Journal of Cleaner Production 233 (2019) 522–537

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Market-based stochastic optimization of water resources systems for improving drought resilience and economic efficiency in arid regions

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ARTICLE INFO

Article history:
Received 27 August 2018
Received in revised form
23 April 2019
Accepted 30 May 2019
Available online 31 May 2019

ABSTRACT

Efficient reallocation and conjunctive operation of existing water supplies have been receiving increasing attention as the competition among water users are intensified in worldwide. In this paper, a market-based stochastic optimization model is developed to address inherent uncertainties and complexities in water resources planning in arid regions. This model can be used not only to explore the water conservation potential via three strategies as cropping pattern optimization, irrigation infrastructure improvement and water trading, but also to help generate related water policy that promote the local welfare and facilitate local cleaner production.

A real case study of the pumping irrigation system located in Yellow River basin is conducted to demonstrate applicability of the proposed model. Our findings indicate that the adjusted cropping pattern significantly increases the irrigator's income by growing economic crops such as herb and wolfberry; meanwhile, it does not sacrifice the food production. With the efficient infrastructural development, substantial water resources are saved and traded to other industries, thereby stimulating the local economy. Optimum subsidization policy is identified to increase the local welfare by allowing seasonal water trading while lessening the financial burden of the local government.

1. Introduction

Agriculture in northwestern China is relying on irrigation, which accounted for approximately 85% of water consumption in arid regions of Yellow River Basin (Ningxia water resources bulletin, 2017). As the increasing water demand from urbanization, industry and ecosystem, the water conflict among consumers in arid regions of China has been intensified and become more difficult to be meditated by administrative orders (Li, 2015; Sun et al., 2017). To address such challenge, water market was proposed as a demand-management strategy to reduce potential conflicts among stakeholders and reallocate water to achieve more important social gains (Ruth, 2014; Wheeler et al., 2017). For agricultural practice with intensive water use, water markets provide incentives for irrigators to apply advanced irrigation schemes and innovative irrigation infrastructures, which allow water to be traded to other consumers with higher water use efficiency (Easter and Huang, 2014; Zhao et al., 2015). However, water market is sparingly applied in Northwestern China because the economic and institutional structures still encourage inefficient water use (Gleick, 2000).

The understanding of water use behavior, water policy and incentives of water trading are the prerequisite for the design of water market (Zhu et al., 2015). Previous studies encompasses the analysis of several successful water trading cases in developing countries where the rights of water in agricultural sector need to be clearly defined for a healthy trading environment (Shen and Speed, 2009; Easter and Huang, 2014). In addition, policy heritage (i.e. low water price and high quota allotted to irrigators), irrigators' benefit and subsidization policies should be considered as key factors when designing a water market (Feder and Umali, 1993; Dridi and Khanna, 2005).

In worldwide, market-based water resources management has been investigated thoroughly regarding to various nature impacts and human activities. By integrating hydrologic, environmental, economic, and institutional constraints, the short- and long-term third party impacts arising from temporary water trading was quantified (Zaman et al., 2009); and hydrologic and economic impacts towards water trading was modelled (Gohar and Ward.,

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https://doi.org/10.1016/j.jclepro.2019.05.379
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Nomenclature

$i = 1, 2\ldots5$	for corn, wolfberry, herb, apple and millet respectively
$c = 1, 2\ldots4$	for four counties as Zhongning(ZN), Changshantou(CST), Tongxin(TX) and Haiyuan(HY) respectively
j=1, 2…18	denotes 18 irrigation districts
k= 1, 2	denotes 2 planning horizons as first and second phase
m= 1, 2…3	for three hydrological years as wet, normal and dry
t= 1, 2…5	for gypsum powder, dry wall, cashmere, blanket and fur respectively
$B^{\pm}_{kjicm}$	water deficit (m^3/ha) of crop i at j_{th} district, c_{th} county for the k_{th} phase under hydrological year m.
$BUD^{\pm}_{c}$	government budget (ha) (irrigation infrastructural investment area)
C_j	unit agricultural water cost at j_{th} district (Yuan/m^3)
C_{ind}	unit industrial water cost (Yuan/m^3)
C_{Agri}	unit agricultural water cost for land reclamation (Yuan/m^3)
$D^{\pm}_{jicm}$	irrigation quota (m^3)
DA_{ijcm}	irrigation volume (m^3) for advanced irrigation technology
$DB^{\pm}_{ktc}$	times of industry expansion (integer)
$DNB^{\pm}_{ijc}$	unit water benefit (Yuan/m^3) from advanced irrigation technology
$\exp^{\pm}_{tc}$	maximum expansion times (integer)
$ENS^{\pm}_{m1}$	minimum percentage (%) of corn yield rate
$FTW^{\pm}_{ijc}$	total evapotranspiration (ha/m^3)
$FMIN^{\pm}_{ijc}$	minimum evapotranspiration (ha/m^3)
$FNB^{\pm}_{ijc}$	unit water benefit (Yuan/m^3) with traditional irrigation method
$FPRO^{\pm}_{ijc}$	maximum production (kg/ha)
$FA^{\pm}_{ijcmk}$	irrigation volume (m^3) for troditional irrigation method (flood irrigation)
P_m	probability of m_{th} hydrological year
PR_i	Unit price (Yuan/kg)
$prec^{\pm}_{m}$	precipitation (m^3/ha) under hydrological year m
$PUMC^{\pm}_{j}$	maximum volume of water (m^3) can be delivered to j_{th} district
$SAVE_i$	volume of water (m^3/ha) can be saved when shifting from TIM to AIT for crop i.
$SEC^{\pm}$	minimum percentage (%) for food area in $(k-1)_{th}$ phase
η_e	annualized factor for perennial crops e, which are subsets of i
$RA^{\pm}_{kic}$	crop growing area (ha) of land reclamation
$INB^{\pm}_{t}$	unit water profit (Yuan) for industry type t
IP_{kt}	production capacity (unit) for industry type t
$IPW^{\pm}$	transferable portion (%) of conserved water to industries
$IA^{\pm}_{kt}$	water consumed per unit product (m^3/unit)
$TW^{\pm}_{km}$	seasonal traded water (m^3)
$TWD^{\pm}_{m}$	total available water (m^3) (pump delivered and precipitation)
$MUN^{\pm}_{ck}$	municipal water usage (m^3)
$UCP^{\pm}_{kjicm}$	Unit area crop (kg/ha) production under traditional irrigation
$WTS^{\pm}_{km}$	trading prices of water
$X^{\pm}_{ijck}$	growing area (ha) with flood irrigation
$Y^{\pm}_{ijck}$	growing area (ha) with advanced irrigation methods

2010). As the water trading could be affected by various stochastic events (e.g., precipitation and stream flow), many stochastic water trading models were proposed to reflect the uncertainties existing in the water trading process (Zeng et al., 2015). However, these demand-oriented models only provide decision makers with “how much” of water that can be traded for a high benefit, without modelling a comprehensive trading solution. For the real-world practices, water trading always involves decision-makings from all related stakeholders (e.g., irrigators, entrepreneurs, and administrators) who require a detailed trading options to choose from. For example, under the deficit irrigation (DI) practice, irrigators may choose whether to irrigate their lands or trade their water depending on the marginal water cost associated with different water availabilities. Therefore, the insights of water trading need to be revealed from models and provide decision-makers practical solutions.

Apart from the above-mentioned simplification, limitations on current water trading models are also reflected as a lack of consideration on technological innovation (Li et al., 2014). In fact, a majority of irrigated agriculture in developing countries are still using flood irrigation (Lu et al., 2017), which provides huge potential for water conservation and trading. These facts are influencing the value of water and irrigation behaviors that should not be neglected when designing a market-based water resources planning model.

