Simulation of Dualistic Hydrological Processes Affected by Intensive Human Activities Based on Distributed Hydrological Model

Zuhao Zhou[a], Yangwen Jia[b], Yaqin Qiu[c], Jiajia Liu[d*], Hao Wang[e], Chong-Yu Xu[f], Jia Li[g], Lin Liu[h]

Abstract: Affected by intensive human activities, the basin hydrologic system shows characteristics of a dualistic structure. Thus, when simulating the hydrological processes, it needs to consider the social water cycle system to get a more accurate result. In this study, a dualistic water cycle simulation system is promoted to simulate the hydrological processes affected by intensive human activities, which comprise of

---

[*] Corresponding author: Tel: +86-15910461844; Fax: +86-10-68785610; Email: vaver@foxmail.com

[a] Z. Zhou, professor, doctor; (1) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (2) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No1, Yuyantan Road, Haidian District, Beijing, China

[b] Y. Jia, professor, doctor; (1) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (2) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No1, Yuyantan Road, Haidian District, Beijing, China

[c] Y. Qiu, professor, doctor; (1) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (2) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No1, Yuyantan Road, Haidian District, Beijing, China

[d] J. Liu, doctor; (1) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (2) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No1, Yuyantan Road, Haidian District, Beijing, China

[e] H. Wang, professor, doctor; (1) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (2) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No1, Yuyantan Road, Haidian District, Beijing, China

[f] C. Xu, professor, doctor; (1) Department of Geosciences Hydrology, University of Oslo, Norway. Address: Sem Saelands vei 1, P O Box 1047 Blindern, N-0316 Oslo, Norway

[g] J. Li, doctor; (1) Bureau of South to North Water Transfer of Planning, Designing and Management, Ministry of Water Resources; (2) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (3) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No3, Yuyantan Road, Haidian District, Beijing, China

[h] L. Liu, doctor; (1) China Construction Water Affairs Environmental Protection CO.，LTD; (2) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research; (3) Engineering and Technology Research Center for Water Resources and Hydroecology of the Ministry of Water Resources. Address: No 13, Hangfeng Rd., Fengtai District, Beijing, China.

natural water cycle system and social water cycle system. The social water cycle system includes the agricultural water cycle system, industrial water cycle system, domestic water cycle system, and cross-regional allocation system. As part of the dualistic water cycle simulation system, an integrated dualistic hydrological model is developed, which couples distributed hydrological simulation module with water resource allocation module. The integrated modeling approach is applied to the Haihe River basin. The results show that the model performance can be improved when considering coupled simulation of natural and social water cycle systems. This model can also be used to investigate the evolutionary relationships among the natural and social water cycle systems in the study region, and to assess the regional water resources in other basins affected by intensive human activities.

Keywords: Dualistic water cycle; distributed hydrological model; intensive human activities; WEP-L model; social water cycle; Haihe River basin;

1 Introduction

The scientific research of water resources, hydrology, and hydroecology is based on water cycle processes. With growth in population and development of the economy, intense human activity has disturbed natural water cycles, resulting in severe changes in the driving forces, structure, and parameters of these cycles. The water cycle system has gradually evolved from a single natural feature into a nature-society dualistic water cycle system (Wang and Yang, 2010; Wang et al., 2013; Qin et al., 2014; Schmidt, 2014; Liu et al., 2014). Different from the natural water cycle (Horton, 1931), the social water cycle is a new research field necessitated through the development of urbanization and water shortage that focuses on the impacts of human activities on the water cycle (Ridolfi, 2014; Merrett, 1997; Linton, 2014). Thus, the new Scientific Decade (2013-2022) of the International Association of Hydrological Sciences (IAHS) takes hydrological-social modeling as the fourth science question: “How can we use improved knowledge of coupled hydrological-social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?” (Montanari et al., 2013).

The natural water cycle is driven only by natural forces such as the sun and wind. In contrast, a dualistic water cycle system is driven by natural forces in addition to mechanical, electrical, and other forces having obvious artificial features, which lead to complicated hydrological processes. The dualistic water cycle system combines the natural water cycle system, which includes the natural transformation processes of Soil–Vegetation–Atmosphere continuum, with the social water cycle system, which includes the processes of water storage, water intake, water conveyance, water use, drainage, and water reuse (Wang et al., 2006, 2013). The social and natural water cycle systems are dependent on and affected by each other. The social water cycle system takes the available water resources from the natural water system, whereas the latter is affected by the former because of its water intake and drainage process.

Because the impact of human activity varies among regions, distributed hydrological models are widely used in water cycle simulation. The most recent distributed hydrological models focus mainly on the evolution mechanism of the natural water cycle, which simulate the natural processes of precipitation, evaporation, infiltration, runoff yield, and confluence. However, these models, such as SWAT (Arnold et al., 1998; Piniewski et al., 2017; Liang et al., 2017; Shrestha et al., 2017), SHE (Abbott et al., 1986), DBSIN (Garrote and Bras, 1995), DHSVM (Wigmosta et al., 1994), GBHM (Yang et al., 1998, 2002), VIC (Liang and Xie, 2001; Luo et al., 2013), SWIM (Krysanova et al., 1998), and TOPOMODEL (Beven and Kirkby, 1979; Famiglietti et al., 1992), simplify or neglect the influence of the social water cycle process. Many works have been done to emphasize the influences of social factors but with simplified natural water cycle (using conceptual hydrological model or using the observation data) (Döllet et al., 1999, 2003; Alcamoet et al., 2003; Carey et al., 2014; DeFries and Eshleman, 2004; Harou, 2009; Kyle et al., 2013; Blanc et al., 2014; Hejazi et al., 2014; Liu et al., 2015; Kim et al., 2016). Thus, many researchers developed or improved the hydrological models to evaluate the human activities (such as water use, irrigation schemes, groundwater pumping, reservoir operations) impact on the hydrological (Biemans et al., 2011; Condon et al., 2014, 2015; De Graaf et al., 2014, 2015; Sacks et al., 2009; Leng et al., 2013, 2014, 2015; Van Der Knijff et al., 2010; Döllet et al., 2009, 2012; Pokhrel et al., 2015; Voisin et al., 2013, 2017; Wada et al., 2014). Most of them are global and continental scale, and not focus on all aspects of the social water cycle.

