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Watershed Modeling of Surface Water-Groundwater Interaction under Projected Climate Change and Water Management in the Haihe River Basin, China

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Authors' contributions

This work was carried out in collaboration between all authors. Authors ZW, YL and MZ designed the study, performed the statistical analysis, and wrote the first draft of the manuscript. Authors XZ and WL contributed on the model applications of SWAT and MODFLOW. Author RW investigated the climate change impacts on hydrological variables. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

The Haihe River Basin (HRB), located in northern China with a drainage area of 318,200 km^2, is one of the most developed regions in China. With rapid population growth and economic development, the combined problems of water shortage and groundwater over-pumping significantly constrain the sustainable development in this area. In order to strengthen the unified management of groundwater and surface water, we developed hydrologic modeling of surface water and groundwater interaction by coupling SWAT (for surface water simulation) and MODFLOW (for groundwater simulation). The newly developed modeling framework reasonably captured the spatiotemporal variability of the

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hydrological processes of the surface water and groundwater in the study area. The modeling results showed a good agreement with the measurements of surface water and groundwater during 1996-2006. Results of model evaluation indicated that the developed model could be a promising tool in watershed management planning under the context of global climate change and the "South-North Water Transfer Project". In the HRB, climate change has significant effects on surface hydrology as indicated by the predicted increases on actual evapotranspiration and precipitation during 2041-2050 relative to those during 1991-2000. Changes of groundwater storage were mainly contributed by water diversion which would reduce the requirement of water pumping from groundwater especially for domestic and industrial uses. By the middle of the 21st century, increased water supply by projected precipitation and water diversion would result in annual increases of 3.9~9.9 billion m^3 for river discharge and 1.7~2.9 billion m^3 for groundwater storage as annual averages.

Keywords: Groundwater; surface water; model coupling; Haihe River Basin.

1. INTRODUCTION

The growing water demand in developing countries would potentially cause over-exploitation of water resources, and decline in water availability for agricultural and industrial uses. This inevitably leads to loss of production and also affects human health and environmental quality. Climate change and human activity are usually recognized as two primary influencing factors contributing to water shortages in surface water and groundwater. For example, higher air temperature is expected to increase PET and potentially decrease water yield to rivers and recharges to groundwater. However, global warming may also intensify hydrologic cycle and further lead to streamflow increase [1]. In addition, over exploitation of water for production and domestic consumptions leads to changes in the spatial distribution of water availability. While General Circulation Models (GCMs) together with greenhouse gas emission scenarios generate future climate data virtually for any place of the world, their implications for regional hydrologic cycle are yet poorly understood.

Hydrologic studies have been conducted in the context of climate change and sustainable socio-economic development for regions with rapid economic growth and serious water shortage [2-5], including the Haihe River Basin (HRB) of North China [6-8]. Enclosing Beijing and other metropolitan areas, the HRB is the political, economic, and cultural center of China. Total gross domestic product (GDP) and water demand in the HRB significantly increased during the last decade. However, this basin is located in the semi-arid region and associated with limited water resources. Annual per capita water availability is only 300 m^3, accounting for 1/7 of national average, and 1/24 of global average [9, 10]. Declines in precipitation and stream runoff have been reported. For example, comprehensive analysis of precipitation data over the entire basin were conducted in our previous study [11], indicating a 20% decrease of precipitation between two periods of 1951-1979 and 1980-2008. Studies also reported declined stream runoff in some mountainous catchments of the basin. For example, five out of eight studied catchments showed significant declines in annual stream runoff from 1960s to 1990s [7]. Similar to other developing regions in the world, crisis in water resources is getting worse in the HRB due to the increasing demand by economic development and more restrictive regulations on groundwater exploitation. According to the water resources bulletin of China, about 2/3 of the total water supply in the Haihe River basin depends on groundwater [12]. Cumulative amount of groundwater over-pumping in the basin was estimated 89.6 billion m^3 during 1958-1998 [13, 14]. Ever-increasing groundwater pumping has caused massive and continuing depletion in the aquifer of the HRB [15]. Eco-environmental degradations have been caused by insufficient surface water and over-exploitation of groundwater in this area [12, 16-18].

Due to the limited water resources and ever-worsening eco-environment in the HRB, climate change and water management (e.g., water diversion, restrictions in groundwater exploitation, and regulations in water allocation) would play important roles in the sustainable development of the region. It's predicted that precipitation in the HRB will increase during the 21st century according to the projection of Intergovernmental Panel on Climate Change (IPCC) climate models [6, 19, 20]. In addition to the projected increase in precipitation, the "South-to-North Water Transfer Project" (SNWTP) of China is planned to divert 13 billion m^3 of water annually from the Dajiangkou Reservoir on the Hanjiang River, a tributary of the Yangtze River to the North China Plain (9.0 billion m^3 of which to the HRB). Upon the completion of the project, new water regulation will be implemented to minimize groundwater exploitation in the area. While the projected weather condition and proposed water diversion and regulations are favorable to the HRB, their integrated effects on the hydrologic cycle and water resources are not yet quantitatively evaluated based on modeling approaches.

The interactions between surface water and groundwater is a key component of the hydrologic budget in the HRB. For the regional water resource management and planning, therefore, integrated modeling for surface water and groundwater interaction is required for the HRB. However, the linkage between surface water and groundwater resources and their driving factors is not yet established for basin-wide management decisions. Surface hydrology simulations have been successfully conducted to the basin and its watersheds [21-24]. Most of these studies were based on watershed-scale models with lumped parameters and very limited capability for groundwater simulation. For example, SWAT (Soil and Water Assessment Tool) [25] does not accept spatially distributed groundwater parameters such as hydraulic conductivity, and is incapable to predict the distribution and dynamics in groundwater levels and recharge rates [26, 27]. Although modeling approaches for surface water and groundwater involve different hydrologic processes, they both include the description of water movement cross the interface between vadose zone and saturated soil. Therefore, modeling approaches for surface water and groundwater could be coupled to provide comprehensive solutions to watershed hydrologic and management problems. The paired models included the Common Land Model and the ParFlow [28], Precipitation-Runoff Modeling System (PRMS), and the Modular Ground-Water Flow Model (MODFLOW) [29], and Duflow and MicroFem [30]. More studies have been presented by combining SWAT and MODFLOW [31] at various level of integration. For example, the potential applications of watershed/groundwater coupled modeling system on water resource management were discussed with watersheds in Kansas, USA [31]. Kim et al. [26] combined SWAT-MODFLOW modeling by formulating water transfer across the HRU-cell conversion interface. A similar approach was also presented by Guzman et al. [27]. Those studies usually focused on the effects of distributed groundwater simulation on predicting hydrologic conditions of surface water (e.g., streamflow). Groundwater data from very limited number of wells were utilized in model evaluation; and the modeling capability in capturing the spatial and temporal variability on groundwater level were not fully validated. In addition, the source codes and executables for the coupled SWAT-MODFLOW are not available to public access.