Therefore, the aim of this research is to propose a market-based stochastic water resources planning model for arid regions. The model will be applied to a pumping water distribution system in the Yellow River Basin (YRB). It will improve upon the previous studies through:

1. Considering agricultural infrastructural development and adaptation of new irrigation scheme for water conservation.
2. Building the linkage between irrigation infrastructural development and institutional arrangements.
3. Incorporating crop yield simulations under stochastic nature events, allowing a precise agricultural water allocation plan.
4. Providing both permeate and seasonal water trading possibilities to irrigators for more flexible water management strategies and increased social gains.

2. Overview of the study system

The middle region of Ningxia (104°47′14″-105°28′00″E and 36°00′56″-37°20′26″N), which located in arid region of the Yellow River Basin, is suffered by water scarcity and poverty. The annual precipitation and potential evaporation of this region range from 190 to 370 mm and 1600 to 1210 mm (gauged by E601) respectively (Yang et al., 2015), from north to south. The water shortage situations were even intensified since the last century, presenting as increased dry spell and decreased rainfall (as shown in Fig. S1) (Wang et al., 2017, 2018). Due to such unfavorable climate conditions, this region heavily relies on Yellow River. The study system

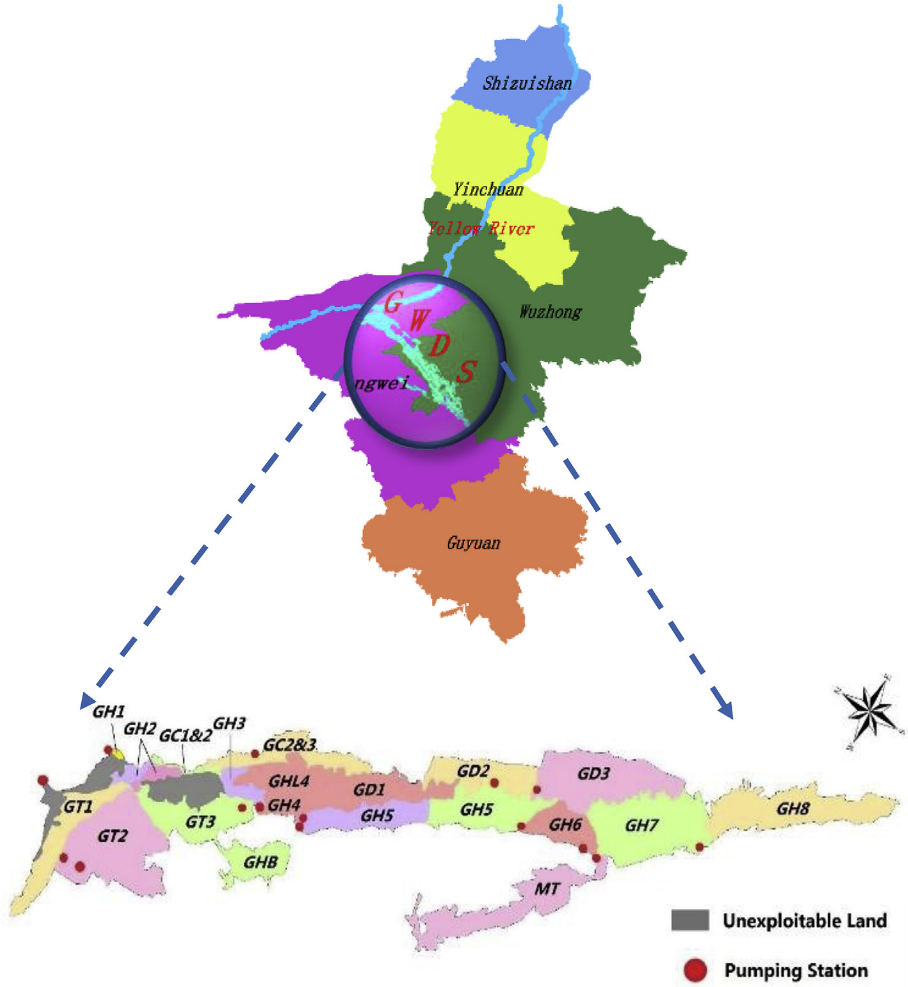


Fig. 1. The Guhai water distribution system.

is called Guhai Water Distribution System (GWDS), which draws water from the Yellow River through 22 pumping stations and 18 channels (districts) and delivers to five counties with a total service area of 44,800 ha. Fig. 1 shows detailed composition of the GWDS.

By far, most of the water supply carried by the system is consumed by agriculture activities. The heritage of water policies since 1970s encourage irrigators to growing corn as a low-risk and labor-easy crop owing to high allotted irrigation quota and low agricultural water price. The baseline investigation shows that 78% of the total irrigation area is growing corn with flood irrigation, which has been applied to nearly all of the irrigated land with a high irrigation quota (usually two or three times higher than using modern irrigation methods) (Li et al., 2008). The government subsides local irrigators with 75% of the shadow water price, which is defined as the difference between the given water rate for irrigation and the actual economic value of water as a natural resource (Ziolkowska, 2015). Even though local government already realized that flood irrigation is not favored by local economy, considering the water policy heritage, local economic conditions and growing patterns, current irrigation state may take time to alter by means of engineering and management approaches.

The total amount of water can be delivered to the study area is about 259×10^6 m^3 with 4.4% of variance annually, consisting 6% of water rights from Yellow River of Ningxia section (listed in Table S1). The water availability for 18 sub-area is listed in Table S2. The limited water availability has been raising challenges as the increasing water demand from agricultural, industrial and municipal sectors. To face the challenge, Ningxia water resources department initiated a new water pricing system called preferential water price, which put the electricity cost into consideration. Fig. S2 demonstrates the difference of the current water price, preferential water price and shadow water price. Water trading has been another important tool for local government to deal with the water tensions among consumers. In 2006, a series of water trading rules were initiated by the Ningxia government based on the province's social and economic characteristics. The foremost rule is that the water trading program respects the policy heritage and protects current water users' (especially famers) interests. Therefore, long-term water trading was initially practiced by local government, which joins local industries to invest irrigators with advanced irrigation infrastructures. In return, the conserved water allows local government to extend the current irrigation land and issue more water permit for industries to expand their capacity (Li, 2015).

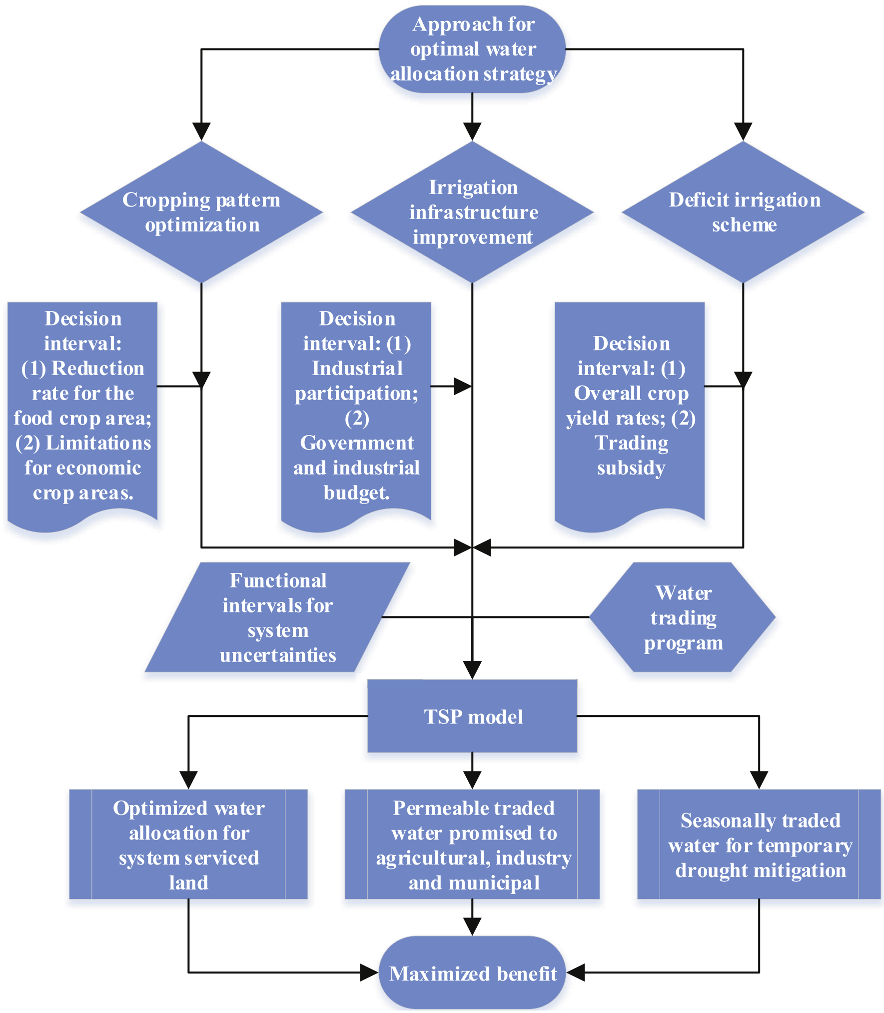


Fig. 2. Generalized model framework.