The aims of this study are to develop an watershed scale integrated dualistic water cycle model to simulate the natural-social hydrological processes, and analyze the impact of social water use on the natural hydrological processes, such as streamflow, evapotranspiration, and so on. The WEP-L model (Jia et al., 2006) is used as the basis of hydrological module, and embedded the social water cycle system module which includes the irrigation water use, domestic water use, industrial water use, reservoir water allocation, groundwater pumping, etc. In this study, the mechanism and principles of the dualistic water cycle process are introduced, and a case study of Haihe River basin is used to investigate the model performance over traditional hydrological model.

2 Study area and data

2.1 Study area

The Haihe River basin is located in North China (112°-120° E, 35°-43° N) across eight provinces, municipalities and autonomous regions (Fig. 1). The total drainage area is 320,041 km^2. The hilly region has an area of 170,460 km^2, accounting for 53% of the total area and the rest is plain area. The climate of this basin is semi-arid and semi-humid. The mean annual rainfall across the study area for the historical period (1956-2005) is 535 mm, and the multi-year average annual total water resources (1956-2005) make up to 37.0 × 10^9 m^3, of which the surface water resources are 21.6 × 10^9 m^3, groundwater resources are 15.4 × 10^9 m^3, and the average utilization is 23.5 × 10^9 m^3. (MWR, 2006)

With the rapid social and economic development, the intensity of human activities in Haihe River basin has increased dramatically since the 1970s. Until 2005, about 1.07×10^7 hm^2, or 33% of the study area, was covered by agriculture, of which about 7.54×10^6 hm^2 constituted effective irrigation area. The large-scale irrigation areas in the Haihe River basin are mainly located in the piedmont plain and the Yellow River irrigation area. With the significant role of national economic and social development, Haihe River basin has become an important industrial and high-tech base, which includes the large cities of Beijing, Tianjin, Shijiazhuang, and Tangshan. In order to increase the water supply capacity and fulfill water demands, a large number of water storage projects have been constructed during the past decades. In 2005, the number of reservoirs reached 1865, with a total capacity of 3.13×10^{10} m^3. Of these, 33 large reservoirs had a total capacity of 26.2×10^9 m^3 (Fig. 2). In addition, a volume of 3.72×10^9 m^3 of water is still needed to be diverted from the Yellow River (MWR, 2005).

In 2005, the total water consumption of Haihe River basin was 38.0×10^9 m^3, in which the consumptions of domestic water, industrial water, agricultural water, and eco-environmental water were 5.6×10^9 m^3 (accounting for 14.6%), 5.7×10^9 m^3 (accounting for 14.9%), 26.4×10^9 m^3 (accounting for 69.5%), and 0.4×10^9 m^3 (accounting for 1.0%), respectively. In other words, the water consumption is bigger than the average yearly available water resources. Thus, human activities have significant affected the formation and transformation of water resources. Therefore, it is a desire to develop a dualistic water cycle system modeling approach that integrates the natural and social cycle in this basin.

2.2 Data

The data used in this case include the following types: (1) daily meteorological data from 57 national weather stations (1956-2005) including air temperature, wind speed, sunshine duration, vapor pressure, and relative humidity, which were provided by China Meteorological Administration (http://data.cma.cn/data/cdcdetail /dataCode/ SURF_CLI_CHN_MUL_DAY_V3.0.html); (2) daily precipitation data of 1560 stations (1956-2005) were obtained from the “Annals of Hydrology in Haihe Basin” distributed by the Haihe River Water Conservancy Commission (HRWCC); (3) monthly flow data of 22 runoff stations (1956-2000), also obtained from the “Annals of Hydrology in Haihe Basin”; (4) Haihe River basin remote sensing evapotranspiration vector map obtained from the Institute of Remote Sensing Applications, Chinese Academy of Science (http://eds.ceode.ac.cn); (5) surface elevation data obtained from the United States Geological Survey (USGS) Land Processes Distributed Active Archive Center (LP DAAC; http://edcdaac.usgs.gov/gtopo30/gtopo30.asp); (6) a river distribution map (spatial resolution 1:25×10^6) supplied by Ren (2007); (7) land use maps of 1996, 2000 (spatial resolution 1:10×10^4), and 2004 (spatial resolution 1:25×10^4) obtained from Landsat TM data (http://www.geodata.cn); (8) spatial distribution data of soil type (spatial resolution 1:10×10^7) obtained from the second national soil survey and related study of Ma et al. (1994); (9) data of plain aquifer hydrogeological unit division and permeability coefficient reported by Ren (2007); (10) data of large reservoir characteristics and sluice parameters were obtained from HRWCC; (11) monthly storage changes of 33 reservoirs during 1956-2005 from HRWCC; (13) data of the area, plant structure, and irrigation patterns of 77 large-sized irrigation zones were obtained from HRWCC; and (14) the water use data of agriculture, industry, and domestic use for 1980-2005 were obtained from HRWCC.