In this study, the spatiotemporal variation of surface water and groundwater resources in the Haihe River Basin was characterized with a modeling approach by semi-coupling SWAT and MODFLOW. The general purpose of this study was to evaluate the modeling capability of coupled SWAT/MODFLOW in simulating groundwater dynamics, and the responses to surface water processes and watershed management in the study area. The specific study objectives included: (1) development of the coupling between SWAT and MODFLOW according to the study area characteristics, data availability, and management requirements of water resources; (2) evaluation of the coupled model with measured surface water and groundwater data in the HRB during 1995-2006; and (3) assessment of the impact of climate change and water management on the hydrologic conditions in the study area. The results of this study are anticipated to provide useful information for further hydrologic modeling practices and water resource management in the Haihe River Basin.

2. METHODS AND MATERIALS

2.1 SWAT-MODFLOW Coupling

SWAT is a conceptual semi-distributed model developed by the United States Department of Agriculture (USDA) for watershed hydrology and water-quality operating on daily time step. In the model, the watershed of interest is divided into explicitly parameterized smaller areas of subbasins and enclosed hydrologic response units (HRUs). The HRUs are delineated by overlaying topography, soil, and land use maps, and assumed to be homogeneous with respect to their hydrologic properties. SWAT simulations can be separated into two major divisions of “land phase” for water and pollutant loadings to channels, and “routing phase” for in-stream water quantity and quality. A full description of SWAT can be found in Neitsch et al. [25].

MODFLOW is developed by USGS to describe subsurface flow and pollutant transport [31]. MODFLOW include a main program and independent packages organized in a modular structure. Spatially, numerical solution is based on three-dimensional finite difference method with options for users to design complex irregular system. Temporally, MODFLOW uses the concept of stress period to divide the simulation period. Solution of MODFLOW requires input parameters and boundary conditions, including soil water content, lateral flow, groundwater recharge, evapotranspiration, and water uptake. Those boundary conditions could be specified by model user. In addition, MODFLOW has the modeling capability to simulate some surface-subsurface interactive processes, including prescribed recharge and linear dependence of recharge in groundwater and surface water heads [32].

While SWAT includes both shallow and deep aquifers in the watershed-scale water balance, it does not simulate the temporal and spatial variations in groundwater components. In addition, SWAT has limitations in dealing with groundwater flow with spatially distributed parameters such as hydraulic conductivity. Without a comprehensive simulation of surface hydrologic processes, conversely, MODFLOW may not accurately estimate the groundwater recharge rates. SWAT components of surface runoff, streamflow routing, reservoir management, evapotranspiration, and agricultural activities can be calibrated to reasonably generate MODFLOW input data of water recharge, landscape evapotranspiration, and groundwater exploration (Fig. 1). Therefore, a coupling of the two models is required to have a better understanding on the water movement in both surface water and groundwater domain.

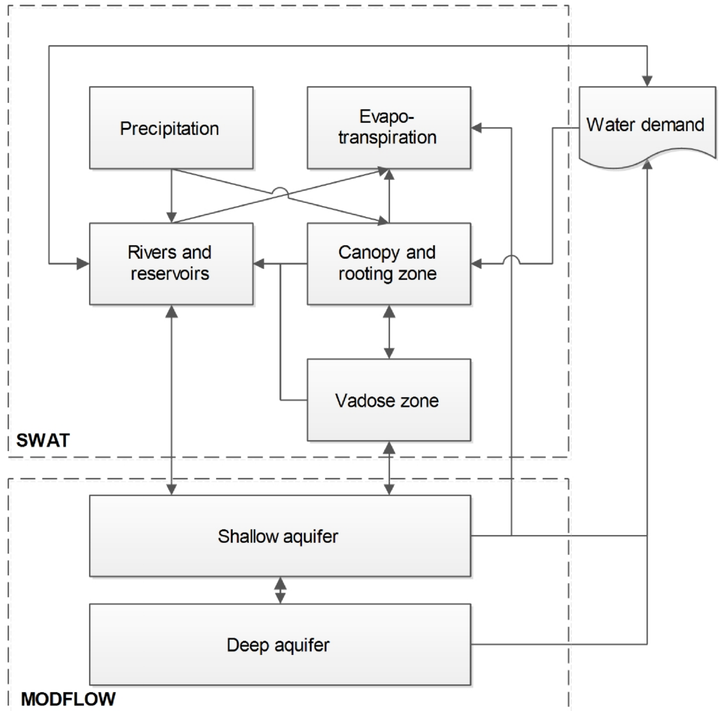

Fig. 1. Hydrologic components and water flows in the coupled SWAT-MODFLOW

SWAT and MODFLOW were coupled by following the four procedures below,

(1) Landscape characterization and SWAT parameterization. Watershed delineation was conducted based on Digital Elevation Model (DEM) and stream network maps. The subbasins, rivers, and reservoirs in the study area were geo-referenced.

(2) Horizontally, a 4km×4km grid system was developed as computational units for MODFLOW simulations.

(3) Under the same geographic projection, a mapping table between the computational units for surface water (subbasins) and groundwater (grid cells) were developed. Since subbasin areas were usually larger than groundwater grid cells (in the size of 4km×4km), one-to-many mapping from the subbasins to the grid cells were implemented in this study. Similar approach was applied in our previous study in coupling air-ground transport models [33]. Hydrologic components such as ET and recharge were calculated at HRU level, then summarized and evenly distributed over the groundwater cells in the subbasin.

(4) SWAT-predicted groundwater recharge, evapotranspiration, and groundwater pumping were assigned to the grid cells for MODFLOW simulation according to the mapping table. At the same time, the predicted groundwater components such as water table would be passed to the surface water modeling for the determination of groundwater exploration, soil water content, and associated processes such as plant growth and evapotranspiration.

The conceptual model for SWAT-MODFLOW coupling was similar to those by Kim et al. [26] and Guzman et al. [27] in terms of the simulated interface processes between surface water and groundwater. Guzman et al. [27] did not explicitly consider groundwater evapotranspiration. In Kim et al. [26], groundwater recharge was proposed to be distributed by "HRU-CELL conversion", which could be technically difficult according to commonly used HRU definitions. HRU is usually defined by selected types of landuse and soil, while other minor (by area) landuse and soil are not considered in the SWAT simulation. In most case especially for large watersheds, therefore, HRU is not geo-referenced, but only presented as the percent coverage of the subbasin area for a combination of specific landuse, soil, and slope. To spatially locate HRU's, one has to define them by using all available landuse and soil types, and results in a large number of discrete polygons (from the intersection of landuse and soil maps). This requires a very complicated HRU-CELL relationship and also requires a high spatial resolution of groundwater grids.

