Case Study

Comparing the Economic and Environmental Effects of Different Water Management Schemes Using a Coupled Agent–Hydrologic Model

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Abstract: Confronted with diverse water management schemes, policymakers in arid basins face difficulty in choosing a particular scheme due to a lack of appropriate tools to estimate possible physical and economic outcomes in a comprehensive manner. This study develops a coupled agent–hydrologic model to both capture and provide insights into the dynamics and patterns of real-world water management using the midstream area of the Heihe River Basin in northern China as a case study. Water consumption patterns, economic efficiency, and environmental externalities of three different management schemes, namely an administered scheme (AS), a surface-water market scheme (SWMS), and a surface-water–groundwater market scheme (SGWMS) are evaluated. The results show that an agent's (irrigation district) behaviors under market schemes are determined by the difference between equilibrium price and pumping cost, related to water table depth. The annual total benefits are improved under market schemes, especially in dry years. Negative environmental effects of the market schemes do occur but are not significant. The travel time of groundwater corresponds to a delay longer than 2 months in upper agents' pumping influence on drawdown. In general, the proposed model application in this study addresses complex real-world management issues by presenting physically interpretable and verifiable outcomes, and therefore aids policymakers in decision making by providing a broader view of water management. **DOI: 10.1061/(ASCE)WR.1943-5452.0001074.**

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Introduction

Water management schemes usually include centralized administered schemes (AS), decentralized market-based schemes (MS), or a combination of the two (Zhao et al. 2013). The AS is advocated for equity and sustainability of water allocation because the primary responsibility of an AS depends on governments or management authorities (Draper 2008). Although an AS can also lead to efficient water allocation through a subsidy/penalty mechanism (Zhao et al. 2013), a MS is highly recommended by economists because it promotes water trading and increases the output per unit of water used (Howe et al. 1986) because water transfer is altered by trading from relatively low-value, inefficient irrigation canals to a more advanced approach and more valuable users in area suffering from water scarcity (Zhang 2006).

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Faced with multiple management options, policymakers have difficulty in determining the appropriate water management schemes in arid and semiarid basins and as a result, desire transparent methods to model the possible physical and economic outcomes of different management schemes. Complex tools are required to model such outcomes, which emphasize the suitable representation of human activities, hydrologic processes, and their interactions. In such coupled social–ecologic systems, human activities in river basins are influenced by environmental circumstance and also alter natural components in return (Vörösmarty et al. 2013; Berglund 2015). Thus, adequate consideration of human–water interactions is an important component required to improve the understanding of hydrologic processes and the management of river basins (Cai 2008; Linhoss and Ballweber 2015). This consideration challenges the emphasis on purely natural-science-based hydrologic modeling and purely social-science-based institutional analysis (Vogel et al. 2015).

In this context, models coupling human activities with hydrologic processes have been successfully developed as solution-oriented tools for integrated water resources management (Mariño and Simonovic 2001; Harou et al. 2009; Pulido-Velazquez et al. 2016) and water policy analysis (Mulligan et al. 2014; Wu et al. 2015). Hydroeconomic models are frequently used methods for water management study because they can represent temporal and spatial patterns of water resource systems, management choices, and economic values in an integrated manner (Draper et al. 2004; Marques et al. 2006; Harou et al. 2009). When focus is given to the behavior of stakeholders, an agent-based modeling (ABM) approach is widely adopted for simulation of domestic water consumption in complex water systems (Galán et al. 2009; Ma et al. 2012), groundwater management (Mulligan et al. 2014; Castilla-Rho et al. 2015), water allocation management (Yang et al. 2009, 2012), and water contamination events (Zechman 2011;

Shafiee and Zechman 2013) because ABM can explicitly illustrate impact factors in the decision-making process (Soman et al. 2008). ABM usually includes (1) individual water users, i.e., agents; (2) the natural environment (e.g., river basin or groundwater aquifer) and engineering infrastructure where agents are physically located; (3) management schemes or rules; and (4) outcome metrics at the system-level, including both economic and environmental effects (Zhao et al. 2013).

For the application of ABM in coupled human–hydrologic modeling, surface and groundwater source interaction have mainly been simplified because of the high complexity level in whole river basin modeling (Kahil et al. 2016). This causes a gap of human–hydrologic models being able to simulate the policy outcomes accurately and address the policy debates clearly, especially in the basins where the aquifer system and river are closely related. The modular three-dimensional finite-difference groundwater flow model (MODFLOW) approach applied in this study, on the other hand, considers spatially varying components by gridded spatial discretization. It is basically software that can simulate groundwater dynamics and surface-water balance with three-dimension cells in the continuum volume of saturated zone, which is more suitable for simulating complex hydrological processes in the real world.

A coupled agent–hydrological model (CAHM) is then proposed by coupling the MODFLOW with the ABM framework presented by Zhao et al. (2013) to simulate the dynamics of groundwater and surface–groundwater exchange. Linked by the value of water table depth (WTD), the CAHM captures the systematic behaviors of the agents and compares the economic and environmental effects of different schemes. Hence, the CAHM proposed in the study is more suitable for exploring physical and economic patterns of water management by modeling the interaction between human activities and hydrological processes. This modeling approach will provide policymakers with insight into the viability of particular water management schemes to aid in decision making. A case study scenario of the Zhangye Basin (ZB) located in the midstream portion of China's Heihe River Basin (HRB) is applied by the CAHM, where acute conflict between midstream irrigation and downstream environmental flows exists due to the scarcity of water resources.

Methodology

Site Description

The HRB (Fig. 1) is located in northwestern China, covering an area of approximately 143,000 km^2. The Heihe River runs north from the southern Qilian Mountains to Juyanhai Lake, which is surrounded by grassland and a crucial oasis ecosystem downstream. The groundwater table of the aquifer varies from approximately 200 m upstream to approximately 5 m downstream, and the surface water and groundwater exchange is frequent. Approximately 95% of the HRB population live in the midstream area of the basin. The local economy depends on agriculture and as a result, consideration of the relationship between the midstream irrigation operations and the downstream ecosystem is critical for the whole basin's sustainable development. Therefore, this study focuses on the ZB in the midstream area of the HRB (Fig. 1). The ZB has an area of 8,778 km^2 from the Yingluo Valley to the Zhengyi Valley. It contains 30 irrigation districts (IDs) depicted in Fig. 1(b), which are defined as agents in this study. The potential evaporation of this area is 1,325 mm/year. whereas the precipitation is just 190 mm/year, indicating an extremely arid climate and an irrigation-based agricultural mode.