3 Model development

3.1 Natural water cycle part

Natural water cycle processes and the model simulation results are affected by evaporation and other factors driven by precipitation. Watershed subdivision and codification are critical for the water cycle simulation process. The simulated drainage network was first extracted from a digital elevation model (DEM) modified to include the surveyed river network. Then, the simulated drainage network was used for the watershed subdivision and codification based on the coding rule (Luo et al., 2006; Liu et al., 2014). In the model the entire basin was subdivided into 3067 sub-watersheds to reflect the upstream and downstream relationship, and the sub-watersheds were further subdivided into 11752 contour bands (Fig. 3) to reflect the height effect and flow movements on the overland route (Fig. 4a). As shown in Fig. 4b, the vertical structure of the contour bands includes the interception layer, depression layer, upper soil layer, transition layer, unconfined aquifer, and confined aquifer. The mosaic method (Avissar and Pielke, 1989) was used to consider the heterogeneity of land use, which is divided into five groups within each contour band: Water Body, Soil–Vegetation, Impervious Area, Irrigated Farmland, and Non-irrigated Farmland. Essentially, we classified the land use units and estimated the water and heat fluxes of each land type, and the area's mean value was then used as the water and heat fluxes of the unit.

The natural water cycle was simulated based on WEP-L model, which is a distributed hydrologic model that combines the merits of PBSD (Physically Based, Spatially Distributed) and SVAT (Soil–Vegetation–Atmosphere Transfer scheme) models. The model is capable of dynamically assessing water resources in various forms, such as the surface water, groundwater, and rainfall water consumed by vegetation. It is also capable of modeling infiltration excess, saturation excess and mixed runoff generation mechanisms. For more details refer to Jia et al. (2001, 2006).

3.2 Social water cycle part

3.2.1 Social water cycle system

The social water cycle system was subdivided into three subsystems according to the water supply targets: agricultural, industrial and domestic water cycle systems. In addition, there is a cross-regional water supply system for the water transfer from reservoirs or another river basin to the study area. The generalizations of the social water cycle system are shown in Fig. 5. In this model, the social water cycle has the same basic calculation unit with natural water cycle which is contour bands within the sub-watershed, and the same daily time step for the coupled calculation.

The social water cycle focuses on the social water circulation, which includes six aspects: the water intake, water conveyance, water storage, water use, water drainage, and water reuse (Wang et al., 2013). Mostly, the water intake and water drainage are the two critical processes related natural water cycle. The coupling mechanism occurs mainly during these two processes. Rivers, reservoirs, and groundwater can be considered as water intake sources. The water intake processes decrease the water in the river and groundwater, whereas the drainage processes increase the water in the river and underground. Moreover, waste water reuse was considered in the model. The coupling principals are shown in Fig. 6.

To simulate the social water cycle, every water cycle subsystem must first be generalized by determining the distribution of demand nodes in each subsystem and examining the hydraulic connection between the demand nodes and the water intake position. This step assumes that groundwater intake position is located in the contour centroid and its water supply is used only for the social water system in the contour band. For surface water, the intake position is the sub-watershed outlet if no diversion work or water intake projects exist. The reservoir intake position is located in the outlet of its own sub-watershed dam site. Once all of the subsystem structures were generalized, the social water cycle was simulated in terms of water storage, intake, conveyance, use, drainage, and reuse. It is noteworthy that the water intake process was omitted in the case of water division engineering without dams and water lifting engineering.

3.2.2 The unit of social water cycle system

In agricultural water cycle system, the demand nodes are the irrigated farmland, forestland with irrigation facilities, and fishponds. The spatial distribution of demand nodes can be determined by using statistical data of the cultivated land (or irrigated forestland, fishponds) in addition to a spatial distribution map of the irrigated farmland (or artificial forestland, reservoirs and ponds). There are two types of irrigation areas in each contour band: large-medium-sized area and small-sized area. Each large-medium-sized area can be viewed as a combined demand node, whereas the other areas can be generalized as one demand node. For large-medium-sized areas, the hydraulic connection can be determined by examining the relationship between irrigation area and water intake. In terms of small-sized areas, it is assumed that surface water and groundwater water intakes are located in sub-watersheds and contour bands where the small-sized irrigation areas are. Each irrigated forestland (or fishpond) can be generalized to one demand node. It is assumed that surface water and groundwater intakes are located in sub-watersheds and contour bands where the irrigated forestlands (or fishponds) are.

In industrial water cycle system, the demand nodes are industrial and mining enterprises, whose spatial distribution could be determined by the map of industrial and mining enterprises distributions. The industrial and mining enterprises are generalized into two categories: those who use local water could be generalized to one demand node, while others who take water from water transfer project could be generalized to another demand node. It is assumed that surface water and groundwater intakes are located in the sub-watershed and contour bands where the industrial and mining enterprises are. In terms of the conditions in which water is taken from an inter-basin water diversion project, the hydraulic connection between the demand nodes and the water intakes can be determined by examining the conditions of the water diversion project.

In the domestic water cycle system, the demand nodes are urban residents and rural residents. The spatial distribution can be determined by using the statistical data of urban population (or rural populations) in addition to a spatial distribution map of urban land (or rural residential) areas. Two types of urban residents are considered during the generalization process: those who use local water can be generalized to one demand node, and those who take water from an inter-basin water transfer project can be generalized to a different demand node. For the first type of residents, it is assumed that the surface water and groundwater intakes are located in the sub-watershed and contour bands where they reside. In terms of the residents who take water from an inter-basin water diversion project, the hydraulic connection between the demand nodes and the water intakes can be determined by examining the conditions of the water diversion project. Rural residents in each contour band can be generalized to one demand node. It is assumed that surface water and groundwater intakes are located in the sub-watershed and contour bands where they reside.