2.2 Site Description

The HRB is located in North China, covering an area of 318,200 km^2 between 35~43 °N latitude and 112~120ºE longitude (Fig. 2). Majority of the basin is within the Province of Hebei, and other enclosed provinces are Liaoning, Inner Mongolia, Shanxi, Henan, and Shandong. Detailed description of the study area was documented in our previous studies [11]. A very complex hydrology system is observed in the basin. All rivers are originated from the Taihangshan Mountains to the west or from the Yanshan Mountains of the Mongolian Plateau to the north. The mountain and plateau region accounts for 60% of the total area, while the basin floor, conventionally defined as areas with elevation less than 100 m, accounts for 40% of the total area. Streams generally flow from west to east, forming nine major watersheds, and discharge into the Bohai Sea. In the basin floor, stream runoff is highly controlled by dams and reservoirs to satisfy water demands by agricultural and industrial productions.

The study area belongs to the semi-humid climate in the monsoon region of the East Asia warm temperate zone [10, 34], characterized by hot and wet summers and cold and dry winters. Average temperatures in the basin are between -4.9 and 15.0ºC. Annual precipitation ranges from 359 to 848 mm, and majority of annual precipitation was contributed by summer months of June to September, which are conventionally defined as flood season.

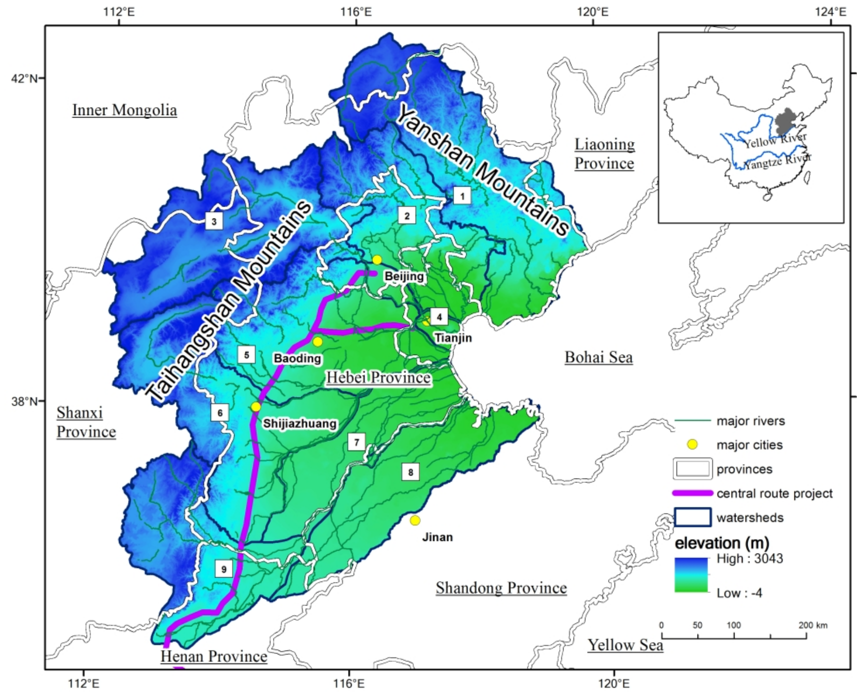

Fig. 2. Location of the Haihe River basin. See watershed description in Table 1

Table 1. Descriptions of the watersheds and groundwater regions delineated in this study

River system	Watersheds (Fig. 2)	Groundwater regions (Fig. 4)
Luanhe River and East-Ji Rivers	[1]	[14]
Beisihe River	[2]	[11] (in Hebei Province) [13] (in Tianjin City) [15] (in Beijing City)
Yongdinghe River	[3]	
Haihe River mainstream	[4]	[8]
Daqinghe River	[5]	[9] (in Hebei Province) [10] (in Hebei Province) [12] (in Beijing City)
Ziyahe River	[6]	[6]
Heilonggang and Yundong Rivers	[7]	[7]
Tuhaihe River and Majiahe River	[8]	[1] (in Henan Province) [3] (in Hebei Province) [5] (in Shangdong Province)
Zhangweihe River	[9]	[2] (in Henan Province) [4] (in Hebei Province)

2.3 Simulation Design

2.3.1 Landscape characterization

The study area was delineated into 283 subbasins according to stream network and irrigation districts. Elevation data is taken from Haihe Digital Elevation Model (DEM) at resolution of 90m×90m. Stream network was based on 1:250,000 hydrography data. Stream network is very complex in the plain area of the basin due to agricultural production and irrigation water diversion. In those areas, manual delineation was conducted in addition to DEM-based automatic delineation. Watershed delineation in HRB also considered the administrative districts, availability of climate data, and reservoir locations. Outlets of rivers to the Bohai Sea were also generalized to simplify the hydrologic system. Finally, 17 outlets were defined for the entire simulation domain (Fig. 3). Daily weather data was retrieved from China Meteorological Data Sharing Service System [35]. Hargreaves method in SWAT was selected for the calculation of potential evapotranspiration (PET).

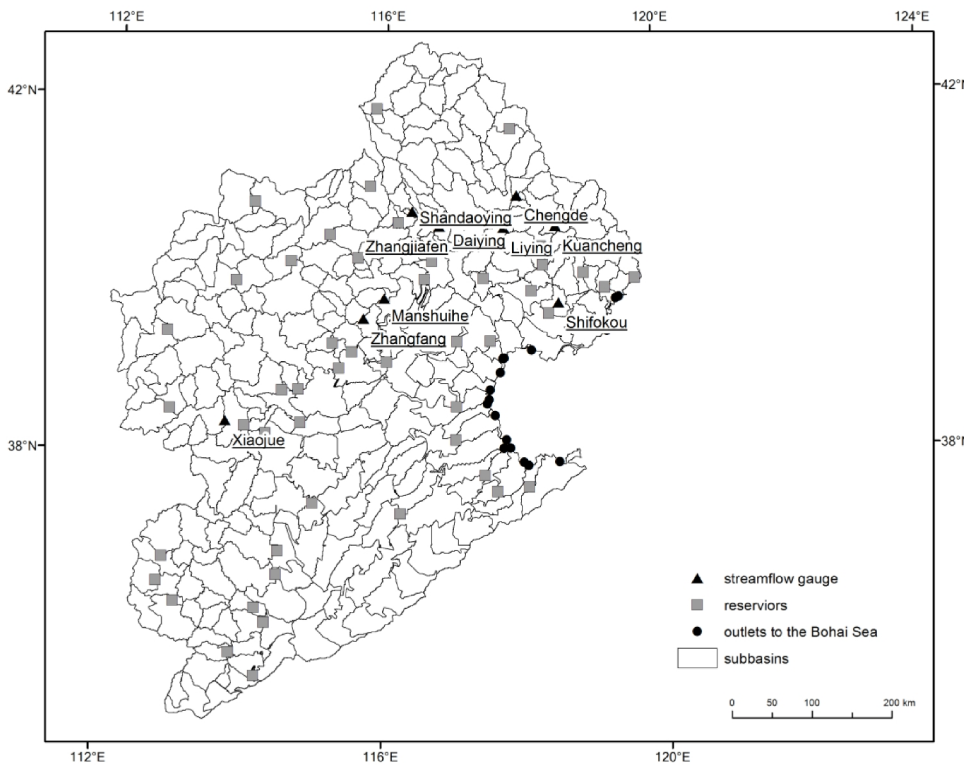

Fig. 3. Watershed delineation in the HRB

More than 1,800 reservoirs were built in the basin, with total storage capacity of 31.4 billion m^3, similar to the total natural runoff amount of 37.2 billion m^3 [9]. Only 48 reservoirs with middle or large capacities were selected lumped in the model simulation. For each subbasin, at most one reservoir can be defined and assigned near to the subbasin outlet to downstream subbasin. In this study, reservoirs were simulated based on prescribed monthly discharges.