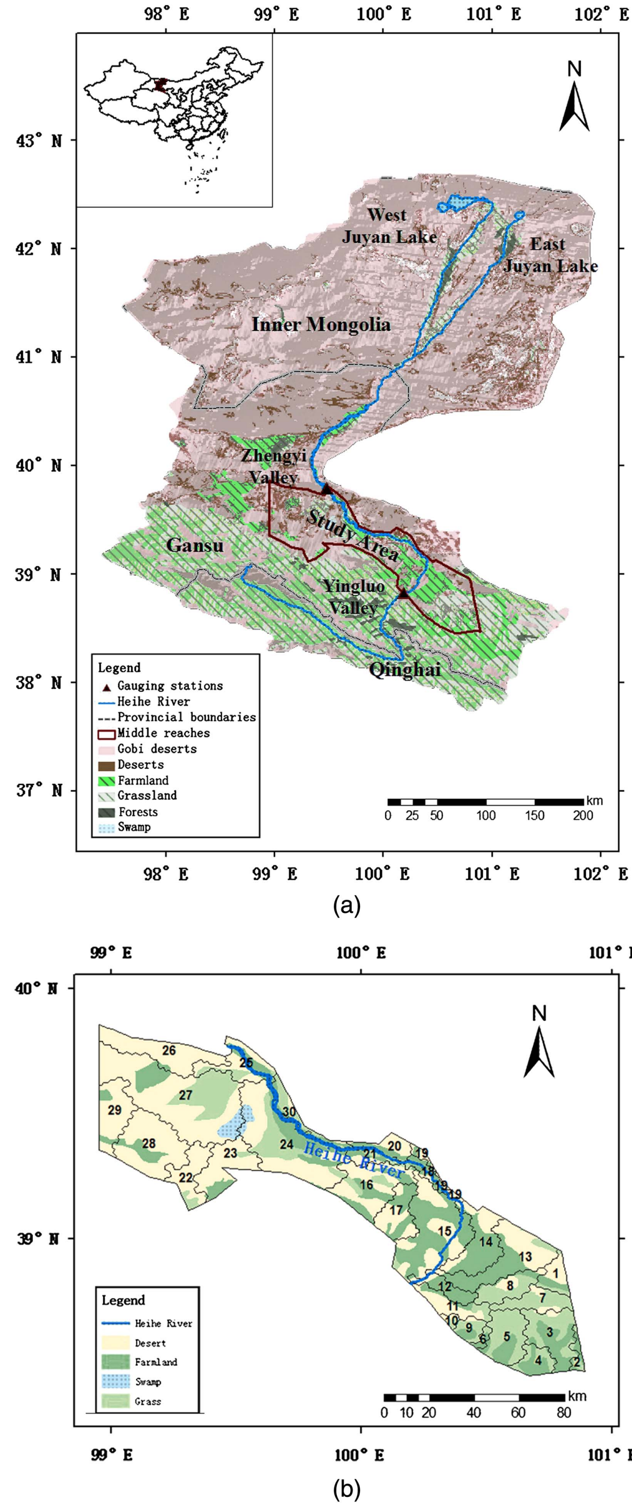

Fig. 1. Map of (a) Heihe River Basin; and (b) study area in midstream area including 30 agents (irrigation districts).

The rapid development of irrigation alongside growing water consumption in the midstream area have caused serious ecological problems downstream (Zhao et al. 2016). Action has been taken by the government to address these ecological problems by identifying an appropriate water-allocation policy involving stakeholder negotiation and government regulation. In 2000, a unified basin-scale regulation on water flow was carried out by the central government of China to balance human water demands in the midstream area of the HRB and the environmental flow required to protect fragile ecosystems downstream. This policy secured environmental flow at the Zhengyi Valley station (i.e., the boundary of the middle stream and downstream) under variable hydrologic conditions (Wu et al. 2015). Subsequently, the Ministry of Water Resources initiated a pilot project to build a tradable water market in the ZB; however, the water market system failed to be popular because of infrastructure and administrative barriers (Zhang 2006). It was reported that water trading in the arid northwest region of China usually occurred on a relatively small scale due to the lack of basic infrastructure and incorrect institutional settings (Xu et al. 2016). This study is thus motivated to support policymaking by providing tools to model the physical and economic results of different water management schemes.

Coupled Model: CAHM

Logic Framework

Taking the ZB as background, the CAHM was developed by linking the previously derived agent-based model with a hydrologic model built into MODFLOW. The agent-based model follows agents' behaviors in the MS as described by Zhao et al. (2013), and the formulation of the AS does not include penalties and subsides in the administered system, which is more realistic in the study basin. The hydrologic model described by Zhu et al. (2015) simulates the dynamics of groundwater and surface–groundwater exchange. It takes into account spatially variable components such as hydraulic parameters, boundary conditions, and volumetric fluxes through the incorporation of packages by gridded spatial discretization. The recharge module (RCH) simulates surface replenishment flux consisting of three parts: (1) irrigation return infiltration (including conveyance losses and field return) and drainage infiltration; (2) precipitation infiltration; and (3) groundwater exchange between cells, whereas the stream module (STR) simulates the surface-water consumption and downstream environmental flow at the Zhengyi Valley station.

The MODFLOW model and ABM are linked through surface-water consumption, groundwater pumping, and instream flow balance (determined by groundwater–streamflow exchange) at a monthly scale. Fig. 2 shows the logic framework of the CAHM. The final output includes economic and environmental factors that represent the effects and externalities of a scheme. Due to data availability, the simulation provided ran from 2001 to 2005 at a monthly timescale covering wet and dry years. Different policies are compared against the basin-scale unified water flow regulation scenario, which is an administered water allocation policy that started in 2000.

Assumptions and Data Preparation

The necessary condition of establishing a water market is the shortage of water; otherwise, agents are satisfied with their own quota and no transaction is required. Therefore the ZB was chosen because it is a location where conflict between human demands and environmental flow is severe. In practice, the MS is operated for the trade of temporary and permanent rights to water (Grafton and Horne 2014). The former is a sale of water for only certain time, whereas the latter is transfer of the long-term entitlements. In this study, the focus is on the temporary water trading market, which is more popular in the HRB, and permanent water trading can be considered as a special case with fixed temporary water trading for all time periods. It is assumed that when the equilibrium price is achieved, a transaction would happen among the agents regardless of the matching process. According to the *Heihe River Water Allocation Agreement* issued by the State Council of China in 1996, the environmental flow at the downstream Zhengyi Valley should satisfy the Water Allocation Line (WAL), representing the relationship between the flow at the upstream Yingluo Valley and downstream Zhengyi Valley. The surplus of streamflow between the upstream and downstream is the total available surface-water allocation for the midstream area, which should be different between March to June and July to October. From November to February, when no crops are planted, all the surplus flow runs downstream and no water transactions happen. Water allocation for each agent is administratively assigned, and water consumption within the quota is free of charge. The surface water (s_i) is allocated based on land area whereas the groundwater allocation (g_i) is based on the WTD and area. Agents located far away from the river without a channel to deliver surface water (IDs 1–10, 22, 23, and 26–29) [Fig. 1(b)] do not participate in the allocation and transaction of surface water.

The cost of facility maintenance is undertaken by the government (Huang et al. 2010); therefore, maintenance costs are not

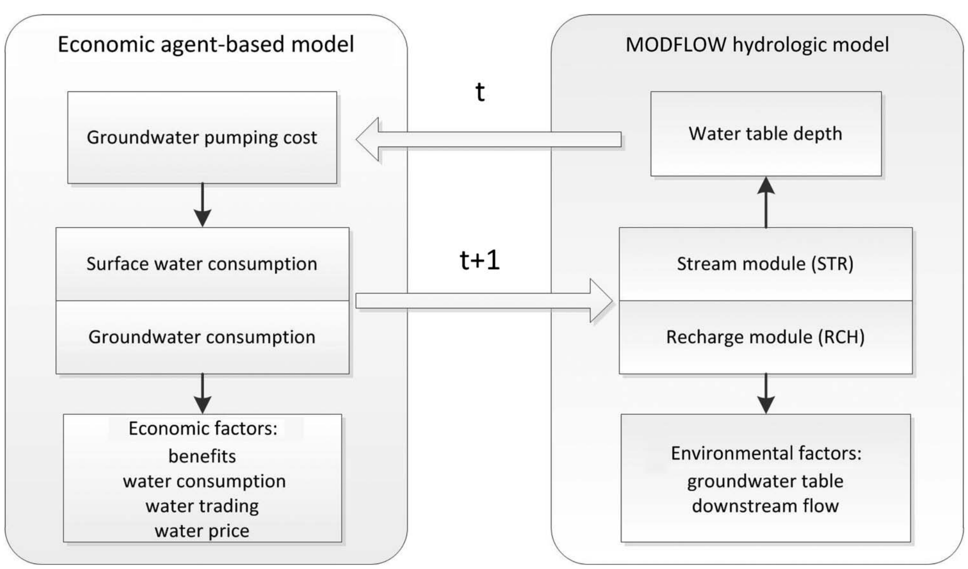

Fig. 2. Logic framework of the CAHM.

considered from the perspective of agents. No delivery cost is required because the surface-water flow in channels is gravity driven. The delivery coefficient of the conveyance system is set as 0.4 (Gao et al. 2004) due to the weak infrastructure with several decades of usage. The coefficient is applied when calculating the transaction amount of surface water (X_i) from the surface-water demand of the crop (x_i). The conveyance losses become recharge to the groundwater system in the RCH of MODFLOW, which is available for the agents to use by pumping. The ZB, as one of the four groundwater basins in the HRB, covers all the 30 IDs in the midstream (Fig. 1). Therefore, the ZB is considered the boundary of the case study supported from the perspective of hydrogeology (Nie et al. 2005). The pumping rights can be traded in the basin instead of the entity being transported by carriers or channels. The pumping cost is derived based the relationship between the electricity cost and the WTD (Ding et al. 2008) in Eq. (1)

$$c_i = 0.0194e^{0.0207h_i} \quad (1)$$

where c_i = pumping cost of agent i; and h_i = WTD. No other transaction costs are involved. The pumping capability k_i of each agent is assigned from the total capability of the region derived from Bai et al. (2008) due to a lack of detailed historical data.