For simplifying the model structure, the historical statistical water use data are used directly in the dualistic water cycle model. Usually, the available historical statistical water use data are on yearly scale and administrative regional level, which is larger than the model scale. Therefore, it is necessary to downscale these data to obtain daily water use in each calculation unit in both spatial and temporal aspects. The yearly water use of each subsystem could be written as:

$$W_a = \sum_{t=1}^{Y} \sum_{u=1}^{N} f(W_{u,t}, P_t, R, M) \tag{1}$$

$$W_i = \sum_{t=1}^{Y} \sum_{u=1}^{N} G_{u,t} \times W_u \tag{2}$$

$$W_l = \sum_{t=1}^{Y} \sum_{u=1}^{N} W_t \times \rho_u \times A_u \tag{3}$$

where W_a (m^3) is the total annual water consumption for agricultural irrigation; $W_{u,t}$ (m^3) is the water demand of various calculation units for the number of days t, which is calculated by Penman-Monteith equation (Monteith, 1973); P_t (m^3) is the amount of daily rainfall which is calculated by the precipitation (mm) multiplying by area of agricultural irrigation; R (m^3) is the amount of available water resources in the area; M represents the agriculture irrigation management factors such as irrigation water management level and irrigation patterns; f is the functional relationship between practical water consumption and water requirement under certain conditions; W_i (m^3) is the total annual water consumption for industrial use; $G_{u,t}$ (million yuan) is the daily Gross domestic product (GDP) value in each calculation unit; W_u (m^3/million yuan) is the GDP water consumption in every calculation unit; W_l (m^3) is the total annual water consumption for domestic use; W_t (m^3/day/per person) is the daily water consumption per capita in a calculation unit; ρ_u (per person/km^2) is the population density in a calculation unit; A_u (km^2) is the area of calculation unit; u is the calculation unit number; t is the daily serial number; N is the total number of calculation units within the region; and Y is the total days in a year (365 or 366).

In model applications, the daily irrigation water consumption in the calculation units is downscaled from yearly irrigation water use data considering precipitation, evapotranspiration, and irrigation management factors. The daily industrial water consumption in the calculation units is downscaled from yearly industrial water use and used GDPs as weight. The daily domestic water consumption in unit calculation is downscaled from yearly domestic water use data and used population as weight. The detailed method follows that reported in previous researches (Cui et al., 2010; Cao et al., 2010).

3.2.3 Water resources and water allocation system

The water resources of the social water cycle system include four types: local surface water, cross-regional surface water, cross-basin surface water and groundwater. Water is supplied by the four types of sources consequently. The local surface water comes from the streamflow of the local river, the storage of the local reservoir or pond, the retain water and so on. The cross-regional surface water comes from the storage of large reservoirs in the upstream of the water use unit, in which the water will be transferred with long distance. The cross-basin surface water comes from the streamflow out of the local basin or water transferred from lager water diversion project. In Haihe River basin, it could be water from Yellow Rive basin or the South-to-North Water Diversion project of China.

The generalized cross-regional water distribution system is shown in Fig.7. The demand nodes of the cross-regional water distribution systems are for industrial, agricultural, and domestic water use. Every sub-watershed in the water supply area can be generalized to one demand node. The hydraulic connection between demand nodes and the reservoir can be determined according to the water supply range.

Some reservoirs supply water to the region near to it. However, some supply water to more regions far from it. For these reservoirs, the entire water supply area can be divided into several water use zones, and the amount of reservoir water supply is equal to the sum of water consumption of each zone. The simulation of the reservoir is estimated as:

$$S_r = \sum_{z=1}^{N_z} W_z = \sum_{z=1}^{N_z} (W_{a,z} + W_{i,z} + W_{l,z} - S_{local}) \tag{4}$$

$$\Delta S = W_{in} \ - S_r \ - E - D \tag{5}$$

where S_r (m^3) is the reservoir water supply; W_z (m^3) is the water consumption in the water supply zone z; z is the serial number of each water use zone; N_z is the sum of all the zones supplied water by the reservoir; $W_{a,z}$ (m^3) is the amount of agricultural irrigation water consumption in the water use area *z*, which can be calculated by Eq. (1); $W_{i,z}$ (m^3) is the industrial water consumption in the water use zone *z*, which can be calculated by Eq.(2); $W_{l,z}$ (m^3) is the domestic water consumption in the water use zone *z*, which can be obtained by Eq. (3); S_{local} (m^3) is the available amount of water supply by local water resources, including surface water, groundwater, and reclaimed water; ΔS is the water storage change of the reservoir; W_{in} is the income water of the reservoir from upstream streamflow; *E* is the evaporation of the reservoir; and *D* is the drainage of the reservoir when the storage is over the storage capacity of the reservoir.

In the model, both the surface water and groundwater use data are introduced into the model separately and downscaled using the above mentioned method. The natural water cycle is simulated using WEP-L model, while the social water cycle is simulated based on the statistical data, so, there needs an allocation scheme for the coupling. First, the local surface water and groundwater within the subbasin where the computation unit located is used to meet the demand of the social water cycle system; second, the cross-regional surface water is used for the remainder demand; third, the cross-basin surface water if exists is used for the remainder demand; and finally, if it still couldn't meet the amount, a 'caution' will be recorded in the output file.

In the social water cycle system, the irrigation water is used like additional precipitation, which lays on the Irrigated Farmland and Non-irrigated Farmland area and takes part in the infiltration and evapotranspiration processes. Most of the industrial water drains back to river, the rest is classified into evaporation which contains the evaporation within water use process and the water solidified in the commodity. The domestic water also is subdivided into two groups, backing to the river and evaporated.