In each subbasin multiple hydrologic response units (HRUs) were distributed by overlapping slope, land use, and soil maps. Totally 2100 HRUs were defined in the study area. Land use maps were developed based on MODIS remote sensing data and re-arranged into 250m×250m grid system. Totally 20 types of land use were defined and associated with SWAT standard land use codes. Table 2 shows the inventory of input data for SWAT model initialization.

Table 2. Inventory of GIS databases for modeling parameterization in the Haihe River basin

Dataset	Description
I. Basic geographic information [36]	
DEM	90m×90m
Stream network	1:250,000
Reservoir	Location, dimension, and capacity
Hydrologic and administrative districts	River system, water resource region, province, county, and city
Irrigation districts	33 districts with irrigated area
Soil map	1:1,000,000 with 27 soil classes and associated soil properties
II. Weather data [35]	
Precipitation	Daily data from 286 stations
Temperature, wind speed, relative humidity, and solar radiation	Daily data from 54 stations
III. Remote sensing data [37]	
Land use	250m×250m
Evapotranspiration	Remote sensing generated annual ET for 2002-2005
IV. Water consumption	Agricultural, domestic, and industrial uses; and groundwater exploitation. Data was retrieved from the Water Resources Bulletin published by the China Ministry of Water Resources [12]. Data description and analysis were available in the previous studies [17,18]

Daily stream flow measurements were only available for a few locations along rivers in the study area. For most regions of HRB, only monthly or annual averages of hydrologic variables were recorded. In addition, human-controlled water releases from reservoirs and water diversions in agricultural areas, especially those during dry seasons, did not significantly reflect the weather condition and landscape characteristics in upstream subbasins. Therefore, an integrated model evaluation method was developed in this study to develop and validate the SWAT model in HRB. In this method, different hydrologic variables were selected as target parameters for different subbasins according to their characteristics. For subbasins in mountainous areas with limited human impacts, i.e., those without large reservoirs, traditional model evaluation was applied by comparing predicted and measured streamflow as monthly averages at the subbasin outlets. For subbasins in plain areas which are heavily influenced by human activities, measured stream flow data was not usually associated with the hydrologic processes and not comparable to the simulated monthly variations. For those subbasins, we compared annual averages of river discharges to sea and water balance established at administrative district level. In addition, model validation was based on the comparison between predicted and measured evapotranspiration as suggested by experts in the World Bank. Based on the newly developed integrated model evaluation, the calibrated model was anticipated to provide reasonable simulation on the spatial distribution and temporal pattern of hydrologic processes in HRB.

2.3.2 Groundwater characterization

Groundwater exploitation and management are mainly focused on the basin floor of the HRB. The basin floor was selected as simulation domain for MODFLOW, which is generally defined by DEM>100m and covers an area of 120,000 km^2. This area was further divided into 4km×4m grid cells. Compared to the average HRU area of 151 km^2, the spatial resolution of groundwater segmentation was roughly 10% of that for landscape delineation. Horizontally, the aquifer of interest was delineated into 15 regions according to the lithologic characterization and survey areas. Vertically, the aquifer was segmented into 3 layers: the first layer for roughly 25~75m below the ground surface, the second layer from 75~200m and the third layer for >200m.

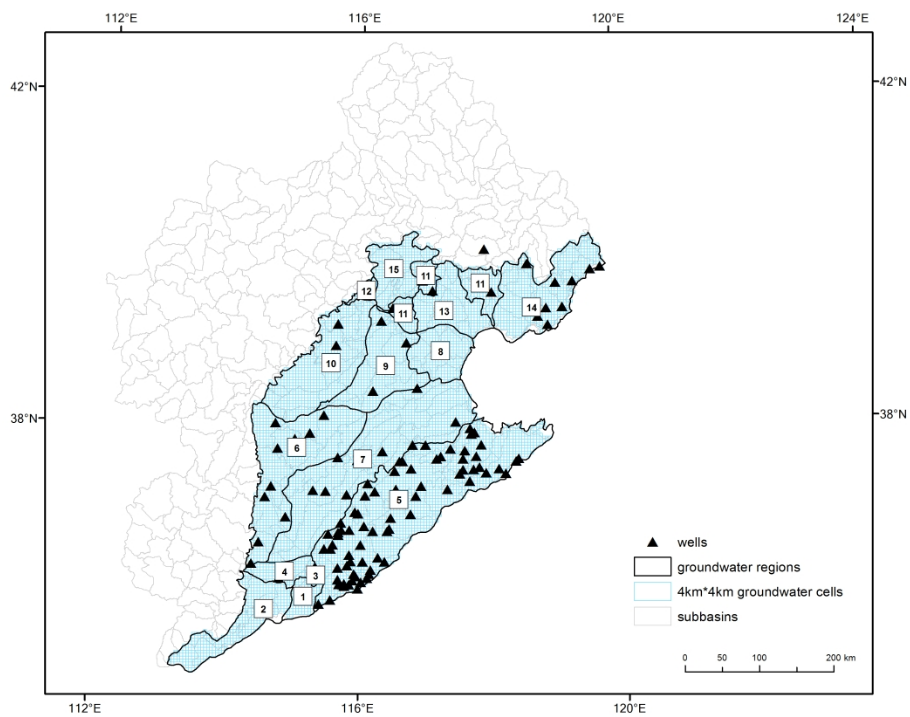

Fig. 4. Groundwater characterization in the HRB. See groundwater region description in Table 1. MODFLOW boundary conditions: general-head condition for the north and west sides to the Yanshan and Taihangshang mountains, no-flux condition to the south side, and fixed head condition for the east side adjacent to the Bohai sea

In addition to infiltration from land surface and river channels, the simulated groundwater domain was also significantly supplied by the Yanshan and Taihangshang mountain systems (Fig. 2). Therefore, general-head boundary condition was implemented for the north and west sides of the domain. The south side of the study area is adjacent to the lower Yellow River basin. The south boundary was generally perpendicular to the groundwater head contours [38]. Therefore, we assumed that there was insignificant flux cross the south boundary, and a no-flux condition could be introduced in the subsurface model. When data is collected, the boundary conditions could be further redefined. In addition, a fixed head boundary condition was assumed for the east side of the study area adjacent to the sea, and no flux boundary for the bed rock. The groundwater flow is based on a transient simulation. We had head measurements from the year 1995 to 2004. We interpolated head measurement in the year 1995 to a head field as initial condition, which was also the boundary condition for the north and west boundaries for the water supply from the mountainous areas. We used the measurements from 30 wells during the year 1996 to 2004 in our calibration (1996-1998) and validation (2002-2004) processes.