3. Design of market-based stochastic water resources planning model

To extend the current water trading framework, a market-based stochastic water resources planning model will be designed as illustrated in Fig. 2. The proposed model will incorporate three water conservation strategies as cropping pattern optimization, irrigation technology improvement and deficit irrigation (DI) schemes. The first two strategies will help decision makers perform long-term water trading. The DI practice will enable seasonal water trading as an additional water management option to further improve the system water resiliency and maximize the irrigators' welfare.

3.1. Model construction

The objective of the proposed model is to maximize the local overall benefit (including agriculture and other industries) under a series of constrains. The decision variable includes growing area with traditional and improved irritation technology, water use under deficit irrigation scheme and industrial expansion options. Based on water use behavior (Government of Ningxia Hui Autonomous Region, 2012), market demand (Jiang et al., 2017), water market policy, system carring capacity (Xu et al., 2018), crop water demand (Liu et al., 2013) and trading subsidies, a total of 16 constraints were considered in the modelling process.

To reflect the randomness of natural resources, the conventional TSP model (Huang and Loucks, 2000) was tailored for the study system where the precipitation was treated as stochastic term and pumped water became the decision variable. In addition, penalty term was split into two parts including: (a) paying for the water resources when using the water from system and (b) taking the production loss by practicing deficit irrigation schemes. Such adaptation allows irrigators to trade their seasonal water. The expected outputs will be analyzed in terms of water allocation, permeant and seasonal water trading and economic benefit from water conservation strategies.

Therefore, the market-based stochastic water resource programming model can be formulated as follows:

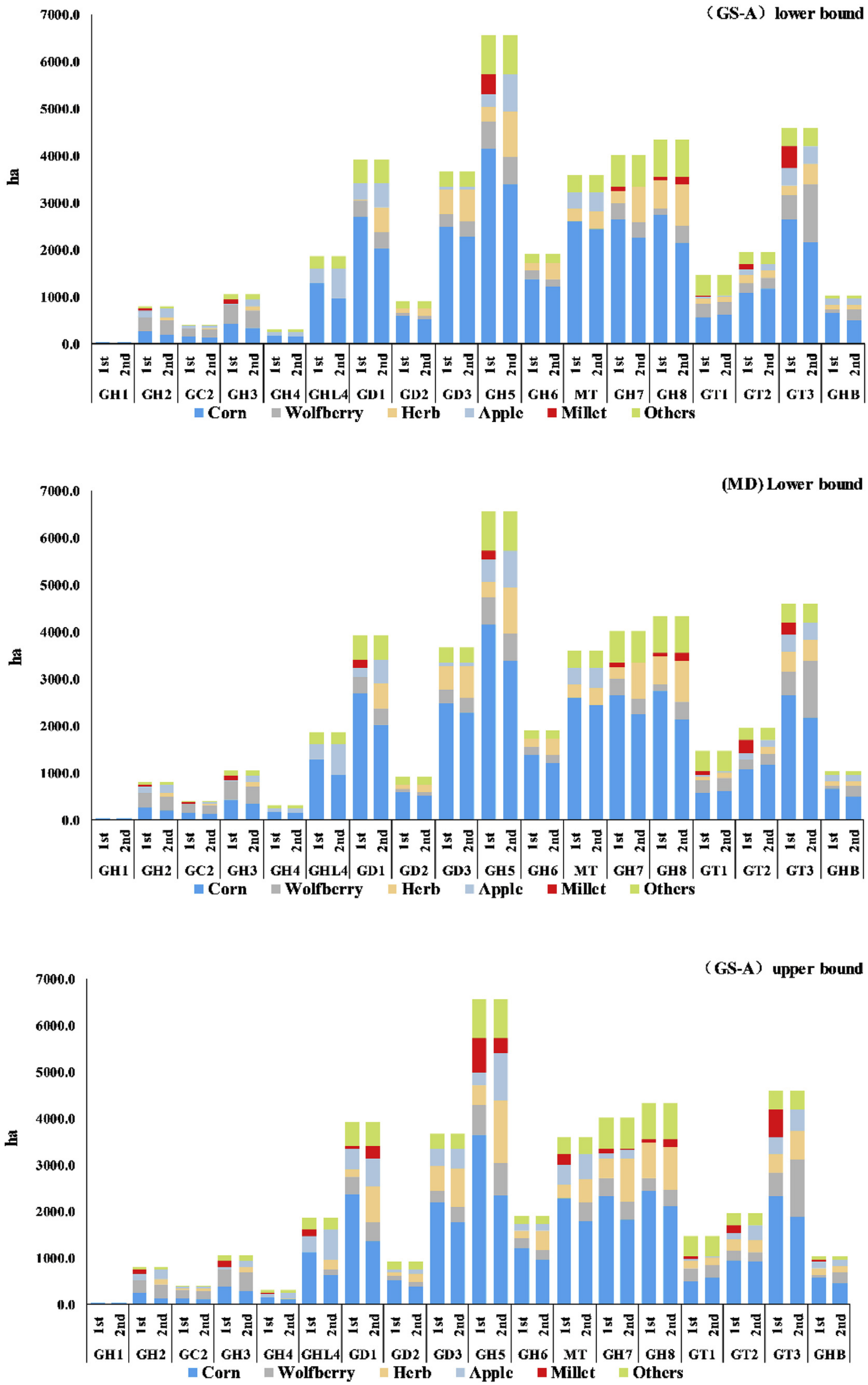


Fig. 3. Cropping pattern for Guhai water distribution system.

$$
\begin{aligned}
Max\,f = & \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{c=1}^{C}\eta_e\cdot X^{\pm}_{ijck}\cdot FNB^{\pm}_{ijc}\cdot FTW^{\pm}_{ijc} - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{c=1}^{C}\eta_e\cdot X^{\pm}_{ijck}\cdot C_j\cdot FA^{\pm}_{ijcmk}\cdot P_m \\
& - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{c=1}^{C}\eta_e\cdot X^{\pm}_{ijck}\cdot PR_i\cdot\left(FPRO^{\pm}_{ijc} - UCP^{\pm}_{kijcm}\right)\cdot P_m \\
& + \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{c=1}^{C}\eta_e\cdot Y^{\pm}_{ijck}\cdot\left(DNB^{\pm}_{ijc} - C_j\right)\cdot DA_{ijcm}\cdot P_m \\
& + \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{c=1}^{C}\eta_e\left(DNB^{\pm}_{ic} - C_{Agri}\right)\cdot RA^{\pm}_{kic}\cdot DA_{icm}\cdot P_m \\
& + \sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{c=1}^{C}\left(INB^{\pm}_{tc} - C_{Ind}\right)\cdot IP_{kt}\cdot IA^{\pm}_{kt}\cdot DB^{\pm}_{ktc} + \sum_{k=1}^{K}\sum_{m=1}^{M}P_m\cdot WTS^{\pm}_{km}\cdot TW^{\pm}_{km}
\end{aligned}
\tag{1}
$$

where:

$$
\begin{aligned}
UCP^{\pm}_{kijcm} = & FA^{\pm}_{kijcm}\cdot FA^{\pm}_{kijcm}\cdot CA^{\pm}_{ijcm} + FA^{\pm}_{kijcm}\cdot CB^{\pm}_{ijcm} \\
& + CO^{\pm}_{ijcm} \qquad \forall\,; k, j, i, m, t
\end{aligned}
\tag{2}
$$

simulation function as equation (2) describes the relation of irrigation volume and crop production. The function parameters $CA^{\pm}_{ijcm}$, $CB^{\pm}_{ijcm}$ and $CO^{\pm}_{ijcm}$ should be calibrated with years of observed crop yield data (Reca et al., 2001).