3.3 The distribution of social water use

The areas of land use categories in the contour bands were used as weights for downscaling the administrative regional level water use data to the computation units. Then, the annual water use data were further downscaled to each day according to the characteristics of different social water cycle subsystems. The spatial distribution of the diversity social water cycle subsystems in 2005, including the distributions of irrigated water use, industrial water use, and residential water use and so on, is shown in Fig. 8 for illustration purpose.

4 Results

4.1 Impact on stream flow

Three types of model parameters have been designated by Jia et al. (2006): low-sensitive parameters such as vegetation coverage leaf area index, vegetation height, aerodynamic parameters, and saturated hydraulic conductivity; medium-sensitive parameters such as soil water characteristic curves, soil infiltration capacity, aquifer thickness, and water permeability coefficient; and high-sensitivity parameters such as soil water content, soil depth, and transmissibility coefficient of river-bed materials. Model calibration is mainly used for parameters with high sensitivity and those related to runoff yield and concentration.

The data series of 1956–2000 were used for long-term daily simulation of the dualistic water cycle system structure of Haihe River basin, of which, the calibration period was from 1956 to 1979, and the validation period was from 1980 to 2000. The main calibration parameters include the aforementioned high-sensitive parameters. Because in hydrological modeling of large scale, we normally concern about the hydrological stations in the main streams of the rivers with longer data records, and many of the other stations do not have long-term observation data. The hydrological stations of Chengde, Luanxian, Daiying, Guantai, Guanting, and Huangbizhuang are selected to show the impact on validation period (Table 1 and Fig. 9). Moreover, the box-plot of Nash–Sutcliffe coefficient of validation period of all 22 stations are shown for comparison (Fig. 10). The results indicate that the performance of the coupled model matches the observation data better than the non-coupled model. We choose Guantai station to show the details of the impact of coupled and non-coupled model at typical year. The observation data were matched better by the coupled model than the non-coupled model. Moreover, the coupled simulation had a significant influence on normal and low flow years. However, it had a lesser effect on high flow years due mainly to the relatively large amount of water in these years. Moreover, the impact on the flood season is less than that in the non-flood season.

Table 1: Model validation results of 1980-2000

Hydrological stations	Coupled Model			Non-Coupled Model		
	Relative error	Nash–Sutcliffe coefficient	Correlation coefficient	Relative error	Nash–Sutcliffe coefficient	Correlation coefficient
Chengde	−5.8%	0.72	0.85	2.8%	0.72	0.72
Luanxian	−1.3%	0.60	0.86	-2.7%	0.40	0.76
Daiying	−4.0%	0.65	0.81	7.1%	0.50	0.54
Guantai	3.6%	0.81	0.93	3.1%	0.71	0.79
Huangbizhuang	−9.6%	0.68	0.83	-17.6%	0.72	0.73

4.2 Impact of social water cycle on evapotranspiration

The comparison results between the coupled and non-coupled model simulations of watershed evapotranspiration processes are shown in Fig. 12. The remote sensing image indicates that evapotranspiration in plain areas was higher than that in the hilly areas. Considering the two different simulation scenarios, we determined that the coupled model matched the observation data better than the non-coupled model in the piedmont and Yellow River diversion irrigated areas, due to that the coupled model considers the impact of social water cycle on the basin evapotranspiration.

Fig. 13 is the comparison of with and without cross-regional allocation. Without cross-regional allocation situation means the water only comes from the local surface water. With cross-regional allocation situation means the water comes from the local, cross-regional and cross-basin surface water. The figure shows the shortage of the local river streamflow on meeting the social water demand. It indicates that considering the cross-regional allocation scheme could make the social water cycle more accurate. Because the water allocation of coupled model is more close to the actual water use, the simulated basin evapotranspiration of the coupled model is 520 mm, which is bigger than that of the non-coupled model (455 mm), especially in the piedmont and Yellow River diversion irrigated areas. Meanwhile, the simulated streamflow of the not-coupled model is bigger than that of the coupled model.

4.3 Impact on reservoir storage change

Four typical large reservoirs are selected for studying the impact on reservoir storage change of with and without reservoir operation. The selected reservoirs are typical in Haihe River basin which locate on the upstream mountain area of the main river and have complicated water supply connection (Fig. 2). Another reason is that they have a long-term storage change observation data. The observations of the Wangkuai reservoir and Huangbizhuang reservoir are from the year of 1980 to 2005. The observations of the Miyun reservoir are from the year of 1980 to 2000. The observations of the Panjiakou reservoir are from the year of 1984 to 2000.

Two situations are considered for testing the impacts of with or without cross-regional reservoir allocation. With cross-regional reservoir allocation, the reservoir storage variable is equal to precipitation plus runoffs, and then deduct evaporation and cross-regional water transfer. Without cross-regional reservoir allocation, the storage variable of the reservoir is equal to the precipitation and runoffs deduct evaporation. It is obvious that the monthly reservoir storage change was stable when the cross-regional reservoir allocation is neglected. It can be found from Fig. 14 that the reservoir change at the situation of with cross-regional reservoir allocation is more close to the observations, although there are some underestimations and overestimations. Because the water transfer of the reservoir is affected by the water supply range and the water supply amount, and the deviation in the calculation of water demand may cause a deviation in the water supply. Generally speaking, the storage was reduced in the pre-flood period and increased in the flood recession period, which is consistent with regional water operation laws.