2.3.3 Climate change and water diversion scenarios

Modeling scenarios were incorporated into the developed SWAT-MODFLOW model to characterize the effects of climate change and water resource management on the hydrologic variables. Projected climate data was taken from Chinese National Climate Center (CNCC) for the IPCC SRES A2 (high emission) and B1 (low emission) emission scenarios at a resolution of 1º by 1º. The data was processed by arithmetic averaging or Reliability Ensemble Averaging from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset [39] (Table 3). Data was processed as monthly average precipitation and temperatures (maximum temperature, minimum temperature, and average temperature) for the East Asia.

Table 3. The list of GCMs models for the two scenarios *SRES A2 and B1*

SRES A2	SRES B1
BCCR_BCM2_0	BCCR_BCM2_0
CCMA_3-T47	CCMA_3-T47
CNRMCM3	CNRMCM3
CSIRO_MK3	CSIRO_MK3
GFDL_CM2_0	GFDL_CM2_0
GFDL_CM2_1	GISS_AOM
GISS_E_R	GISS_E_R
INMCM3	IAP_FGOALS1.0
IPSL_CM4	INMCM3
MIROC3	IPSL_CM4
MIUB_ECHO_G	MIROC3
MPI_ECHAM5	MIROC3_H
MRI_CGCM2	MIUB_ECHO_G
NCAR_CCSM3	MPI_ECHAM5
NCAR_PCM1	MRI_CGCM2
KMO_HADCM3	NCAR_CCSM3
	UKMO_HADCM3

Retrieved data included monthly precipitation and air temperature for two 10-year periods of 1991-2000 (representing a current climate condition) and 2041-2050 (the middle of the 21st century). Relative changes of the GCM data between the two periods were calculated as long-term averages for each month. Compared to the present-day climate, annual precipitation in the HRB will increase by 10.9% and 15.6% for A2 and B1 scenarios, respectively, according to the climate projections. Temperature was also projected to increase between the two periods (e.g., 1.0~3.5 ºC increments for B2 scenario over the study area). Similar trend was also identified for the study area by previous studies [6, 19, 20, 40]. For example, based on the HADCM3 model only, Chu et al. [6] reported increases in annual precipitation by 7% in A2 scenario during 2011-2040.

The "delta change" method [41] was used to incorporate the climate change data into SWT simulation. For each weather station, the future climate scenario was defined by the observed precipitation and temperatures during 1991-2000, adjusted by the relative changes between 1991-2000 and 2041-2050 based on GCM data in the nearest 1°×1° node to the station. No changes were made for other climatic variables of solar radiation, wind speed, and relativce humidity. The calibrated SWAT model was applied to two climate scenarios: baseline climate scenario (1991-2000) and climate change scenarios (2041-2050). The baseline simulation was based on observed precipitation and temperature data. For the climate change scenario, the relative changes derived from the GCM data between the two periods 1991-2000 and 2041-2050 were introduced into the baseline simulation, by assigning the corresponding values to the user-defined monthly adjustments on precipitation and temperature for each subbasin (SWAT input parameters of RFINC and TMPINC, respectively, in the "sub" input files).

In addition to climate change, proposed water diversion will also have significant influence on the water resources in the study area. To remedy the imbalance of water supply and demand in northern China, China aims to finish the "South-to-North Water Transfer Project" (SNWTP), which is designed to funnel 44.8 billion m^3 of water per year by three routes from Yangtze River to the north. The central route (Fig. 2) of the project would divert up to 9.0 billion m^3 of water per year water to the HRB. For model simulation, spatially, the 9.0 billion m^3 of water would be distributed to the target counties in the study area by following the designed water demands. Temporally, since the diverted water would be mainly for domestic and industrial uses, we assumed evenly amount of water delivery in a year. Water diversion is also associated with a new regulation for water allocation. Generally, the diverted water is mainly used for domestic and industrial demands to minimize their dependence on local sources. Saved water will be used for agricultural sectors to reduce the amount of groundwater exploitation in the area. Therefore, agricultural water supply in the future will be more rely on surface water. The central route will be ready to divert water since the year 2014, and reach its full capacity by 2030 [42]. However, the construction and operation of the SNWTP are associated with great uncertainty. For example, our previous study indicated that the water supply area for the central route might not have sufficient water for diversion in the near future [43]. Therefore, model simulations were conducted with two scenarios: [1] climate change only (without water diversion), and [2] climate change with water diversion. Scenario-based simulations were conducted by introducing new climate data and water allocation to the SWAT-MODFLOW calibrated for the current condition. To simplify the model configuration and focus on the effects of future climate and water diversion on groundwater in the HRB, therefore, we assumed that other conditions such as land use, soil data, population, and water demand were invariant between the current condition and the simulated scenarios.

3. RESULTS AND DISCUSSION

3.1 SWAT Calibration and Validation

SWAT input parameters to be calibrated were selected based on our previous studies [44, 45] and preliminary sensitivity analysis, mainly including the SCS runoff curve number (CN), available soil water content (SOL_AWC), baseflow alpha factor (ALPHA_BF), and groundwater "revap" coefficient (GW_REVAP). For mountainous areas, SWAT performance was evaluated by comparing predicted streamflow with measured data at the 10 streamflow gauges (Fig. 2). Daily streamflow was retrieved from Chinese Academy of Sciences [7], and summarized as monthly data for model evaluation. Model was initialized for the year 1995, and simulation was conducted for 1996-1998 (model calibration) and for 1999-2006 (validation). The objective function was defined to maximize the Nash-Sutcliffe efficiency (NS) [46] between observations and predictions at the outlet of each selected watersheds. The coefficient of determination (R^2) was also provided as an additional statistics for model performance. According to guidelines for evaluating watershed simulations, "satisfactory" simulations can be judged by statistics of NS>0.5 for hydrologic processes [47]. For each gauge, model performance was similar for the periods of calibration and validation, so we only reported statistics over the whole 11-year simulation period of 1996-2006 (Table 4). Generally, the model reasonably captured the spatial variability and temporal trend on river discharges in the study area. With appropriate calibrations, SWAT generated satisfactory (NS>0.5) results at most gauges in comparison with the observed monthly streamflow. The average NS for the 10 gauges was 0.59, ranging from 0.33 to 0.70. Comparison between observed and predicted discharges to sea indicated a median relative error of -4% (Table 5). Large errors were observed for dry years for the corresponding watersheds, such as Luanhe River and East Ji Rivers in 2000 and Tuhaihe River and Majiahe River in 1997. Therefore, results of model evaluation on predicted streamflow suggested that the developed model had the capability in simulating essential hydrologic processes including surface runoff generation and in-stream routing in the field conditions of HRB. This supported the model capability in water resource management, and the modeling results and their statistics might be used as references for the future water resource analysis. At some gauges, SWAT failed to capture the flood events with very high flow rate. This may be related to the homogeneous assumption of SWAT, e.g., basin-wide average parameters for snowmelt simulation and one set of parameters for all channels in each subbasin. Further calibration, especially by including more input parameters, may improve the model performance, but increases the modeling complexity and goes beyond our study scope.