The objective function (Equation (1)) is subject to the following

$$
\begin{aligned}
TW^{\pm}_{km} = & TWD^{\pm}_{m} - \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X^{\pm}_{jick}\cdot FA^{\pm}_{kijcm} + Y^{\pm}_{jick}\cdot DA^{\pm}_{jicm}\right) - \sum_{t=1}^{T}\sum_{c=1}^{C}IP^{\pm}_{ktc}\cdot IA^{\pm}_{ktc}\cdot DB^{\pm}_{ktc} \qquad \forall\,; k, j, i, m, t \\
& - \sum_{i=1}^{I}\sum_{c=1}^{C}RA^{\pm}_{kic}\cdot DA_{icm} - \sum_{c=1}^{C}MUN^{\pm}_{kc}
\end{aligned}
\tag{3}
$$

In above equations, superscripts '+' and '−' represent upper and lower bounds of the interval values, respectively. An interval is defined as a number with known lower and upper bounds but unknown distribution information (Huang, 1998). A crop yield constraints as (a) irrigation area constraint (Equation (4)), which limits irrigation area of the system within its boundary; (b) crop water demand constraint (Equations (5)–(8)) that satisfy the crop water demand for different hydrological years; (c) water balance constraint (Equations (9) and (10)); (d) cropping pattern constraint

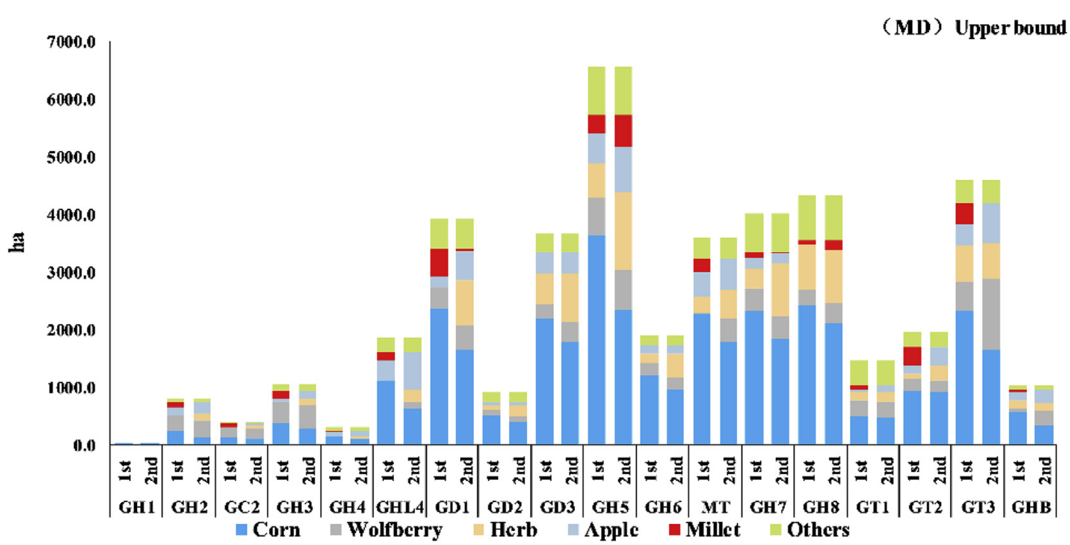


Fig. 3. (*continued*).

(Equation (11)), which limits the area of each crop based on market demands, crop adaptability and crop rotations for each district; (e) food security constraint (Equations (12) and (13)), which bounds the food crop yield rate and growing area reduction rate; (f) industrial expansion constraint (Equation (14)–(16)), which indicate production chains among industries and water availability; (g) technical constraint (Equation (17) and (18)), which indicate that the growing area with improved irrigation technology and growing perennial plants should not be reduced during the planning phase; and (h) government budget constraint (Equation (19)).

$$\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{kjic}^{\pm}+Y_{kjic}^{\pm}\right)=\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{(k-1)jic}^{\pm}+Y_{(k-1)jic}^{\pm}\right)\forall;j,k \tag{4}$$

$$FA_{kjicm}^{\pm}+B_{kjicm}^{\pm}\leq D_{jicm}^{\pm}\forall;k,j,i,c,m \tag{5}$$

$$FTW_{jic}^{\pm}-FA_{kjicm}^{\pm}-B_{kjicm}^{\pm}\leq prec_{m}^{\pm}\ \ \forall;k,j,i,c,m \tag{6}$$

$$0\leq FA_{kjicm}^{\pm}+B_{kjicm}^{\pm}\leq FTW_{jic}^{\pm}\forall;k,j,i,c,m \tag{7}$$

$$FMIN_{jic}\leq FA_{kjicm}^{\pm}\leq FTW_{jic}^{\pm}\forall;k,j,i,c,m \tag{8}$$

$$\begin{aligned}&\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{jick}^{\pm}\cdot FA_{kijcm}^{\pm}+Y_{jick}^{\pm}\cdot DA_{jicm}^{\pm}\right)+\sum_{j=1}^{J}\sum_{c=1}^{C}RA_{kic}^{\pm}\cdot DA_{icm}\\&\quad+\sum_{t=1}^{T}\sum_{c=1}^{C}IP_{kt}^{\pm}\cdot IA_{kt}^{\pm}\cdot DB_{ktc}^{\pm}+\sum_{c=1}^{C}MUN_{c}^{\pm}\leq TWD_{m}^{\pm}\end{aligned}\ \forall;k,m \tag{9}$$

$$\sum_{i=1}^{I}\sum_{c=1}^{C}\left(X_{kjic}^{\pm}\cdot FA_{kjicm}^{\pm}+Y_{kjic}^{\pm}\cdot DA_{kjic}^{\pm}\right)\leq PUMC_{j}^{\pm}\forall;k,m \tag{10}$$

$$a_{i}^{\pm}\leq\sum_{j=1}^{J}\sum_{c=1}^{C}\left(X_{jc}^{\pm}+Y_{jc}^{\pm}\right)\leq b_{i}^{\pm}\forall;i \tag{11}$$