5 Discussions and Conclusions

Simulation of dualistic hydrological processes is of vital importance for dynamic water resources management of regions with intensive human influence, but such studies are rarely seen in the literature. In this study, an integrated dualistic water cycle modeling approach was developed to analyze the impact of social water use on the natural hydrological processes, which mainly contain natural water cycle and social water cycle. The natural water cycle was simulated using WEP-L model, so the social water cycle is a key point in this study. Normally, the social water cycle system could be divided into agricultural water cycle system, industrial water cycle system, domestic water cycle system, and cross-regional allocation system. Two hydrological models, a natural-social dualistic water cycle model and a natural water cycle model, were used to simulate hydrological processes of Haihe River basin. The streamflow, evapotranspiration, the changes of reservoir storage, and cross-regional surface water allocation are comparatively analyzed in this paper. In addition, the coupling principals between natural and social water cycles were also discussed in this work.

The study concludes that (1) the model simulation efficiency can be much improved when considering coupled simulation of natural and social water cycle systems; (2) Influenced by human activities, the streamflow of the basin is significantly less than the natural runoff, which is more prominent in the normal and dry years; (3) As a result of the substantial increase in social water consumption, while the river streamflow is greatly reduced, the amount of watershed evapotranspiration increased significantly. Based on the modelling results, the evapotranspiration in the piedmont and Yellow River diversion irrigated areas is higher than that in other areas; (4) The natural-social dualistic water cycle model is developed in this paper, the modeled water balance process of the reservoir and the processes of storage are in good agreement with the measured processes; (5) The impact of the cross-regional surface water allocation is investigated, which indicates that considering the cross-regional allocation scheme could make the social water cycle more accurate.

Aiming to propose an integrated dualistic water cycle model, and apply it on Haihe River basin, the findings of the study have the following implications. With the dualistic model, it could evaluate the future trends of water resources, ecology and the water environment by setting scenarios based on the predictions of a climate model and water control conditions (this work could refer to Wang et al., 2013). As the dualistic model could simulate different hydrological process and human activities (corresponding to the subsystem of social water cycle), it could be used for the water resources attribution analysis (this work could refer to Jia et al., 2012). The integrated model still has some shortcomings need to be addressed in the future study, such as, strengthening the close coupling of the social water cycle rather than using the statistical data as external input, improving the function of simulating agricultural practices with rule-based behavior, operating the reservoir using dynamic scheduling rule, and strengthening the coupled simulation of surface water and groundwater, and so on.

Acknowledgments

This research was financially supported by the National Key Research and Development Program of China (2016YFC0402405), the National Science and Technology Major Project of Water Pollution Control and Prevention of China (2008ZX07207-006, 2012ZX07201-006) , and the National Natural Science Foundation of China (41601032). The authors also acknowledge the help of Natural-Social Dualistic Water Cycle Model Research Group and the helpful suggestions of external reviewers.

Reference

Abbott, M., Bathurst, J., Cunge, J.A., O'Connell, P.E., and Rasmussen, J. (1986). "An introduction to the European Hydrological System–Systeme Hydrologique Europeen, "SHE", 2: Structure of a physically-based, distributed modeling system". *Journal of Hydrology*, 87(1–2), 61-77.

Alcamo J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S. (2003). "Development and testing of the Water GAP 2 global model of water use and availability". *Hydrological Sciences Journal*, 48(3), 317–337.

Arnold, J.G., Srinivasan, R., Muttiah, R., and Williams, J.R. (1998). "Large area hydrologic modeling and assessment part I: model development". *Journal of the American Water Resources Association*, 34(1), 73–89.

Avissar, R., and Pielke, R.A. (1989). "A parameterization of heterogeneous land-surface for atmospheric numerical models and its impact on regional meteorology." *Mon. Wea. Rev.*, 117, 2113–2136.

Beven, K.J., and Kirkby, M.J. (1979). "A physically based, variable contributing area model of basin hydrology". *Hydrological Sciences Bulletin*, 24(1), 43–69.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R.W. A., Heinke, J., von Bloh, W., and Gerten, D. (2011). "Impact of reservoirs on river discharge and irrigation water supply during the 20th century". *Water Resources Research*, 47, W03509, doi:10.1029/2009WR008929.

Blanc, E., Strzepek, K., Schlosser, A., Jacoby, H., Gueneau, A., Fant, C., Rausch, S., and Reilly, J. (2014). "Modeling U.S. water resources under climate change". *Earths Future*, 2(4), 197–224,

Carcy, M., Baraer, M., Mark, B.G., French, A., Bury, J., Young, K.R., and McKenzie, J.M. (2014). "Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru)". *Journal of Hydrology*, 518, 60–70.

Cao, Z., Qiu, Y., and Zhou, Z. (2010). "WATER DISTRIBUTION OF SONGLIAO BASIN IN TIME AND SPACE". in *Proceedings of the 9th International Conference on Hydroinformatics 2010*. Beijing, China: Chemical Industry Press, 2, 1663-1670.

Condon, L.E., and Maxwell, R.M. (2014). "Feedbacks between managed irrigation and water availability: Diagnosing temporal and spatial patterns using an integrated hydrologic model". *Water Resour. Res.*, 50 2600–2616.

Condon, L.E., and Maxwell. R.M. (2015). "Evaluating the relationship between topography and groundwater using outputs from a continental-scale integrated hydrology model". *Water Resour. Res.* 51, 6602-6621.

Cui, X., Zhou, Z., and Qin, D. (2010). "SIMULATION AND ANALYSIS OF AGRICULTURAL IRRIGATION IN SONGLIAO BASIN". in *Proceedings of the 9th International Conference on Hydroinformatics 2010*. Beijing, China: Chemical Industry Press, 2, 1655-1662.