Table 4. Predicted and observed annual average streamflow at the streamflow gauges for model evaluation (Fig. 3) during 1996-2006

Gauge ID	Gauge name	Drainage area (km^2)	Average flow (cms)	NS	R^2
136	Xiaojue	14000	11.3	0.70	0.89
163	Zhangfang	4810	6.5	0.64	0.66
166	Manshuihe	653	1.3	0.61	0.65
172	Shandaoying	1600	2.2	0.33	0.64
176	Zhangjiafen	8506	8.1	0.57	0.62
193	Chengde	2460	2.8	0.60	0.66
186	Kuangcheng	1661	2.8	0.63	0.83
218	Shifokou	429	1.4	0.54	0.73
273	Liying	626	2.2	0.62	0.66
280	Daiying	4700	4.5	0.64	0.80

Notes: NS=Nash-Sutcliff coefficient, R^2=coefficient of determination, and cms=cubic meter per second

Water discharge to the sea is a very important parameter in evaluating water balance in the entire HRB. Assessment of model capability was based on the comparison of water discharge between predicted and observed data at three river outlets. Results of comparison indicated that the model generally simulated the annual variation of water release from the three major rivers in the study area. Further data analysis also suggested that human activities had strong influence on the hydrologic processes, especially for the middle and lower reaches in plain regions. One of the consequences is the large and episodic drop in stream flow during irrigation months. This finding was also consistent with those in Feng et al. [48] and Chen et al. [49] which reported decreased water discharge during dry seasons and associated eco-environmental problems in other semi-arid watersheds of China.

Table 5. Predicted and observed river discharge to sea (billion m^3/year) in the study area

Year	Watershed [1]			Watershed [8]			Watershed [4]		
	O	**P**	**E**	**O**	**P**	**E**	**O**	**P**	**E**
1996				2.51	2.19	-0.13			
1997	0.44	0.37	-0.15	0.06	0.64	8.82	1.30	1.14	-0.13
1998	1.65	1.42	-0.14	1.88	1.80	-0.04	5.44	5.67	0.04
1999	0.21	0.29	0.41	0.10	0.17	0.59	0.77	0.34	-0.55
2000	0.10	0.39	2.95	0.22	0.36	0.65	2.21	0.80	-0.64

Notes: O=observed discharge (billion m^3/year); P=predicted discharge (billion m^3/year); and E=relative error (dimensionless). Watershed [1]: Luanhe River and East Ji Rivers; [4] Haihe River mainstream; and [8] Tuhaihe River and Majiahe River (Fig. 2). For each watershed, if there are multiple outlets to the Bohai Sea, their discharges are summarized and reported in the table.

Predicted ET was compared to the ET values derived from remote sensing based on Surface Energy Balance Algorithm for Land (SEBAL) [50, 51]. Remote data processing was conducted in a separate project by Institute of Remote Sensing Applications, the Chinese Academy of Sciences. The relevant methodology and results have been published previously [37, 52-54]. Fig. 5 shows the comparison of predicted and observed annual ET over the 283 subbasins during 2002-2005. SWAT model reasonably predicted the spatial variability on ET with NS ranging from 0.72 to 0.86. According to Thoreson et al. [55], SEBAL remote sensing ET was very close to the water balance based ET in arid, advective environments. By calibrating with SEBAL ET, therefore, the model predicted ET could be used in the district-wide water balance calculation. The application would generate helpful information for improved agricultural water management at watershed and region scales.

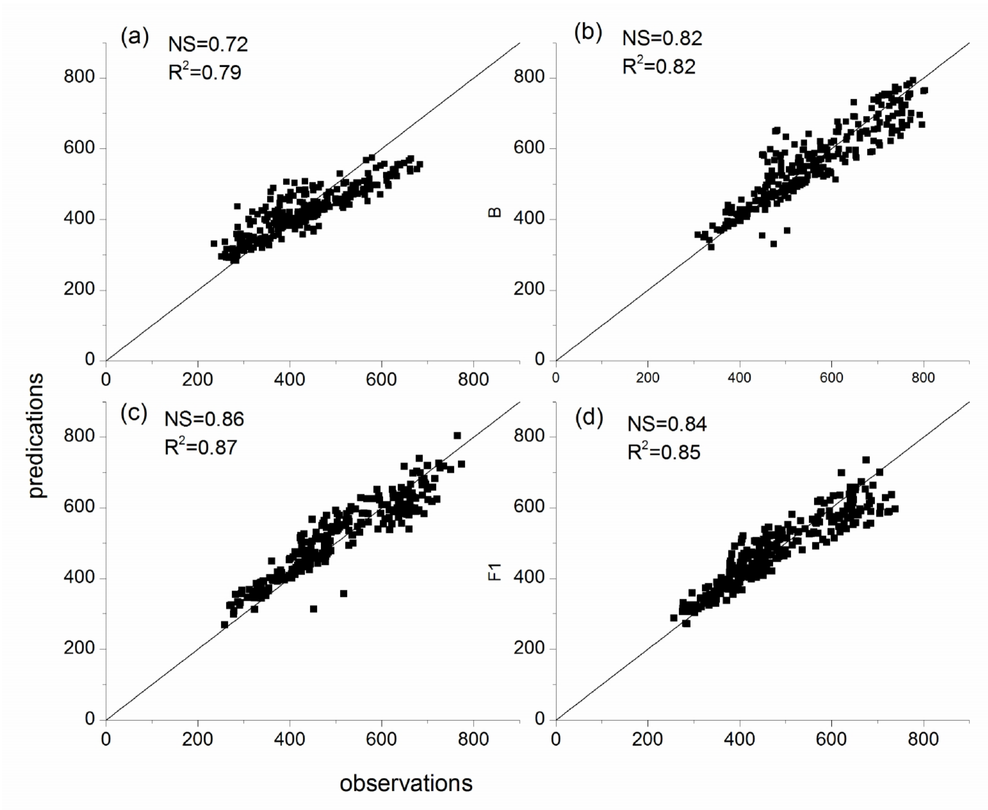

Fig. 5. Predicted and observed evapotranspiration rate (mm/year) in the 283 subbasins for (a) 2002, (b) 2003, (c) 2004, and (d) 2005.