Agriculture water use dominates the total water use in the ZB; therefore, the main focus of agents is on the irrigation utility of water use. In China, a water-user association (WUA) system is adopted to sell and buy water on the behalf of a group of farmers (Xu et al. 2016). In this study, the WUAs were set at the ID scale as the 30 agents in the model, as shown in Fig. 1(b). The agents are assumed to make decisions based on the consideration of present benefits because no interseason water carryover is allowed for farmers due to the seasonal water regulation policy induced by the constraint of infrastructure capacity in the ZB. Agents have differing crop percentage areas. The crop portfolio of each agent is assumed to stay constant over the simulation period because the traditional crop portfolio has remained relatively fixed (i.e., wheat, crop, and vegetables) over 2,000 years (Lu et al. 2015). However, the long-term effect of the water market on individual ID crop portfolios should be discussed in a future study. A quadratic water productivity function for each month in the growing season is applied according to Eq. (2)

$$f_{i,k}(x_{i,k}, y_{i,k}) = \left[a_k\left(\frac{1{,}000(x_{i,k}+y_{i,k}+r_{i,k})}{S_{i,k}}\right)^2 + b_k\left(\frac{1{,}000(x_{i,k}+y_{i,k}+r_{i,k})}{S_{i,k}}\right) + d_k\right]\frac{S_{i,k}m_k}{10^4} \quad (2)$$

where i, k = crop k of the ith agent; $f_{i,k}(x_{i,k}, y_{i,k})$ = agricultural benefit (RMB); $x_{i,k}$ and $y_{i,k}$ = surface-water and groundwater consumption (m^3), respectively; $r_{i,k}$ = effective rainfall of growing crop k (m^3); a_k, b_k, and d_k = parameters for the quadratic function; m_k = selling price (RMB/kg); and $S_{i,k}$ = area (m^2). The values of the parameters a_k, b_k, and d_k for each month are determined using a crop water sensitivity index downscaling method (Shang and Mao 2006) from parameters for the whole the growing season (Xiao et al. 2008a, b). The sum of different crops' benefits is the total agricultural benefit of the agent. In the study area, the annual average rainfall is approximately 190 mm/year, of which about 80% (Xu et al. 2010) is the effective rainfall falling during the growing season. Thus, a fixed value of 150 mm/year is given as a basic rainwater supply for crops. The prices for corn, wheat, and vegetables were obtained from the National Bureau of Statistics of the People's Republic of China (2005) and set as constants (i.e., 2.30, 2.26, and 2.36 RMB/kg, respectively) in the model to simplify external impacts. Table 1 lists the required data of the CAHM.

Table 1. List of data collected

Category	Information	Data required
Hydrologic model	—	Basin boundary; river location; ground elevation and depth; location of pump wells; location and elevation of drains; evaporation of phreatic water; hydrogeological parameters (hydraulic conductivity of aquifer, storage, and specific yield); inflow; initial heads; recharge (return flow coefficient of irrigation and rainfall)
ABM	Basic	Location of the agents; relationship between pumping cost and WTD; effective rainfall
	Agricultural	Irrigation area; crop structure; productivity parameters for the quadratic function of irrigation; crop selling price
	Water market	Initial allocation of surface water and groundwater; groundwater pumping capability

ABM Framework

This study follows the agent-based modeling framework proposed by Zhao et al. (2013) in the agent model part when comparing water user's behavior under AS and MS, and then applies it to a real-world case. Three water management schemes are compared: (1) a surface-water market scheme (SWMS), defined as a market place where surface water can be traded for reallocation; (2) a surface water–groundwater market scheme (SGWMS), where surface water and groundwater are traded at a different price due to the transaction and delivery difference; and (3) an administered scheme (AS), where agents can only consume surface water and pump groundwater less than the allocation without subsidy or penalty.

The agent-based formulations of all schemes are presented in Table 2 to provide a theoretical foundation for the economic model, where i represents the ith agent; F_i is the net benefit; f_i is the water use utility function; x_i is the surface-water consumption; y_i is the groundwater use; k_i is the groundwater pumping capability; s_i and g_i are the initial surface-water and ground water allocation; p_s and p_g are the equilibrium price of surface water and groundwater; c_i is the pumping cost of groundwater; λ_1, λ_2, and λ_3 are parameters introduced in the solving process (when the optimal values of the primal variable are achieved, the Lagrange multipliers λ_1, λ_2, and λ_3 of the inequality constraints are nonnegative); and N is the total amount of agents in the study area. The multipliers associated with nonnegativity constraints (i.e., λ_1 and λ_2) were applied in reservoir operation optimization analysis (Zhao et al. 2011).

The optimal behaviors of the agents can be derived according to the Karush-Kuhn-Tucker (KKT) conditions. More detail on these behaviors have been given by Bazaraa et al. (2006) and are discussed in the Appendix. In addition, the marginal utility of groundwater is equal to that of surface water presented in the Equal Marginal Utility row of Table 2. Physically, this indicates that surface water and groundwater can provide the same support effect for crop growth. The mathematical derivations are given in the Appendix.

Thus, one can obtain the relationship among the equilibrium price, pumping cost, and KKT parameters, given in of the last row of Table 2. According to this relationship, an agent's decision can be grouped into four cases by comparing the surface-water price p_s and pumping cost c_i (under the SWMS) or the sum of pumping cost and groundwater price $p_g + c_i$ (under the SGWMS):

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Table 2. Theoretical foundation of MS (SWMS and SWGMS) and AS for the framework

Agent behaviors	SWMS	SGWMS	AS
Objective function $\operatorname{argmax}_{x\in X} F_i(x_i,y_i)$	$f_i(x_i+y_i)-p_s(x_i-s_i)-c_iy_i$	$f_i(x_i+y_i)-p_s(x_i-s_i)$ $-p_g(y_i-g_i)-c_iy_i$	$f_i(x_i+y_i)-c_iy_i$
Constraints	$x_i\geq 0,\ 0\leq y_i\leq k_i$	$x_i\geq 0,\ 0\leq y_i\leq k_i$	$0\leq X_i\leq s_i$, $0\leq y_i\leq k_i$
Balance	$\sum_{N}^{i=1}(X_i-s_i)=0$	$\sum_{N}^{i=1}(X_i-s_i)=0,\ \sum_{N}^{i=1}(y_i-g_i)=0$	—
Solved by KKT conditions	$-\frac{\partial f_i(x_i+y_i)}{\partial x_i}+p_s-\lambda_1=0$ $-\frac{\partial f_i(x_i+y_i)}{\partial y_i}+c_i+\lambda_3-\lambda_2=0$ $\lambda_1x_i=0$ $\lambda_2y_i=0$ $\lambda_3(y_i-k_i)=0$ $\lambda_1,\ \lambda_2,\ \lambda_3\geq 0$	$-\frac{\partial f_i(x_i+y_i)}{\partial x_i}+p_s-\lambda_1=0$ $-\frac{\partial f_i(x_i+y_i)}{\partial y_i}+p_g+c_i+\lambda_3-\lambda_2=0$ $\lambda_1x_i=0$ $\lambda_2y_i=0$ $\lambda_3(y_i-k_i)=0$ $\lambda_1,\ \lambda_2,\ \lambda_3\geq 0$	—
Equal marginal utility	$\frac{\partial f_i(x_i+y_i)}{\partial x_i}=\frac{\partial f_i(x_i+y_i)}{\partial y_i}$		—
Relationship	$p_s=c_i+\lambda_1-\lambda_2+\lambda_3$	$p_s=p_g+c_i+\lambda_1-\lambda_2+\lambda_3$	—