De Graaf, I., van Beek, L., Wada, Y., and Bierkens, M. (2014). "Dynamic attribution of global water demand to surface water and groundwater resources: Effects of abstractions and return flows on river discharges". *Adv. Water Resour.*, 64, 21–33.

De Graaf, I., Sutanudjaja, E., van Beek, L., and Bierkens, M. (2015). "A high resolution global scale groundwater model". *Hydrol. Earth Syst. Sci.*, 19, 823–837.

Defries, R., Eshleman, K.N. (2004). "Land-use change and hydrologic processes: a major focus for the future". *Hydrological Processes*, 18(11), 2183–2186.

Döll, P., Kaspar, F., Alcamo, J. (1999). "Computation of global water availability and water use at the scale of large drainage basins". *Mathematische Geologie* 4, 111-18

Döll, P., Kaspar, F., and Lehner, B. (2003). "A global hydrological model for deriving water availability indicators: model tuning and validation". *Journal of Hydrology* 270, 105–134.

Döll, P., Fiedler, K., and Zhang, J. (2009). "Global-scale analysis of river flow alterations due to water withdrawals and reservoirs". *Hydrol. Earth Syst. Sci.,* 13, 2413-2432.

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., and Scanlon, B. (2012). "Impact of water withdrawals from groundwater and surface water on continental water storage variations", *J. Geodyn.*, 59-60, 143-156.

Famiglietti, J.S., Wood, E.F., Sivapalan, M., and Thongs, D.J. (1992). "A catchment scale water balance model for FIFE". *Journal of Geophysics Research*, 97(D17), 18997–19007.

Garrote, L., and Bras, R.L. (1995). "A distributed model for real-time flood forecasting using digital elevation models". *Journal of Hydrology*, 167(1), 279 - 306.

Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellin-Azuara, J., Lund, J.R., and Howitt, R.E. (2009). "Hydro-economic models: Concepts, design, applications, and future prospects". *Journal of Hydrology*, 375(3), 627 – 643.

Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., Moss, R., and Kim, S. (2014). “Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework”. *Technol. Forecasting Soc. Change*, 81, 205-226.

Horton, R.E. (1931).“The field, scope, and status of the science of hydrology”. *Eos, Transactions American Geophysical Union*, 12(1), 189–202.

Jia, Y., Ni, G., Kawahara, Y., and Suetsugi, T. (2001). “Development of WEP model and its application to an urban watershed”. *Hydrological Processes*, 15, 2175–2195.

Jia, Y., Wang, H., Zhou, Z., Qiu, Y., Luo, X., Wang, J., Yan, D., and Qin, D. (2006). “Development of the WEP-L distributed hydrological model and dynamic assessment of water resources in the Yellow River basin”. *Journal of Hydrology*, 331, 606–629.

Jia, Y., Ding, X., Wang, H., Zhou, Z., Qiu, Y., and Niu, C., (2012). “Attribution of water resources evolution in the highly water-stressed Hai River Basin of China”. *Water Resources Research* 48, W02513. Doi: 10.1029/2010WR009275.

Kim, S. H., Hejazi, M. I., Liu, L., Calvin, K. V., Clarke, L. E., Edmonds, J., Kyle, P., Patel, P. L., and Wise, M. A. (2016). “Balancing global water availability and use at basin scale in an integrated assessment model”. *Clim. Change*, 136, 217-231.

Krysanova, V., Müller-Wohlfeil, D. I., and Becker, A. (1998). “Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds”. *Ecological modelling*, 106(97), 261–289.

Kyle, P., Davies, E., Dooley, J.J., Smith, S.J., Clarke, L., Edmonds, J., and Hejazi, M.I. (2013). “Influence of climate change mitigation technology on global demands of water for electricity generation”. *Int. J. Greenhouse Gas Control*, 13, 112–123.

Leng, G., Huang, M., Tang, Q., Sacks, W. J., Lei, H., and Leung L.Y.R. (2013). “Modeling the effects of irrigation on land surface fluxes and states over the conterminous United States: Sensitivity to input data and model parameters”. *J. Geophys. Res.*, 118(17), 9789–9803.

Leng, G., Huang, M., Tang, Q., Gao, H., and Leung L.Y.R. (2014). “Modeling the effects of groundwater-fed irrigation on terrestrial hydrology over the conterminous United States”. *J. Hydrometeorol.*, 15(3), 957–972.

Leng, G., Huang, M., Tang, Q., and Leung L.Y.R. (2015). “A modeling study of irrigation effects on global surface- and groundwater resources under a changing climate”. *J. Adv. Model. Earth*

Syst., 7, 1285–1304.

Liang, X., and Xie, Z. (2001). “A new surface runoff parameterization with sub grid-scale soil heterogeneity for land surface models”. *Advances in Water Resources*, 24(9), 1173 – 1193.

Liang, Z.M., Tang, T.T., Li, B.Q., Liu, T., Wang, J., Hu, Y.M. (2017). Long-term streamflow forecasting using SWAT through the integration of the random forests precipitation generator: case study of Danjiangkou Reservoir. Hydrology Research, DOI: 10.2166/nh.2017.085

Linton, J. (2014). “Modern water and its discontents: a history of hydro social renewal”. *Wiley Interdisciplinary Reviews: Water*, 1(1), 111–120.

Liu, J., Qin, D., Wang, H., Wang, M., and Yang, Z. (2010). “Dualistic water cycle pattern and its evolution in Haihe River basin”. *Chinese Science Bulletin*, 55(16), 1688–1697.