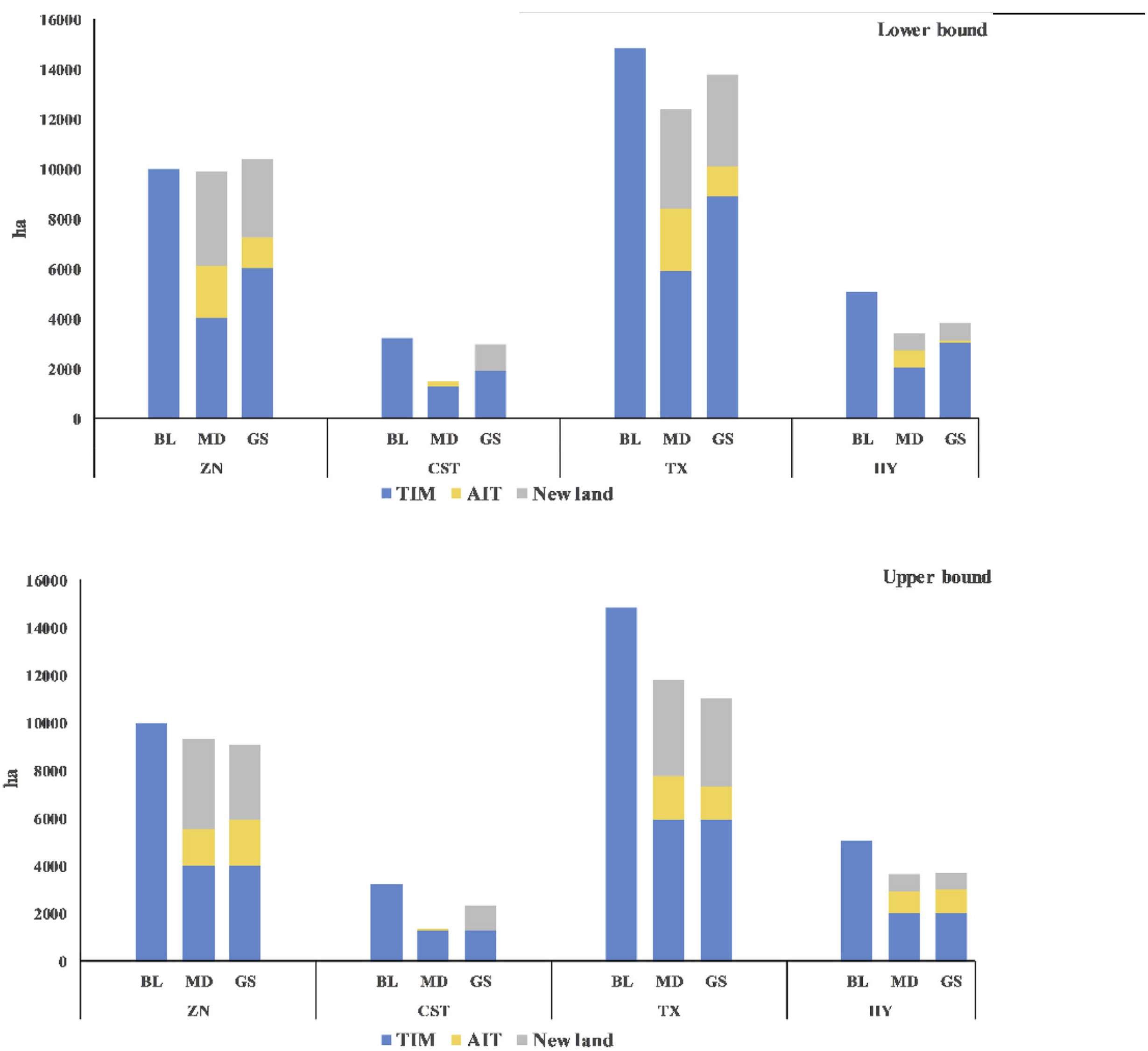


Fig. 4. Corn growing area for each county.

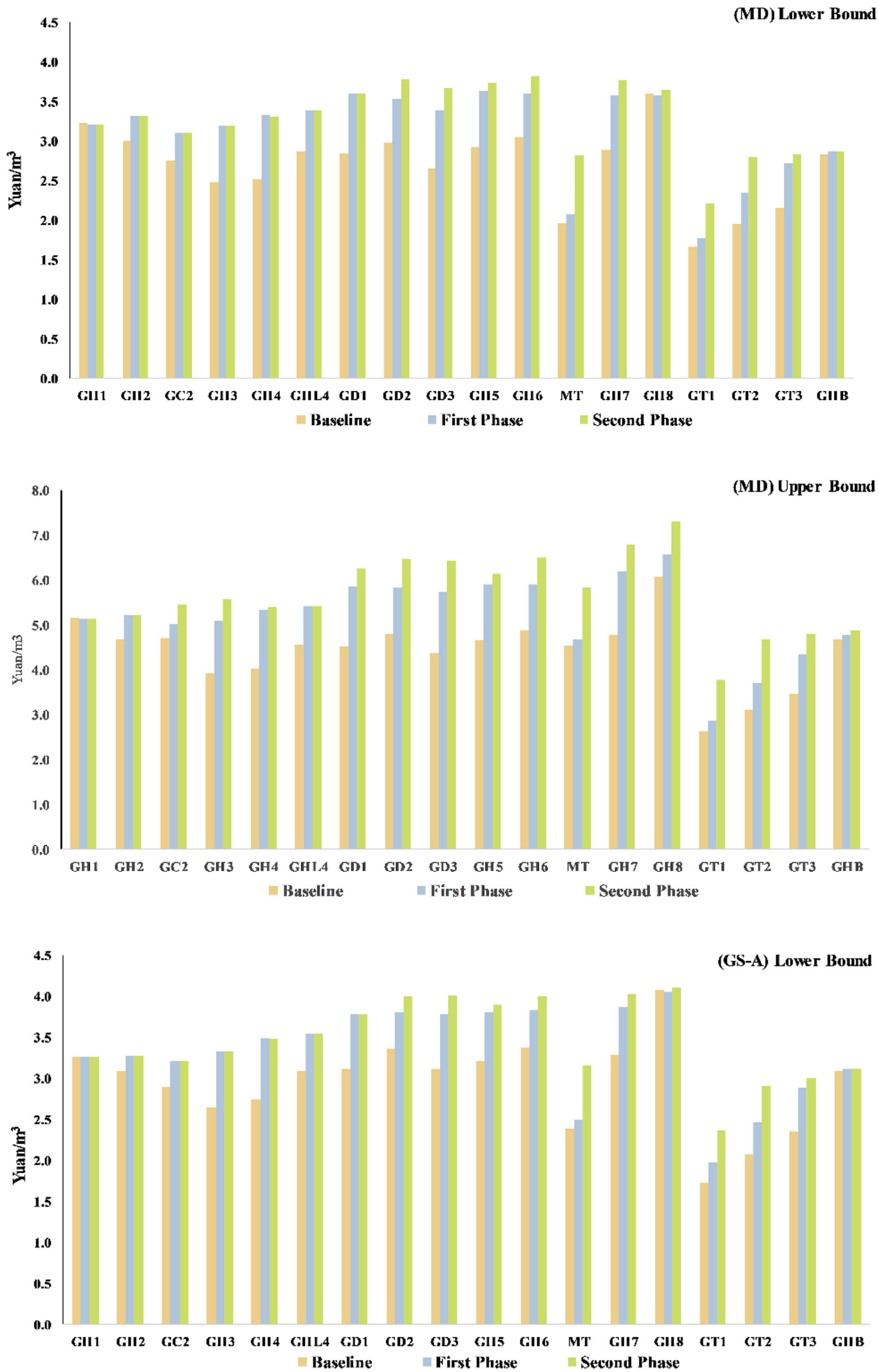


Fig. 5. Corn unit water profit.

$$\sum_{j=1}^{J}\sum_{c=1}^{C}X_{kjc1}^{\pm} \geq \sum_{j=1}^{J}\sum_{c=1}^{C}SEC^{\pm}\cdot X_{(k-1)jc1}^{\pm}\ \forall;k \tag{12}$$

$$\sum_{j=1}^{J}\sum_{c=1}^{C}X_{kjc1}^{\pm}\cdot UCP_{kjcm1}^{\pm} \geq ENS_{m1}^{\pm}\cdot\sum_{j=1}^{J}\sum_{c=1}^{C}X_{kjc1}^{\pm}\cdot FPRO_{kjcm1}^{\pm}\ \forall;k,m \tag{13}$$

$$DB_{ktc}^{\pm} \leq \exp_{tc}^{\pm}\forall;k,t,c \tag{14}$$

$$\sum_{k=1}^{K}DB_{kcx}^{\pm} \leq \sum_{k=1}^{K}DB_{kcy}^{\pm}\ \ x,y\in t\ \ \forall;c,x,y \tag{15}$$

$$\sum_{t=1}^{T}\sum_{c=1}^{C}IP_{ktc}^{\pm}\cdot IA_{ktc}^{\pm} \leq \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{c=1}^{C}Y_{kjic}^{\pm}\cdot SAVE_{i}\cdot IPW^{\pm}\forall;k \tag{16}$$

$$\sum_{i=1}^{I}Y_{kjic}^{\pm} \geq \sum_{i=1}^{I}Y_{(k-1)jic}^{\pm}\forall;k,j,c \tag{17}$$

$$\sum_{e=1}^{E}\left(X_{kjce}^{\pm}+Y_{kjce}^{\pm}\right) \geq \sum_{e=1}^{E}\left(X_{(k-1)jce}^{\pm}+Y_{(k-1)jce}^{\pm}\right)E\in I\forall;j,c \tag{18}$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I}Y_{kjci}^{\pm}-\sum_{j=1}^{J}\sum_{i=1}^{I}Y_{(k-1)jci}^{\pm} \leq BUD_{c}^{\pm}\forall;k,c \tag{19}$$

The above optimization model can be solved by splitting it into two deterministic sub-models corresponding to its lower and upper bound. Then, the lower bound of the model will be solved at first and served as an additional constraint for the model's upper bound.