In Case 1, $x_i=0, 0<y_i<k_i, \lambda_2=\lambda_3=0, p_s=c_i+\lambda_1$ under the SWMS or $p_s=p_g+c_i+\lambda_1$ under the SGWMS. In this case, the trading price of surface water is higher than the pumping cost of groundwater under the SWMS or the sum of groundwater pumping cost and groundwater price. The groundwater pumping capability is not binding; thus, the agent chooses to use only groundwater and sell all the surface water ($x_i=0$). This would happen in an area where the water table is quite shallow. Groundwater use is determined as follows: $\partial f_i(y_i)/\partial y_i=c_i$ under the SWMS or $\partial f_i(y_i)/\partial y_i=p_g+c_i$ under the SGWMS.

In Case 2, $x_i>0,\ y_i=k_i,\ \lambda_1=\lambda_2=0,\ p_s=c_i+\lambda_3$ under the SWMS or $p_s=p_g+c_i+\lambda_3$ under the SGWMS. In this case, the trading price of surface water is higher than the pumping cost of groundwater under the SWMS or the sum of groundwater pumping cost and groundwater price, but the groundwater pumping capability is relatively small compared with the agent's optimal demand. Thus, the agent chooses to use some surface water after exploiting all available groundwater ($y_i=k_i$). Water use is determined as follows: $\partial f_i(x_i+y_i)/\partial x_i=p_s$.

In Case 3, $x_i>0,\ y_i=0,\ \lambda_1=\lambda_3=0,\ p_s=c_i-\lambda_2$ under the SWMS or $p_s=p_g+c_i-\lambda_2$ under the SGWMS. In this case, the trading price of surface water is lower than the pumping cost of groundwater under the SWMS (or the sum of the groundwater pumping cost and groundwater price under the SGWMS), indicating that the available surface water is sufficient to satisfy the agent's demand when the water table is deep. The agent only uses surface water ($y_i=0$), and water use is determined as follows: $\partial f_i(x_i)/\partial x_i=p_s$.

In Case 4, $p_s=c_i$ under the SWMS or $p_s=p_g+c_i$ under the SGWMS. In this case, the price of surface water is equal to that of groundwater pumping (or the sum of the groundwater pumping cost and groundwater price under the SGWMS); thus, the agent can choose to use surface water and groundwater at any proportion. The agent's water use is determined as follows: $\partial f_i(x_i+y_i)/\partial x_i=\partial f_i(x_i+y_i)/\partial y_i=p_s=c_i$ or p_g+c_i under the SGWMS.

When adjusting the p_s (and p_g in SGWMS), the optimal water consumption behaviors (value of x_i and y_i) of agents change correspondingly. However, the final feasible equilibrium price of the market is constrained by the total water amount. At the basin level, the total surface water and groundwater sold and purchased #should be balanced, respectively, as expressed by the balance in Table 2. Only when the mass balance is satisfied does the equilibrium price p_s determined by the water market emerge [Zhao et al. (2013) have given more details]. Therefore, the entire system becomes a set of optimization problems for each agent constrained by the overall water amount, with the decision variables being the water use amount together with the price.

In terms of the AS, the optimal decision of the agent is to use surface water first. If the allocated surface water is not sufficient to meet the maximum demand, groundwater is pumped with an amount determined according to $\partial f(x_i+y_i)/\partial y_i=c_i$.

Results

Relationships among equilibrium price, inflow, and water consumption are discussed to evaluate how water management schemes perform in addition to human–water interactions. Fig. 3 demonstrates the time series of equilibrium price, inflow, and surface-water and groundwater consumption under the SWMS and SGWMS. Influenced by inflow and agricultural demand, the equilibrium price fluctuated similarly under the two market schemes and showed a slight inflow-reversed pattern. During May and June, water demand of crops was the most intensive due to massive growth. Water scarcity resulted in driving the equilibrium price upward. In 2001 and 2004, the inflow was smaller than other years, and this was reflected in equilibrium price differences between March (2.55 and 1.57 $\mathrm{RMB/m^3}$ under the SWMS but 2.87 and 4.03 $\mathrm{RMB/m^3}$ under the SGWMS) and other months (less than 0.05 $\mathrm{RMB/m^3}$). When crops matured after September, water demand decreased correspondingly. Detailed spatial and temporal patterns of water transaction volumes in 2001 for each agent are presented in Tables S1 and S2 and Fig. S1.

Economic Effects of Different Schemes

Total and Unit Economic Profits

Water trading brings economic profits to both sellers and buyers, resulting in incremental benefits at a system level. As shown in