3.2 Evaluation of Coupled SWAT-MODFLOW

We calibrate the coupled model based on available hydraulic-head measurements from year 1996 to 1998 at locations spread out in the basin (Fig. 4). Stress terms are known in our parameter estimation. We also assume that the specific storage coefficients S_0 of the three layers are known. The S_0 for the unconfined aquifer of the first layer is the specific yield S_y. The calibration parameters are the spatial distributions of horizontal hydraulic conductivity (K_h), the anisotropy ratio (K_h/K_v) between the horizontal and vertical hydraulic conductivity (K_v), and a multiplier of the hydraulic conductivity between the upper and lower layer. Here, we assume that hydraulic conductivity decreases with depth and the lower layer has the same pattern of spatial distribution of hydraulic conductivity, but scaled down by a multiplier. These parameters were selected by preliminary sensitivity analysis. The K_h distribution was estimated with the geostatistics-based Pilot Point Method [56, 57]. In this study, 30 pilot points were applied regularly in the simulation domain of MODFLOW.

The estimated hydraulic conductivity field (Fig. 6) was with a mean about 18 m/day and a variance in natural logarithm-scale about 1.5. The model satisfactorily simulated hydraulic heads in the study area, with NS of 0.97 and 0.84 for calibration (the years from 1996 to 1998) and validation (2002-2004) periods, respectively. Hydraulic conductivity was calibrated in parallel for two subregions divided by the longitude about 116ºE. Slightly higher differences were observed between some cells across the subregion boundary in comparison to other locations, showing as abrupt change of hydraulic conductivities in Fig. 6. For the calibration, the mean absolute error between the model simulated hydraulic heads and the measurements was about 1.8 meters, while for validation it was about 4.5 meters. Both calibration and validation showed errors in the same range with large regional models [58, 59]. This indicated that the calibrated hydraulic conductivity field captured the major features of the aquifer in the basin floor. Overestimation was observed during the validation period. As mentioned before, measured data in 1995 was used as boundary conditions for calculating water supply from the mountainous areas in the north and west sides of the study area. However, significant drop of groundwater table was detected between 1995 and the validation period (2002-2004) [15]. Therefore, the use of measured hydraulic heads overestimated the actual condition in the validation period, resulting higher subsurface flow across the boundaries and higher predicted heads than the actual conditions.

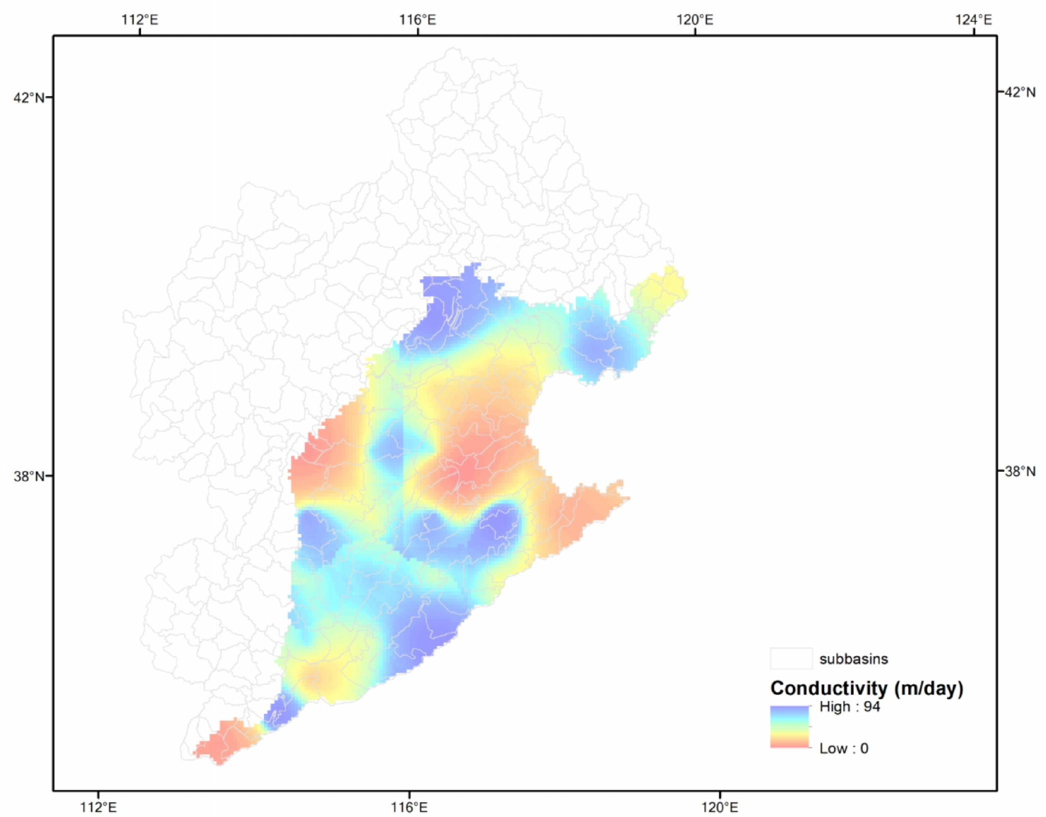

Fig. 6. Estimated field of hydraulic conductivity of the first layer of the subsurface model. Note: MODFLOW was only applied to the area of basin floor

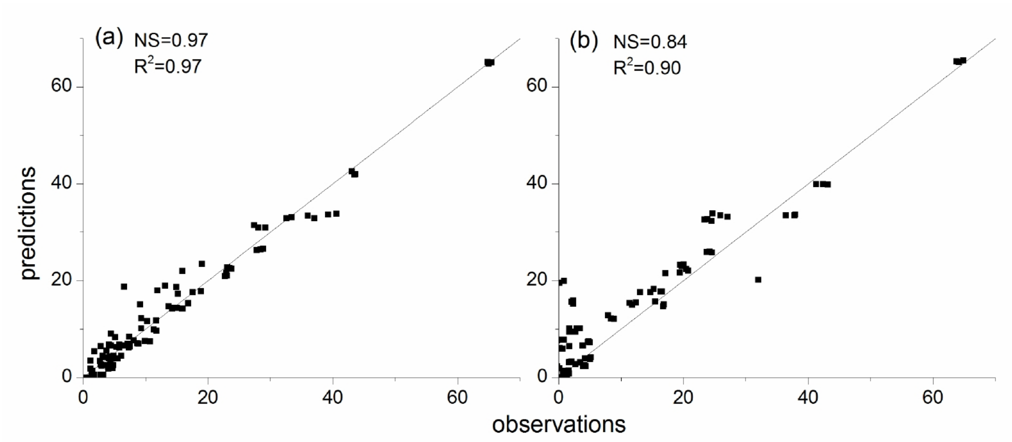

Fig. 7. Predicted and observed groundwater head (m) during (a) calibration period of 1996-1998 and (b) validation period of 2002-2004.

