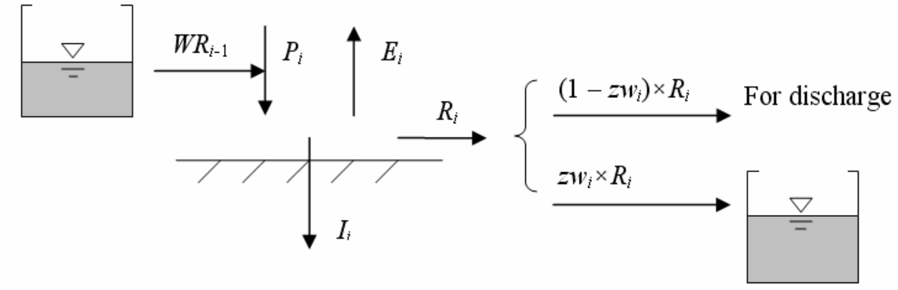

Fig. 4 Sketch of the human activity module newly introduced into the coupled model.

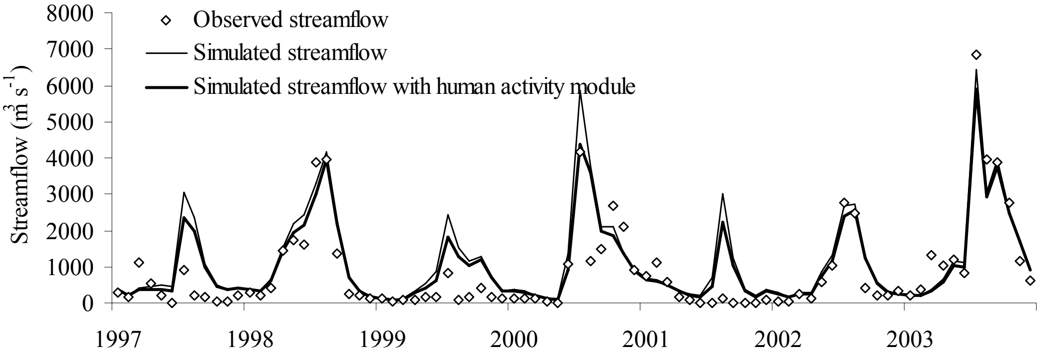

Fig. 5 Monthly observed and simulated streamflows at Bengbu Station from 1980 to 2003.

for infiltration at the land surface. In this study, *WR* has a constant value of 100 kg m^{-2} d^{-1} and *zw* is set as 0.2 in wet years and 0.4 in dry years according to the percentage of surface water withdrawal accounted for using the simulated streamflow, as shown in Table 1.

Compared with the original simulated result, monthly streamflow simulated using the model with the human activity module is obviously smaller in dry years. The annual average of simulated streamflow decreases by 141.1 m^3 s^{-1} in 1997 and 106.1 m^3 s^{-1} in 2001. The model performance was improved for the last decade (Fig. 5). The results indicate that the designed module represents well the effect of human activities on the local land water cycle.

CONCLUSIONS

Hydrological simulation and prediction are facing new challenges due to the expansion of human activities and recent climate change, and are particularly important in long-term simulations. In this study, how to detect the impacts of human activities in Huaihe River Basin was discussed. Results show that more than half of natural streamflow was withdrawn for human use in recent dry years. Reconstruction of the natural streamflow series is necessary for a basin with over-exploitation of water resources, especially for the dry years. The reconstruction method used for streamflow could be improved if monthly withdrawal data are used. Integrating a human activity module can help to improve the performance of the hydrological model in the basin. A more physical and functional module to represent human activities is planned for future study, for example, the water withdrawal factor *zw* and the return rate *WR* vary with soil moisture and annual crop growth stage. It is also planned to assimilate operation records of local water conservancy projects into hydrological models.

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REFERENCES

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E. & Rasmussen, J. (1986) An introduction to European hydrological system – systeme hydrologique Europeen (SHE) Part 1. History and philosophy of physically based distributed modeling system. *J. Hydrol.* **87**, 45–59.

Benoit, R., Pellerin, P., Kouwen, N., Ritchie, H., Donaldson, N., Joe, P. & Soulis, E. D. (2000) Toward the use of coupled atmospheric and hydrologic models at regional scale. *Mon. Weather Rev.* **128**, 1681–1706.

Beven, K. & Kirkby, M. J. (1979) A physically based, variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.* **24**, 43–69.

Hanasaki, N., Kanae, S. & Oki, T. (2006) A reservoir operation scheme for global river routing models. *J. Hydrol.* **327**, 22–41.

Huaihe River Committee, Ministry of Water Resources, China. *Water Resources Bulletin of the Huaihe River Basin* (1997–2003). http://www.hrc.gov.cn/.

ICOLD (1998) *World Register of Dams*. International Commission on Large Dams, Paris, France.

Isik, S., Dogan, E., Kalin, L., Sasal, M. & Agiralioglu, N. (2008) Effects of anthropogenic activities on the lower Sakarya River. *Catena* **75**, 172–181.

Koster, R., *et al.* (2004) Regions of strong coupling between soil moisture and precipitation. *Science* **305**, 1138–1140.

Nijssen, B., O'Donnell, G. M., Hamlet, A. F. & Lettenmaier, D. P. (2001) Hydrological sensitivity of global rivers to climate change. *Climatic Change* **50**, 143–175.

Wood, E. F., Sivapalan, M., Beven, K. J. & Band, L. E. (1988) Effects of spatial variability and scale with implications to hydrologic modeling. *J. Hydrol.* **102**, 29–47.

Xia, Y. (2008) Adjustment of global precipitation data for orographic effects using observed annual streamflow and the LaD model. *J. Geophys. Res.* **113**, D04106, doi: 10.1029/2007JD008545.

Yang, C., Lin, Z., Yu, Z., Hao, Z. & Liu, S. (2010) Analysis and simulation of human activity impact on streamflow in the Huaihe River Basin with a large-scale hydrology model. *J. Hydromet.* **11**(3), 810–821.

Yang, T., Zhang, Q., Chen, Y.D., Tao, X., Xu, C. & Chen, X. (2008) A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. *Hydrol. Processes* **22**, 3829–3843.

Yang, Z. & Niu, G. (2003) The versatile integrator of surface and atmosphere process. Part 1. Model description. *Global Planet. Change* **38**, 175–189.

Yu, Z., Pollard, D. & Cheng, L. (2006) On continental-scale hydrologic simulations with a coupled hydrologic model. *J. Hydrol.* **331**, 110–124.

Zhao, R. (1992) The Xinanjiang model applied in China. *J. Hydrol.* **135**, 371–381.