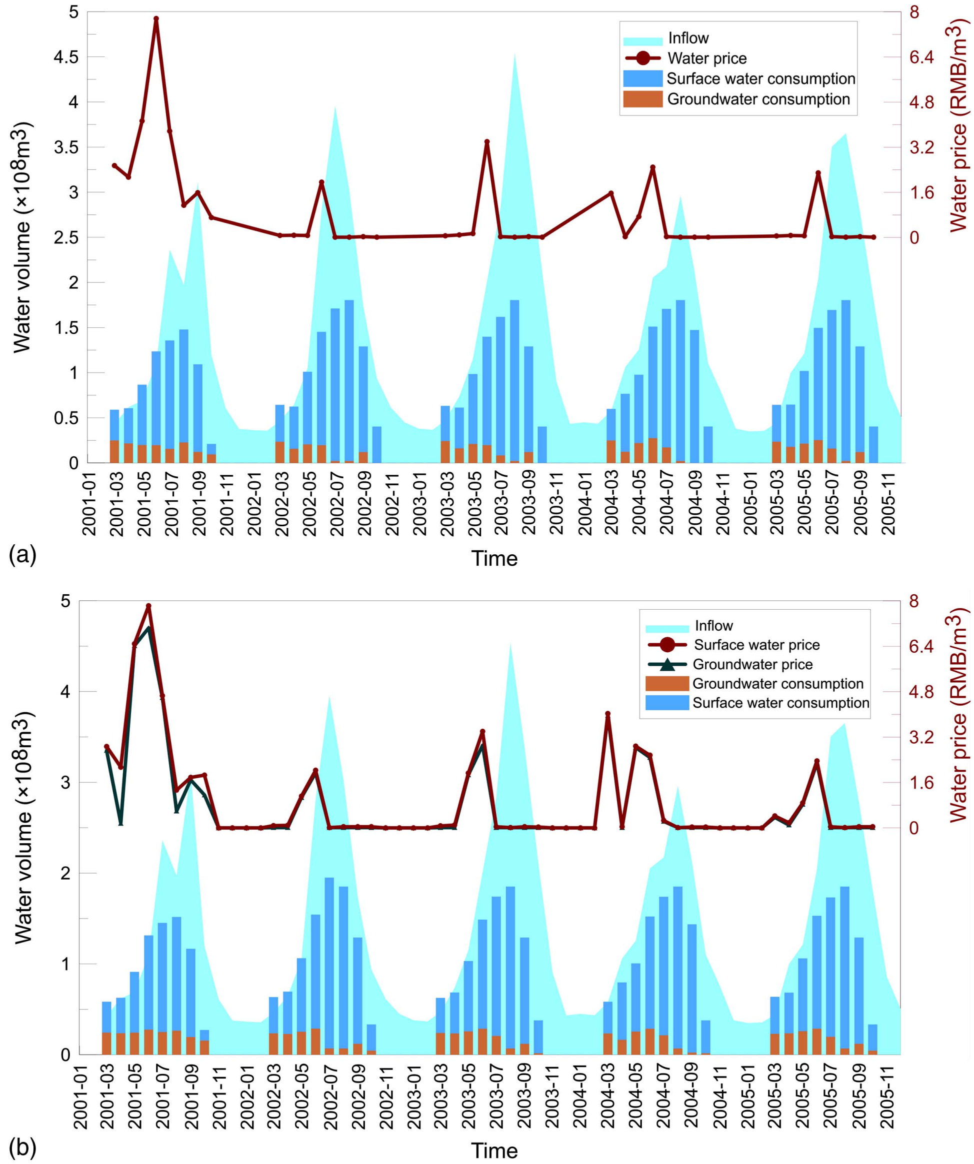

Fig. 3. Time series of inflow, equilibrium price, and water consumption under the (a) SWMS; and (b) SGWMS from 2001 to 2005.

Fig. 4, economic benefits improved significantly under the MS, as expected, including both total benefits and unit water productivity. Because the AS did not have a reallocation mechanism, its total benefit was the smallest during the whole simulation period. The SWMS and SGWMS saw increases of more than 0.2 billion RMB in total benefits each year. The greatest improvement occurred in 2001 with 0.36 billion RMB when annual inflow was the smallest. Under the SGWMS, the agents consumed the most water (approximately 100 million m^3 more water than that under the AS); however, the economic benefit per unit water was still the highest. A water shortage during 2001 resulted in the highest unit benefit under the SWMS and SGWMS, showing that markets can improve total benefits during dry years.

Analysis of Lagrange Multipliers, Equilibrium Price, and Pumping Cost

An agent's behavior is determined by the difference between equilibrium price and pumping cost. The economic meaning of the parameters defined by the KKT conditions in the MS are associated with marginal benefits under various constraints. The variables λ_1 and λ_2 are the Lagrange multipliers corresponding to the nonnegative constraints of surface-water and groundwater use, respectively, and λ_3 is the multiplier corresponding to the pumping limit of groundwater. According to the relationship in Table 2, the values of the Lagrange multipliers are the difference between the water price and the pumping cost. Taking the SWMS as an example, in Case 1 ($\lambda_2 = \lambda_3 = 0$, $p_s = c_i + \lambda_1$), so λ_1 therefore reflects the difference between the costs of surface water and groundwater. Because the pumping cost is lower, the agent would use groundwater rather than surface water. Similarly, in Case 3 ($\lambda_1 = \lambda_3 = 0$, $p_s = c_i - \lambda_2$), λ_2 has the same meaning. Because the pumping cost is higher, the agent would use surface water instead. The physical meanings of the two multipliers λ_1 and λ_2 in this paper are consistent with those in the reservoir operation optimization analysis (Zhao et al. 2011).

On the other hand, the value of λ_3 is the shadow price of groundwater (marginal benefit for the increment of pumping capability k_i). For instance, when Case 2 ($p_s > c_i$, $x_i > 0$, $y_i = k_i$, $\lambda_1 = \lambda_2 = 0$) occurs, $\lambda_3 = p_s - c_i$ under the SWMS or $\lambda_3 = p_s - c_i - p_g$ under the SGWMS. Agents with shallow water tables desire to enlarge their pumping limits in order to expand the benefits. To be more specific, individual agent's WTD and water consumption under

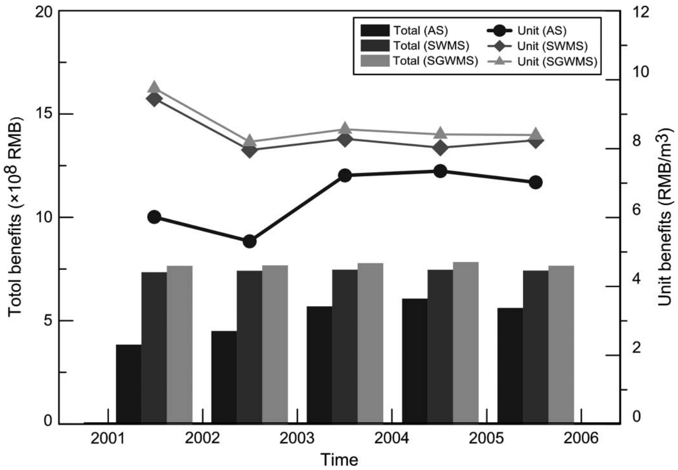

Fig. 4. Total and unit benefits under the three schemes.

different schemes were analyzed combined with the price and cost difference. IDs 11 and 30 were selected to demonstrate the relationship between equilibrium price and cost, as shown in Fig. 5. The temporal variation in WTD, groundwater, and surface-water consumption are presented in Fig. 6.

ID 11, located at the foot of the mountains, has a large WTD of approximately 160 m, and the pumping cost is approximately $0.5\ \mathrm{RMB/m^3}$. In most cases, p_s was smaller than c_i, and the agent preferred surface water to groundwater, falling under Case 3 ($p_s < c_i, x_i > 0, y_i = 0$). Only when surface water was quite scarce (around June and during the dry year of 2001) did the ID 11 agent choose to use groundwater and sell surface water to other agents. For example, in June 2002 under SWMS, p_s was $1.96\ \mathrm{RMB/m^3}$ whereas c_i was $0.55\ \mathrm{RMB/m^3}$. The marginal benefit of water use exceeded the pumping cost, and the optimal water use exceeded the available groundwater, resulting in surface-water consumption greater than zero, falling under Case 2. Therefore, the shadow price of groundwater ($\lambda_3 = p_s - c_i$) was $1.41\ \mathrm{RMB/m^3}$. Similar patterns were observed for the SGWMS where p_s was $2.03\ \mathrm{RMB/m^3}$ whereas $p_g + c_i$ was $1.94\ \mathrm{RMB/m^3}$. The shadow price of groundwater ($\lambda_3 = p_s - c_i - p_g$) became $0.09\ \mathrm{RMB/m^3}$. The smaller λ_3 in SGWMS compared with SWMS resulted in less groundwater consumption and more surface-water consumption. Under the AS, groundwater consumption was largely zero; hence, agents with a large WTD had similar groundwater consumption patterns compared with the MS. Due to intensive water demands, the difference in surface-water consumption between the AS and MS was more evident during the growing season (before August).

In contrast, ID 30, located on the plain and with a small WTD (approximately 7 m), chose to consume groundwater when p_s was high because pumping costs were only approximately $0.03\ \mathrm{RMB/m^3}$. Because the groundwater capacity was large enough to meet the agent's demand, the behavior was classified into Case 1 ($p_s < c_i$ under the SWMS or $p_s < p_g + c_i$ under the SGWMS, $x_i = 0, 0 < y_i < k_i$). The continuous pumping of groundwater made the drawdown increasingly larger. In addition, the WTD gap between the SWMS and SGWMS increased with time. Agents under the SGWMS can also trade groundwater rights; therefore, ID 30 could purchase groundwater rights from others, leading to greater groundwater exploitation.