3.2. Data description and scenarios design

The proposed model was driven by various social-economic and climate data such like initial crop growing area, pumping capacity, water demand, production cost, precipitation and soil conditions. Most of these data were collected from Ningxia water conservancy. The precipitation probability distributions (Table S3) were calculated based on precipitation data from 1955 to 2013. The planting cost is calculated based on the electricity cost at each pumping station and annualized fixed expenses (seeds, labor, infrastructure etc.). The non-liner corn yield simulation functions used for DI practice were simulated using the on-site corn growing observations from 2008 to 2013 as listed in Table S4. Despite the data required for the model calculation, some pre-defined parameters (e.g. corn reduction ratio and yield rate coefficient) were also essential model inputs reflecting local economic conditions and the importance of the crop. As corn is the main source of feed for local husbandry, which consumes 75% of the locally produced corn (Li et al., 2009). Local government pursues self-sufficiency in major staple food such like corn and wheat (Dalin et al., 2015). Therefore, the periodical corn reduction area should be limited to a safe range permitted by government. In this case, 7%–10% of reduction ratio per year is allowed according to the historical food crop changing ratio in this region. To prevent permit holders “cashing” water under DI practice, seasonal water trading is capped by using the unit food production, which is required to meet a yield rate coefficient (as 85%–90% in this case) of its maximum production at each hydrological year.

Subsidization policy is the key to the successful implementation of water market in its initial phase. The seasonal water trading will happen if only permit holders can receive the benefits that are equal to or higher than their opportunity cost of water, which defied as the compensation of losing water and associated benefits. To respect the policy legacy and at the meanwhile stimulate water trading, three sets of subsidization policy scenarios is established. The first scenario is market-driven scenario (labeled as the MD scenario), under which the government has no subdization to water price nor trading price of water. The second is government subsidization scenario (labeled the GS scenario). The GS scenario has two sub-scenarios as GS-A (25%–50% of the opportunity cost subsidy) and GS-B (50%–60% of the opportunity cost subsidy). Both scenarios also have 50% of water cost subsidy (preferential water price). The last two scenarios are the baseline scenario (with 75% subsided water price and no water trading) and a neutral scenario (no subsided water price and no water trading). The detailed subsidized opportunity cost of water is listed in Table S5.

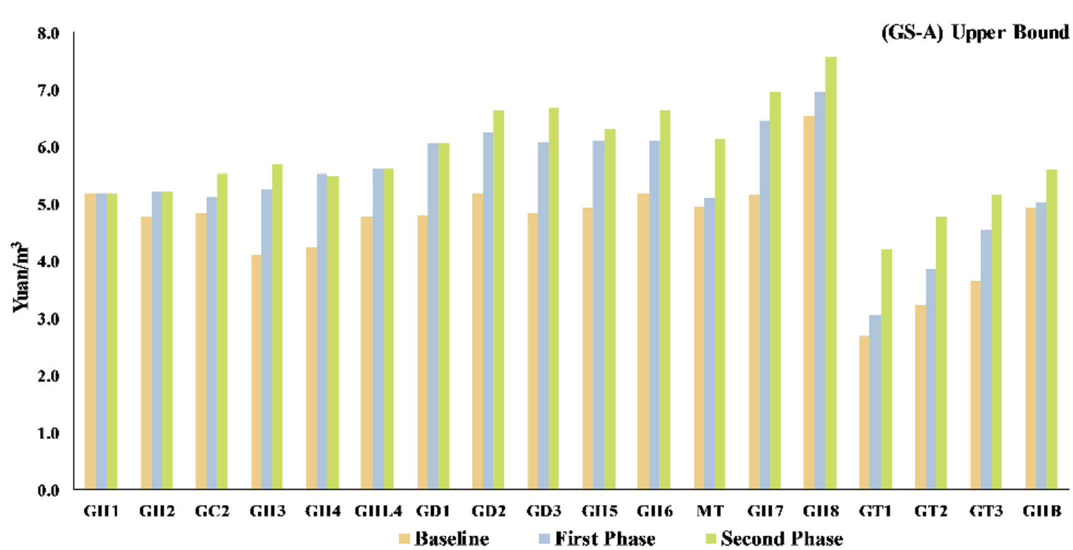


Fig. 5. (*continued*).