3.3 Impacts of Climate Change and Water Diversion

Compared to the baseline simulation of 1991-2000, incorporation of future climate in the coupled SWAT-MODFLOW model suggested an increase of about 10% for annual actual evapotranspiration in the HRB during 2041-2050 for both emission scenarios A2 and B1, mainly contributed by spring and summer seasons (Table 6). Due to the increased precipitation, predicted annual total river discharge would increase by 19.4% for A2 and 41.4% for B1 scenario (Table 6). In addition to the higher precipitation increase (15.6% for B1 vs. 10.9% for A2), change of river discharge for B1 scenario was also associated to the projected seasonality of precipitation: maximum precipitation increase (21.7%) was predicted for summers (i.e., the flood season of the HRB). Consequently, river discharge in summers was increased by 56.1% for B1 scenario. For A2 scenario, springs and falls were associated with significant precipitation increases (18.8% and 15.1%, respectively), resulting in higher river discharges in those seasons (63.3% in springs and 40.4% in falls).

The increases of discharge would be significantly moderated by water diversion and associated new regulations. By considering both projected climate change and water diversion, the annual total runoff over the study area would still increase but in a smaller rate (8.1% for A2 and 20.7% for B1) relative to the scenarios with climate change only. This was related to the proposed water regulation which increases water supply from surface water for agricultural use in order to minimize water exploitation from groundwater. In the modeling viewpoint, part of the increased river discharge (especially during the flood seasons) by increased precipitation would be used to minimize groundwater exploitation, and resulted in relatively small increases compared to the simulation results with climate change only (e.g., relative increase of river discharge during summers was 56.1% with climate change only, and reduced to 31% with water diversion and new regulation, Table 6). This is consistent to the water management practice called "control and utilization of flood water resource" which has been intensively discussed in the semi-arid areas including the HRB [60-62].

Table 6. Predicted relative changes (%) for precipitation, actual evapotranspiration, and river discharge under projected climate change and water management

	Precipitation		Climate change only				Climate change and water diversion			
			Actual ET		River discharge		Actual ET		River discharge	
	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
Spring	18.8	8.0	12.3	7.3	63.3	10	13.1	8.1	51.7	-0.4
Summer	7.7	21.7	10.0	15.1	10.9	56.1	10.3	15.5	-1.8	31.0
Fall	15.1	4.6	9.5	6.4	40.4	2.1	10.3	7.2	28.5	-9.9
Winter	3.8	-6.1	4.0	-1.8	0	0	6.7	1.0	8.1	2.5
Annual	10.9	15.6	10.0	10.3	19.4	41.4	10.7	11.0	8.1	20.7

Groundwater exploitation would be significantly reduced due to water diversion and associated regulations. Predicted relative changes were -28.5% and -36.5% for A2 and B1 scenarios, respectively (Table 7). With water diversion implemented, groundwater would be mainly used for agriculture. This explained the higher reduction in groundwater exploitation predicted during the irrigation seasons in spring and fall. By considering the water balance in groundwater, the predicted reduction in groundwater exploitation suggested annual gains of 1.7 and 2.9 billion m^3 per year in shallow aquifer (indicating net positive changes in groundwater storage), in comparison to the present-day condition of -2.9 billion m^3. Increase of groundwater storage was generally predicted in the basin floor. Larger increase was predicted at the metropolitan areas of Beijing, Baoding, and Shijiazhuang which are the major receptors of the diverted water, with maximum increase of water level of 4.9 m. Changes in groundwater storage were also contributed by that in groundwater recharges (Table 7), which was significantly correlated to the projected precipitation (Table 6). Groundwater recharge was mainly affected by climate change, i.e., similar changes were predicted for both scenarios with climate change only and with climate change and water diversion.

Table 7. Predicted relative changes (%) of groundwater exploitation and recharge under the scenario with climate change and water diversion

	Shallow aquifer exploitation		Groundwater recharge	
	A2	**B1**	**A2**	**B1**
Spring	-44.7	-51.0	63.5	4.1
Summer	-20.2	-29.0	10.3	46.1
Fall	-42.3	-49.4	30.0	-8.4
Winter	-21.8	-30.2	-12.3	-19.4
Annual	-28.5	-36.5	18.2	29.6

Notes: groundwater exploitation change was only predicted after the water diversion.

4. CONCLUSION

With appropriate calibration, the coupled SWAT-MODFLOW satisfactorily simulated the surface water and groundwater interaction in the Haihe River Basin. The coupled model enables simultaneous prediction of hydrologic components in canopy, land surface, soil, and aquifer. Furthermore, the characterization of water exchange across the vadose zone and groundwater makes it possible to represent the potential impacts of climate change and management practices on groundwater, especially for semi-arid and rapidly developing regions such as the Haihe River basin.

The study area is extensively affected by human activities, such as hydrologic construction, groundwater exploitation, and agricultural/industrial development. An integrated approach was applied for SWAT model evaluation, by utilizing limited data of monthly and annual streamflow, runoff depth, discharge to sea, and evapotranspiration. With appropriate calibrations, SWAT model had the capability in simulating essential hydrologic processes including surface runoff generation and in-stream routing in the field conditions of HRB. Average Nash-Sutcliffe coefficient was averaged 0.59 over the 10 streamflow gauges in the model calibration. In addition, comparison between observed and predicted total discharge to seas and evapotranspiration indicated good model performance, suggesting an appropriate level of accuracy for water resource management. Outputs of groundwater recharge and evapotranspiration from the calibrated SWAT, together with groundwater pumping data, were distributed to the grid cells of MODFLOW. By compared to measured groundwater hydraulic head, hydraulic conductivity was calibrated with an average of 18 m/day and a variance of 1.5 in natural logarithm-scale over the HRB. The SWAT-MODFLOW satisfactorily simulated hydraulic heads in the study area, with NSE of 0.97 and 0.84 for calibration (the years from 1996 to 1998) and validation (2002-2004) periods, respectively.

Model application in this study demonstrated the use of surface water-groundwater coupled model for scenario analysis on water resources issues such as water scarcity and groundwater over-pumping. In the HRB, predicted precipitation, actual ET, and river discharge general increased by 10% or more under climate change scenarios. Changes of groundwater storage were mainly contributed by water diversion which would reduce the requirement of water pumping from groundwater especially for domestic and industrial uses. By the middle 21st century with projected climate change and water diversion, 3.9~9.9 billion m^3 increase of river discharge is expected in the study area, and the groundwater recharge will exceed consumption by 1.7~2.9 billion m^3 per year.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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