Impacts of Transaction Costs and Other Factors

Transaction costs, t_c, are gradually being incorporated in water management strategies because acceptable transaction costs for both sides are a basic requirement for water trading (Deng et al. 2017). Transaction costs usually include construction and maintenance costs of the infrastructure used to deliver traded water and institutional costs to ensure operation of the water market. When t_c was introduced into the framework, the optimal solution could not be achieved (Garrick et al. 2013), and this parameter may also influence the occurrence, frequency, pricing, and net benefit of a transaction (Colby 1990; Deng et al. 2017). Fig. 7 demonstrates such influence on the results when the year 2001 is used as an example. The transaction volume and total benefits had negative relationships with the unit transaction cost. When the unit transaction cost reached 70% of the equilibrium price, the annual transaction volume decreased by nearly 6 million $\mathrm{m^3}$ and the total benefits decreased 0.15 billion RMB. As illustrated in terms of total economic profits, the annual value improved more than 0.2 billion RMB under the MS, which provides a realistic statement of transaction costs: when the transaction costs go beyond this value, the extra benefits of the MS do not balance out the transaction costs, leading to market inefficiency.

The profit function Eq. (2) would also be impacted when different values of parameters a_k, b_k, and d_k (parameters in the quadratic

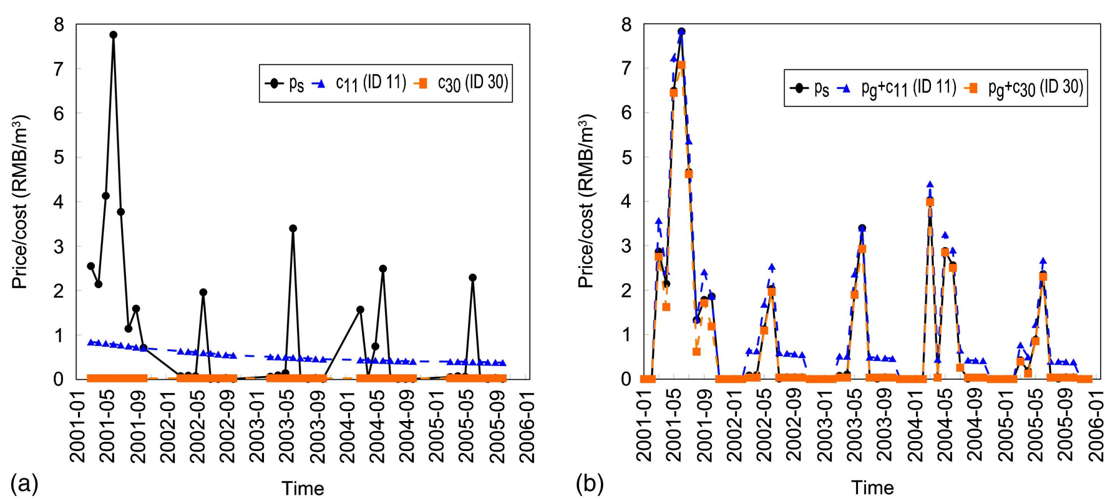

Fig. 5. Comparison between surface-water equilibrium price p_s and pumping cost c_i under SWMS or the sum of pumping cost and groundwater equilibrium price $p_g + c_i$ under SGWMS. IDs 11 and 30 were selected to represent agents with a large and small WTD, respectively.

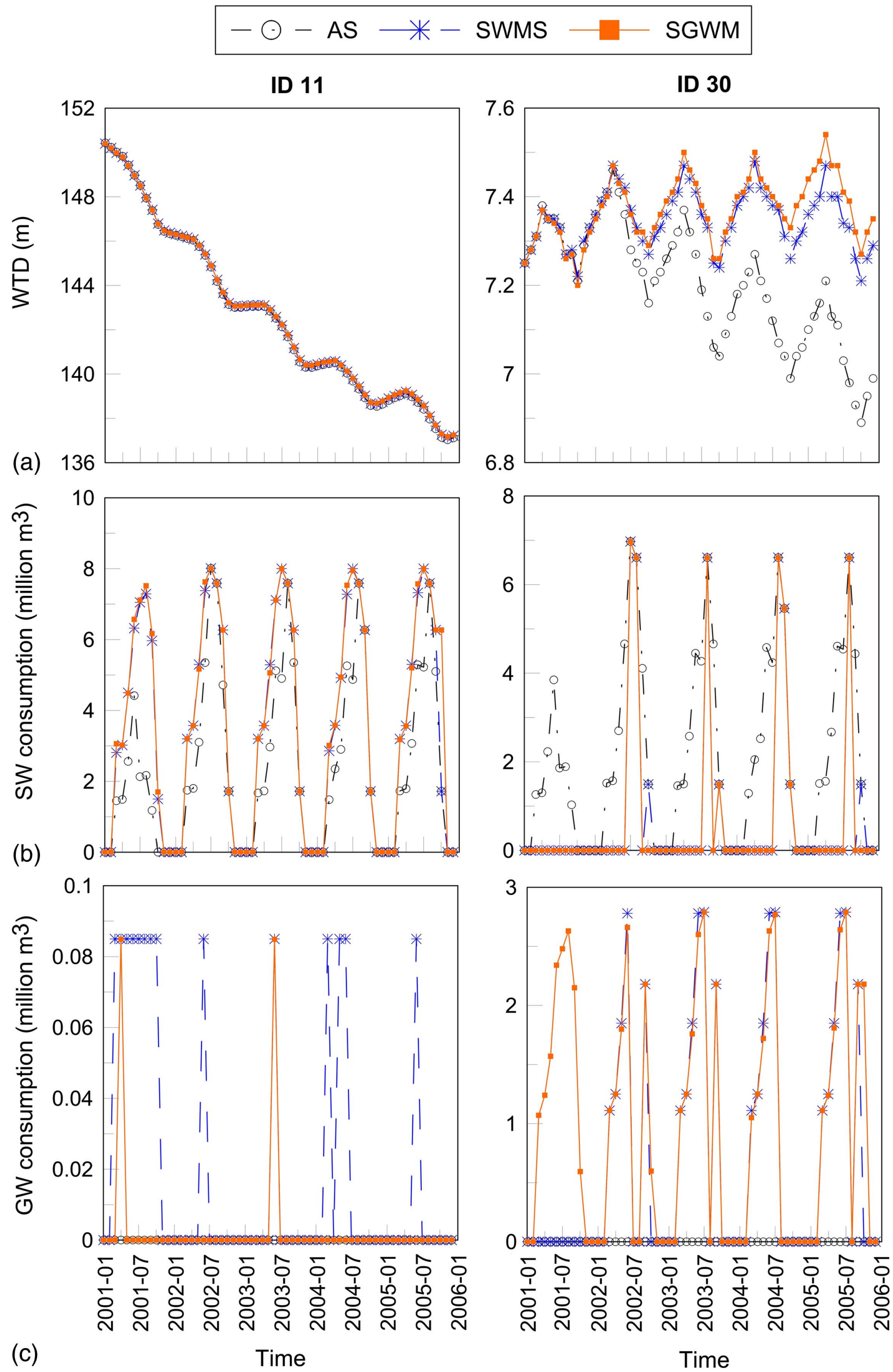

Fig. 6. Temporal patterns of the (a) WTD; (b) surface-water consumption (SW); and (c) groundwater consumption (GW) of ID 11 (large WTD) and ID 30 (small WTD).

function); m_k (selling price for crop k); and $S_{i,k}$ (crop area of crop k in agent i) are used. In this study, $r_{i,k}$ (effective rainfall) is fixed; however, due to climatic variablity, it should be varied monthly to be more practical. Taking SWMS as an example, the agents' optimal decisions are shown as follows:

$$\text{Case 1: } x_{i,k}^* = 0, \qquad y_{i,k}^* = \frac{S_{i,k}(10c_i - b_k m_k)}{2{,}000 a_k m_k} - r_{i,k} \tag{3}$$

$$\text{Case 2: } x_{i,k}^* = \frac{S_{i,k}(10p_s - b_k m_k)}{2{,}000 a_k m_k} - k_i - r_{i,k}, \quad y_{i,k}^* = k_i \tag{4}$$

$$\text{Case 3: } x_{i,k}^* = \frac{S_{i,k}(10p_s - b_k m_k)}{2{,}000 a_k m_k} - r_{i,k}, \quad y_{i,k}^* = 0 \tag{5}$$

$$\text{Case 4: } x_{i,k}^* + y_{i,k}^* = \frac{(S_{i,k}10p_s - b_k m_k)}{2{,}000 a_k m_k} - r_{i,k} \tag{6}$$