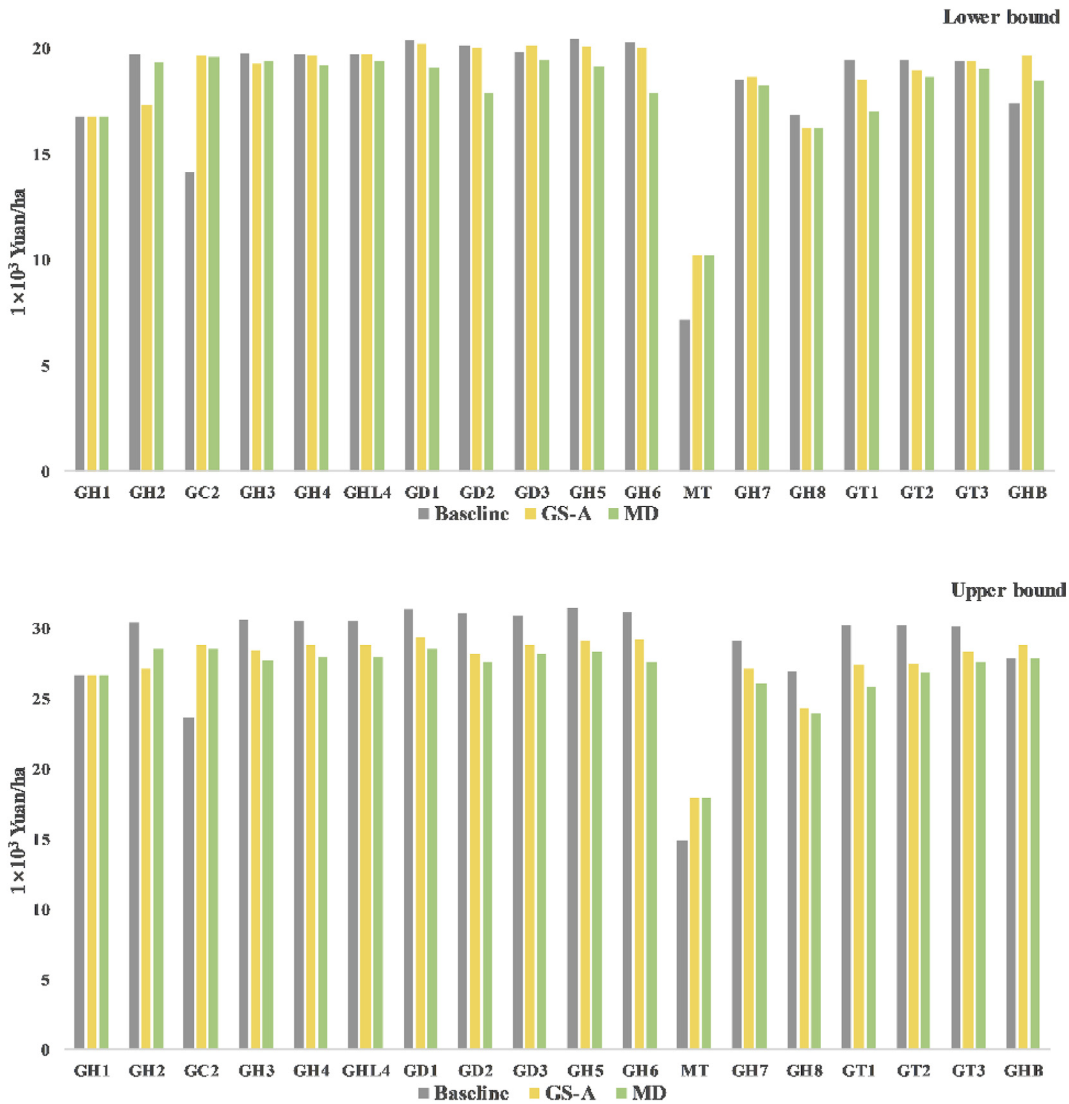


Fig. 6. Corn unit area revenue at the end of second phase.

4. Results and discussion

In this study, two planning phases were proposed with each having a length of three years. Even though the changing climate has intensified the water shortage situation, it is safe to assume that the during the six years planning period, the effect of climate change is neglectable because (1) the water delivered to GWDS only has 4.4% of the annual variance and (2) the average temperature and precipitation change during the planning period is very limited. Five water policy scenarios (MD, GS-A, GS-B, Baseline and Neutral) were examined.

4.1. Water resources management plans

Fig. 3 shows the cropping patterns for two planning periods and two policy scenarios. The interval-valued solutions reflect system uncertainties. The results demonstrate that the corn growing area would be gradually reduced and replaced by economic crops for both scenarios. This implies that the government subsidies and seasonal water trading have limited impacts to cropping pattern change. Fig. 3 also shows that optimal cropping pattern could improve the overall resiliency to water availability. This is evidenced by the millet (as a drought-resistance crop) growing area, which was appeared in the 1st phase and then reduced in 2nd phase for both MD and GS-A scenarios (same evidence can also be found in Fig. S3). During the transition from traditional to advanced irrigation technology, millet is introduced to meet the tight water demand in the 1st phase, with continuing infrastructure improvements, it then will be replaced by economic crops.

Fig. 4 shows that the overall corn production of this region will not be expected to reduce further due to the land reclamation. It also indicates that a considerable flood irrigation area (TIM) of corn will be altered to advanced irrigation area (AIT) at the end of second phase. From the perspective of irrigation schemes, the DI practice will increase the corn unit water profit for both scenarios (as shown in Fig. 5). Correspondingly, Fig. 6 shows that the unit area corn production will not change if 90% of corn yield rates is ensured. In comparison, a more aggressive decision (i.e. 85% corn yield rates) will reduce 4% (under GS-A) and 7% (under MD) of the unit area corn production for higher overall benefits.

The growing area with improved irrigation infrastructure at the end of 2nd phase is shown in Fig. 7. Under the joint investment from local government and industries, over [21, 30] % of the irrigated land will be equipped with advanced irrigation infrastructure

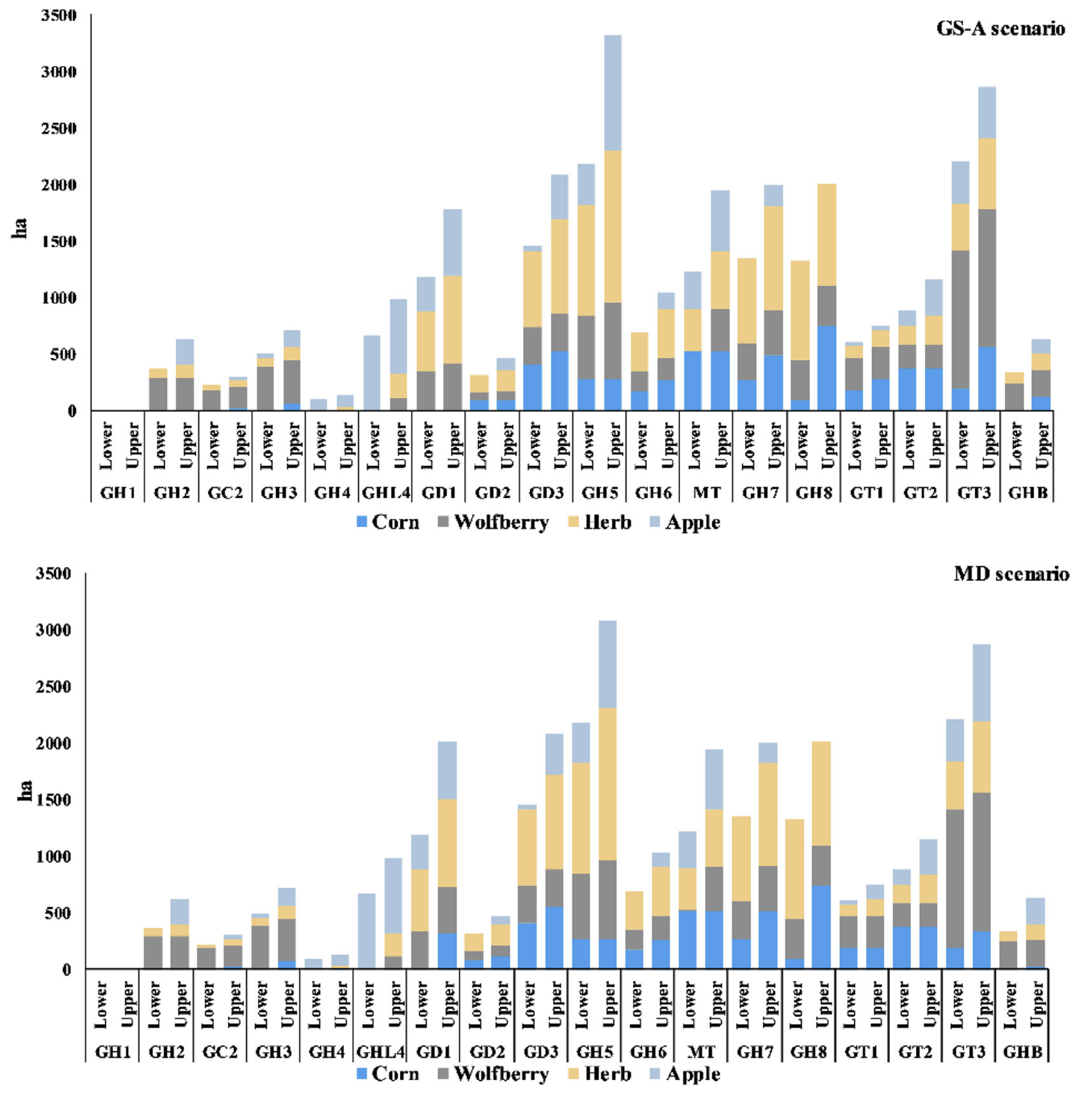


Fig. 7. Improved-infrastructure areas at the end of second phase.