Liu, J., Zhou, Z., Jia, Y., Wang, H., and Chen, X. (2014). “A stem-branch topological codification for watershed subdivision and identification to support distributed hydrological modelling at large river basins”. *Hydrological Processes*, 28(4), 2074–2081.

Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E., Zhou, Y., Clarke, L., and Edmonds. J. (2015). “Water demands for electricity generation in the U.S.: Modeling different scenarios for the water-energy nexus”. *Technol. Forecasting Soc. Change*, 94, 318–334

Luo, X., Jia, Y., Wang, J., Wang, H., Qin, D., and Zhou, Z. (2006). “Method for delineation and codification of a large basin based on DEM and surveyed river network”. *Advances in Water Science*, 17, 259–264. (in Chinese)

Luo. X., Liang, X., and Mccarthy, H. R. (2013). “VIC+ for water-limited conditions: A study of biological and hydrological processes and their interactions in soil-plant-atmosphere continuum”. *Water Resources Research*, 49(11), 7711–7732.

Ma, T. (1994). *Chinese Soils (third version)*. Beijing: China Agriculture Press. (in Chinese)

Merrett, S. (1997). *Introduction to the economics of water resources: an international perspective*. Rowman & Littlefield.

Monteith, J. L. (1973). *Principles of Environmental Physics*. Edward Arnold Publishers, London.

Montanari, A., Young, G., Savenije, H., et al. (2013). “Panta Rhei-Everything Flows: Change in hydrology and society - The IAHS Scientific Decade 2013–2022”. *Hydrological Sciences Journal*, 58(6), 1256–1275.

Ministry of Water Resources of China (MWR) (2005). *China water statistical yearbook 2005*.

Beijing: China Water Power Press.

Ministry of Water Resources of China (MWR) (2006). *China water resources bulletin*. Beijing: China Water Power Press.

Piniewski, M., Szcześniak, M., Huang, S.C., Kundzewicz, Z.W. (2017). Projections of runoff in the Vistula and the Odra river basins with the help of the SWAT model. Hydrology Research, DOI: 10.2166/nh.2017.280.

Pokhrel, Y. N., Koirala, S., Yeh, P., Hanasaki, N., Longuevergne, L., Kanae, S., and Oki, T. (2015). "Incorporation of groundwater pumping in a global land surface model with the representation of human impacts". *Water Resour. Res.*, 51, 78–96.

Qin, D., Lu, C., Liu, J, Wang, H., Wang, J., Li, H., Chu, J., and Chen G. (2014). "Theoretical framework of dualistic nature-social water cycle". *Chinese Science Bulletin*, 59(8), 810–820.

Ren, X. (2007). *Haihe River Basin Water Resources Evaluation*. Beijing: China Water Power Press. (in Chinese)

Ridolfi, E. (2014). "Exploring the urban hydro social cycle in tourist environments". *Investigaciones Geograficas*, (61), 17–38.

Sacks, W. J., Cook, B. I., Buenning, N., Levis, S. and Helkowski, J. H. (2009). "Effects of global irrigation on the near-surface climate". *Clim. Dyn.*, 33, 159–175

Schmidt, J.J. (2014). "Historicising the Hydrosocial Cycle". *Water Alternatives*, 7(1), 220–234.

Van Der Knijff, J.M., Younis, J., and De Roo, A.P.J. (2010). "LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation". *Int. J. Geogr. Inf. Sci.*, 24, 189-212.

Voisin, N., Li, H., Ward, D., Huang, M., Wigmosta, M., and Leung, L.R. (2013). "On an improved sub-regional water resources management representation for integration into earth system models", *Hydrol. Earth Syst. Sci.*, 17, 3605–3622.

Voisin, N., Hejazi, M.I., Leung, L.R., Liu, L., M. Huang, H.-Y. Li, and T. Tesfa (2017). "Effects of spatially distributed sectoral water management on the redistribution of water resources in an integrated water model". *Water Resour. Res.*, 53, 4253-4270.

Wada, Y., Wisser, D., and Bierkens, M. F. P. (2014). "Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources". *Earth Syst. Dyn.*, 5, 15–40,

Wang, H., Wang, J., Qin, D., and Jia, Y. (2006). "Theory and methodology of water resources assessment based on dualistic water cycle model". *ShuiliXuebao*, 37(12), 1496–1502. (in Chinese)

Shrestha, S., Shrestha, M., Shrestha, P.K. (2017) Evaluation of the SWAT model performance for simulating river discharge in the Himalayan and tropical basins of Asia. Hydrology Research, DOI: 10.2166/nh.2017.189

Wang, H., and Yang, G. (2010). "Preliminary study on new concept of water resources management under dualistic water cycle condition". *Chinese Journal of Nature*, 32(3), 130–133. (in Chinese)

Wang, H., Jia, Y., Yang, G., Zhou, Z., Qiu, Y., Niu, C., and Peng, H. (2013). "Integrated simulation of the dualistic water cycle and its associated processes in the Haihe River Basin." *Chinese Science Bulletin*, 58, 3297-3311.

Wigmosta, M. S., Vail, L. W., and Lettenmaier, D. P. (1994). "A distributed hydrology-vegetation model for complex terrain". *Water Resources Research*, 30(6), 1665–1679.

Yang, D., Herath S., and Musiake, K. (1998). "Development of a geomorphology-based hydrological model for large catchments". *Annual Journal of Hydraulic Engineering, JSCE*, 42, 169–174.

Yang, D., Herath, S., and Musiake, K. (2002). "A hill slope-based hydrological model using catchment area and width functions". *Hydrological Sciences Journal*, 47(1), 49–65.