Among the parameters, only a_k is negative. Therefore, the total water consumption for certain crops is positively related to $S_{i,k}$, a_k b_k, and m_k. This clearly demonstrates that a larger crop selling price and irrigation area result in greater water consumption. For a_k and b_k, they determine the optimal water use with the largest yield. In northwest China, for instance, these two parameters are different

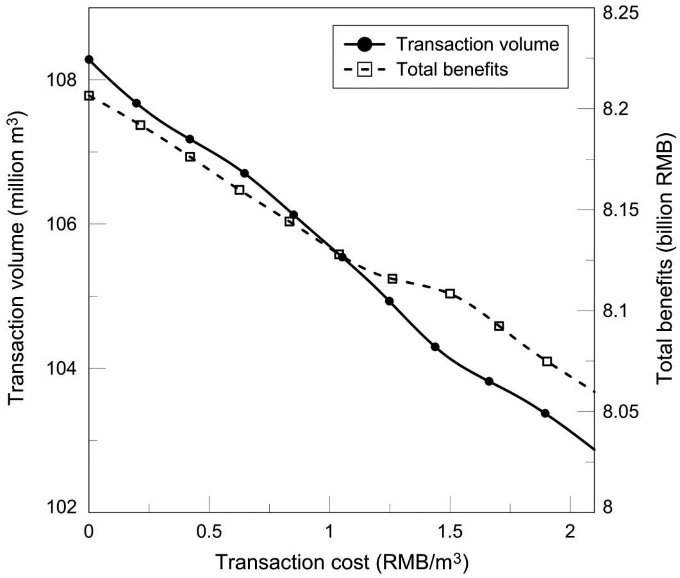

Fig. 7. Influence of transaction cost on the annual transaction volume and total benefits during 2001.

for corn and wheat because the optimal water use for corn is lower than that of wheat.

Environmental Effects of Different Schemes

Temporal Effects on the Streamflow

The streamflow at the Zhengyi Valley station is a crucial indicator for detecting the environmental effects of the three schemes. Compared with the AS, the total streamflow over the simulation period decreased 2.4% under the SWMS and 6.5% under the SGWMS due to greater water consumption. As shown in Fig. 8(a), the overall fluctuation of the streamflow remained nearly the same under the three schemes, indicating that the environmental impact of the MS was not as great as expected. Concentrating on the difference demonstrated in Fig. 8(b) for the SWMS, the variation from September to February was less than 3% compared with that of the AS. However, during the remaining months, the difference reached more than 10% with both negative and positive values. An increase of 200% was even achieved during March because of the low baseline value. For the SGWMS, there was a noticeable increase (approximately 20% compared with the AS) of streamflow from September to October, and the reduction from November to March was more significant than that of the SWMS. This variation pattern of streamflow was associated with water consumption during that time. During the July growing season, the demand for agricultural water was intense. Greater water consumption had a direct influence on streamflow. In contrast, the effects of the increased groundwater pumping under the SGWMS during the growing season would take a long time to become evident, eventually influencing downstream streamflow from November to March.

In order to reflect the time lag of groundwater pumping, a head observation well was set at ID 14 near the river to represent the influence of the pumping occurring in the upper region. The drawdown between SWMS and AS (value under SWMS minus that under AS) at the observation well and the groundwater exploitation were compared in Fig. 9. From the first month of water market operation, the groundwater pumping exceeded that under AS; however, the value of drawdown did not increase until two months later, reflecting the effect of groundwater travel times on groundwater level. The time lag was evident, for example in March 2002, where the pumping difference was positive but the drawdown was not affected until May 2002, changing from a decrease to an increase.

Spatial Effects on the WTD Change

The WTD is also a major concern in this arid region. The effects of different schemes on the spatial patterns of the WTD were compared. Spatial distributions of the WTD difference between the SWMS and AS, as well as between the SGWMS and AS, in the final year 2005 are shown in Figs. 10(a and b). Because the simulation of each scheme began with the same WTD values in 2001, the final WTD values in 2005 can represent the WTD changes during the whole simulation period.

Compared with the AS, both the SWMS and SGWMS revealed significant WTD changes with similar trends but different values. The agents along the river with small areas (IDs 11, 12, 14–20, 25, and 30) and agents on the plain (IDs 1, 7, 8, and 13), which had small WTD values, showed increases in the WTD under the SWMS and SGWMS. On the other hand, the agents with larger areas (IDs 24 and 27) and the agents at the foot of the mountains (IDs 2–6, 9, 10, 22, 23, 26, 28, and 29), which had large WTD values, showed descending trends in WTD under the SWMS and SGWMS. When the surface-water price p_s was higher than the sum of groundwater price and pumping cost $(p_s > p_g + c_i)$, market systems made the agents with large WTD values or demands recover the water table, whereas they encouraged agents with small WTD values

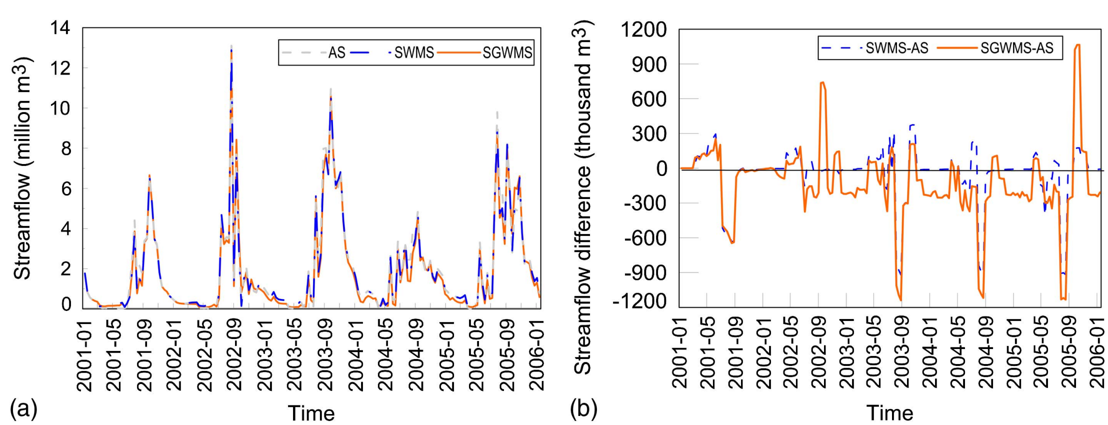

Fig. 8. Streamflow in the Zhengyi Valley from 2001 to 2005: (a) under the AS, SWMS, and SGWMS; and (b) the difference in the Zhengyi Valley between the AS and MS where downstream flow under the AS is set as the baseline.

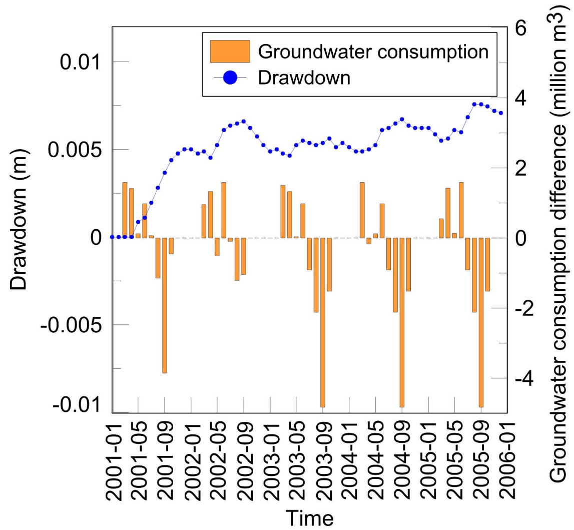

Fig. 9. Drawdown and groundwater consumption difference between SWMS and AS (value under SWMS minus that under AS).

or demands to use more groundwater and sell surface water. In summary, water trading resulted in smaller WTD gaps among the agents compared with the AS. This study reflects the overall impact of water use on the groundwater level. Different pumping behaviors of agents in different systems certainly influence other agents' behaviors located in the same aquifer. These interactions are simulated by the proposed model, in which the agents' behaviors are determined by all related factors.

Conclusions

This study proposed the CAHM, a coupled modeling structure that has an economic model based on the consistent agent-based modeling framework presented by Zhao et al. (2013) and a physically based groundwater model. By the application of the CAHM to a real-world case study, the effects of different water management schemes including an AS, SWMS, and SGWMS were determined. The ZB located at the midstream area of the HRB in northwestern China served as the case-study site to demonstrate the effectiveness of the model. Interactions between the water consumption behavior of humans and natural factors (such as the water table and streamflow) were connected by physical processes, i.e., the pumping cost is dependent on the water table.

It was derived that an agent's (irrigation district) behaviors are determined by the difference between the equilibrium price and pumping cost. The equilibrium price of the MS fluctuated similarly and showed a slight inflow-reversed pattern between inflow and agricultural water demand. The annual total benefit increased by 10.0% and 11.5% under the SWMS and SGWMS compared with that of the AS. This effect was more significant when water resources were scarce; however, when introducing transaction costs, the transaction volume and total benefits both decreased, so the transaction costs should not exceed the incremental benefits from trading. In terms of the environmental impact, the overall distribution of downstream flow became more consistent and the total streamflow decreased by 2.4% under the SWMS and 6.5% under the SGWMS compared with that of the AS, indicating that negative environmental effects of the MS occurred but were not significant. A lag greater than 2 months, due to the travel time of groundwater, was identified before the impacts of pumping on drawdown could be observed.

The CAHM model proposed in the study can capture complex interactions between humans and nature in real-world water management schemes. The model also bridges the gap between physical hydrologic process models and social-science-based models. Thus, it can be employed as a useful tool to analyze water management schemes in a more practical and flexible way, and therefore help policymakers with critical water management decision making.

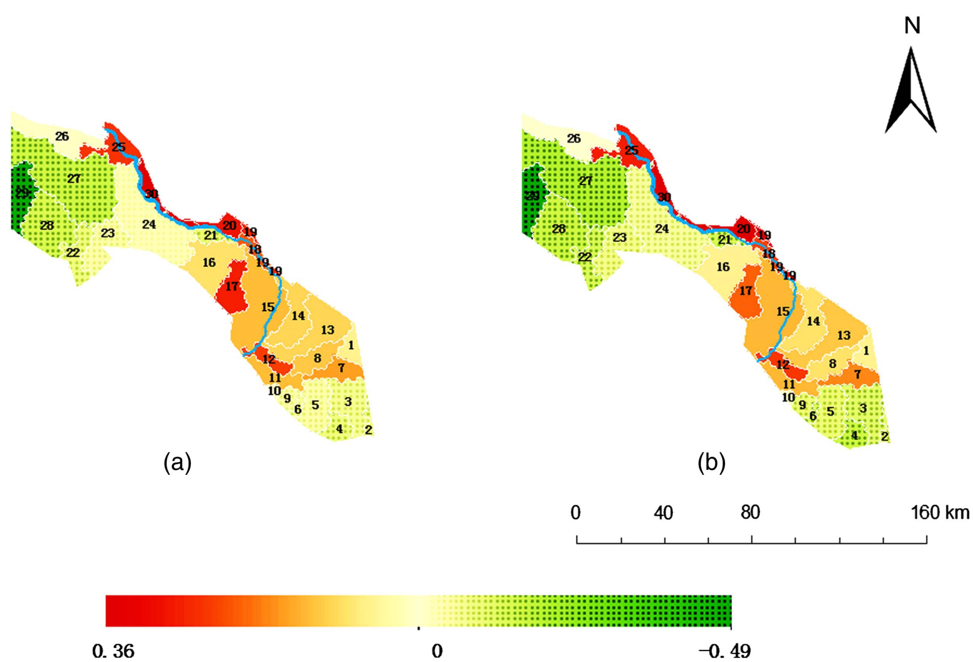

Fig. 10. Spatial distribution of the WTD difference (m) between (a) SWMS and AS (SWMS-AS); and (b) SGWMS and AS (SGWMS-AS) in 2005. IDs with dots represent a WTD decrease.

Appendix. Mathematical Derivations of the Agents' Optimal Behaviors

Consider a general nonlinear programming model as follows:

$$\begin{aligned}&\text{argmin}_{x\in X} f(X) = f(x_1, x_2, \ldots, x_n)\\&\text{subject to } h_1(X) \le e_1\\&\quad h_2(X) \le e_2\\&\quad \ldots\\&\quad h_n(X) \le e_n\end{aligned} \tag{7}$$

The KKT conditions are as follows:

$$\begin{aligned}\nabla f(X^*) + \sum_i \lambda_i \nabla h_i(X^*) = 0\\ \forall\ i{:}\ \lambda_i[h_i(X^*) - e_i] = 0\\ \forall\ i{:}\ \lambda_i \ge 0\end{aligned} \tag{8}$$

KKT conditions are necessary and sufficient when the objective function f and the inequality constraint h_i are continuously differentiable convex functions (Bazaraa et al. 2006). Here in the water management institution model, the constraints are all linear and the benefit function is convex, thus satisfying the conditions. The maximization problem is changed into a minimization problem as follows:

$$\begin{aligned}&\text{argmin}_{x\in X} - F_i(x_i, y_i) = -f_i(x_i + y_i) + p_s(x_i - w_i) + c_i y_i\\&\text{subject to} - x_i \le 0\\&\quad - y_i \le 0\\&\quad y_i \le k_i\end{aligned} \tag{9}$$

Applying the KKT conditions to Eq. (9), one obtains the following:

$$\begin{bmatrix} -\dfrac{\partial f_i(x_i + y_i)}{\partial x_i} + p_s \\ -\dfrac{\partial f_i(x_i + y_i)}{\partial y_i} + c_i \end{bmatrix} + \lambda_1 \begin{bmatrix} -1 \\ 0 \end{bmatrix} + \lambda_2 \begin{bmatrix} 0 \\ -1 \end{bmatrix} + \lambda_3 \begin{bmatrix} 0 \\ 1 \end{bmatrix} = 0 \tag{10}$$

The relationship between water consumption and crop productivity is a quadratic function

$$f_i(x_i, y_i) = A_i(x_i + y_i)^2 + B_i(x_i + y_i) + D_i \tag{11}$$

where A_i, B_i, and D_i = parameters of the productivity function. Therefore, the marginal utility of groundwater and surface water is equal

$$\frac{\partial f_i(x_i + y_i)}{\partial x_i} = \frac{\partial f_i(x_i + y_i)}{\partial y_i} = 2A_i(x_i + y_i) + B_i \tag{12}$$

Then, one can obtain the following:

$$p_s - \lambda_1 = c_i + \lambda_3 - \lambda_2 \tag{13}$$

The economic meaning of the parameters λ_1, λ_2, and λ_3 defined with the KKT conditions are associated with marginal benefits under various constraints. Adjusting p_s allows one to obtain various groups of global optimal solution (x^*, y^*) when $\lambda_1, \lambda_2, \lambda_3 \ge 0$. Restricted by the balance in Table 2 that the surface-water consumption and total allocation water are equal, one can obtain the only solution to the problem.

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Supplemental Data

Fig. S1, Tables S1 and S2, and a detailed description of water transaction volumes in 2001 are available online in the ASCE Library (www.ascelibrary.org).

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