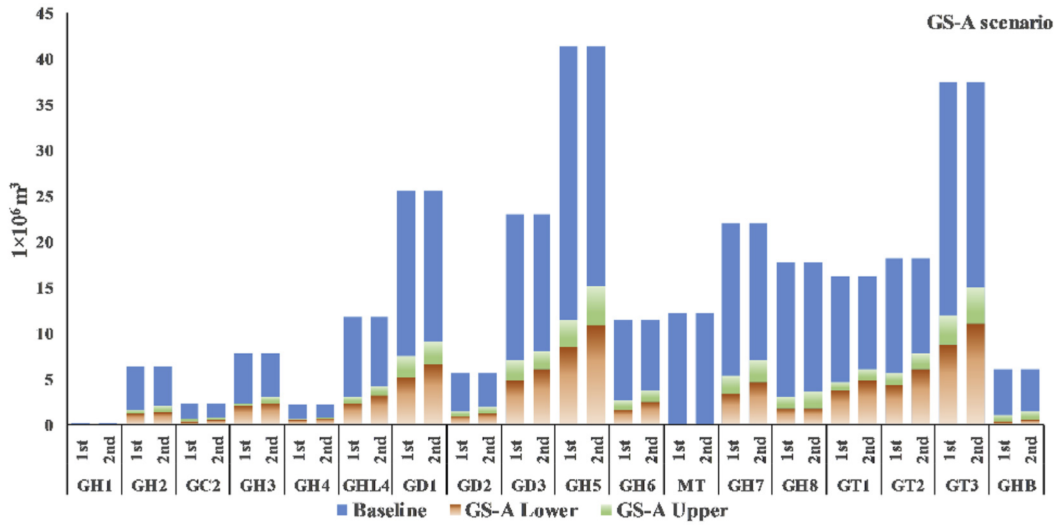
for the first phase, and the number will increase to [42, 62] % at the end of the 2nd phase. Fig. 8 and Table S6 shows the water conservation potentials for each district. The results indicate using the preferential water price only have very limited incentives to infrastructural development. In fact, the crop unit water profit is the most influential factor that considered during the decision-making process (refer to Table S7). Fig. 9 shows a positive correlation of pumping head and water use efficiency, which suggests that the infrastructure modification will contribute to sustainable production by saving water and energy. The water use efficiency in Fig. 9 is defined as the ratio of the advanced against traditional water use.

Combined with all three forms of water conservation strategies, there is remarkable increase in revenue for the original land, reclaimed land and industries. The specified revenue for each district is listed in Fig. S4. The permanent water trading from original land to industrial sector allows all industries to expand their producing capacity during the planning horizon as shown in Table 1. Similarly, water permanently traded to agricultural sector allows local government reclaiming more farmland within GWDS. Fig. 10 indicates the combination use of water conservation strategies will likely to triple the local gross revenue by the end of the 2nd phase.

4.2. Water trading

Fig. 11 shows the detailed water allocation, which indicates that the water will be permanently transferred out of the original land and then reallocated to three sections: municipal, industrial and land reclamation. The municipal water use will consist very small portion of the total water use. On the other hand, the largest share of conserve water will go to land reclamation, which will reach [34, 49] % of the original irrigation area by the end of 2nd phase as shown in Fig. 12.

Effectiveness of seasonal water trading can be reflected through Fig. 11. Under a timely rainfall and scheduled irrigation, a considerable amount of water (permitted minus used) can be conserved and traded during the first planning phase. The influences of different policy scenarios are demonstrated as follows: The seasonal traded water under GS-A scenario will be slightly less than MD scenario. The results suggest that the trading effectiveness under MD scenario can be approached through subsidized trading



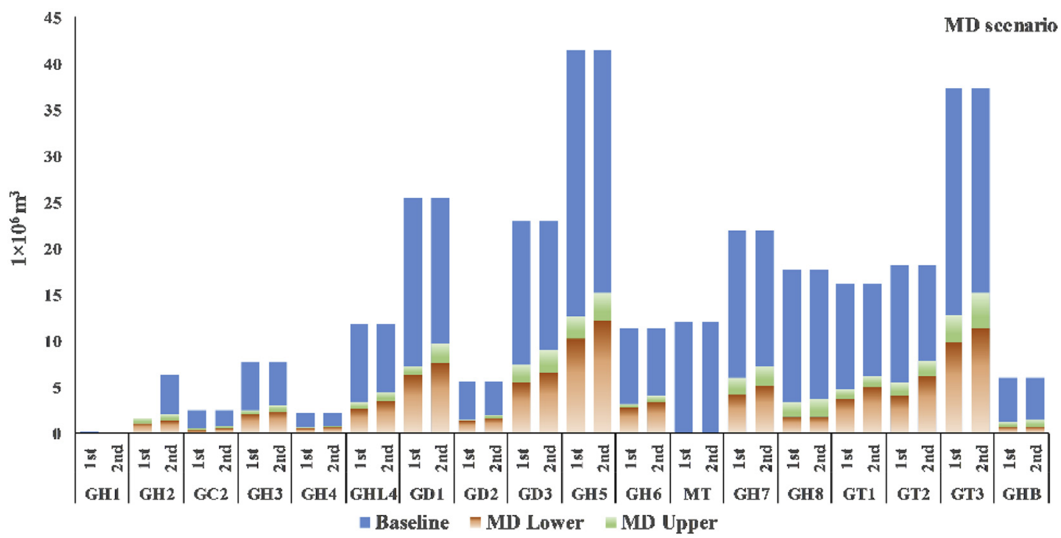


Fig. 8. Water conservation potentials at each district. (Baseline indicates the maximum amount of water can be delivered to the district).

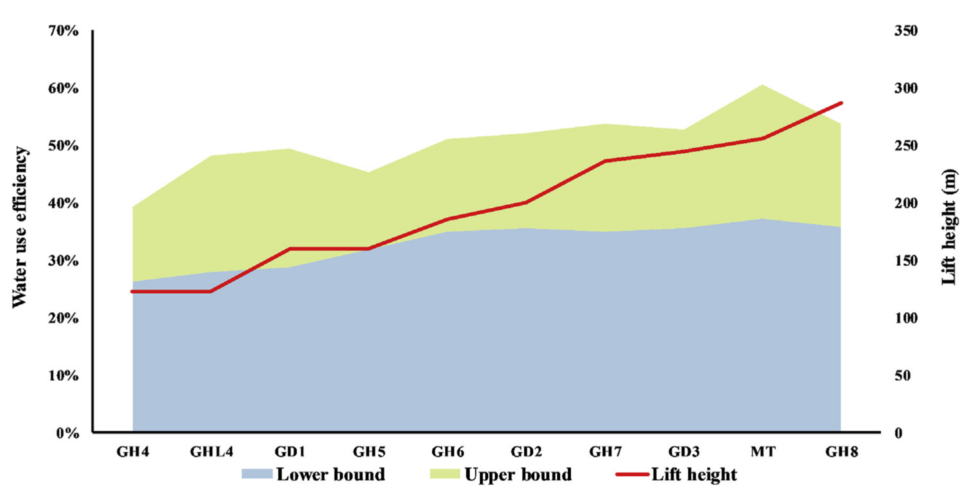


Fig. 9. Relations for pumping head and water use efficiency.

Table 1
Industrial expansions for each county.

Industry catalogs	Phase	ZN	CST	TX	HY
Gypsum powder	First	[1,2]	0	0	0
	Second	[2,4]	0	0	0
Dry wall	First	[1,2]	0	0	0
	Second	[2,4]	0	0	0
Cashmere	First	0	0	[1,2]	0
	Second	0	0	[3,4]	0
Blanket	First	0	0	[1,2]	0
	Second	0	0	[3,4]	0
Sheep fur	First	0	0	[0,1]	[0,1]
	Second	0	0	[0,3]	[1,3]

Note: The interval-valued solutions denote expansion times.

prices of water, as which would encourage permit holders to perform water trading.

Infrastructure modification will be the key factor affecting seasonal water trading because the reduced traditional irrigation area will shrink the DI practice space thus limit the seasonal water trading. This is evidenced by the ratio of seasonal against long-term water trading, which will drop from [29.1, 35.9] % and [22.4, 31.2] % in the first phase to [5.1, 10.9] % and [2.5, 6.0] % in the second phase under MD and GS-A scenarios, respectively.

Deficit irrigation plays a key role in seasonal water trading. The corn water deficit for baseline year is listed in Table S8. The trading price of water in MD scenario is higher than it in GS-A scenario thus irrigators will be more incentivized. In specific, the volumes of water traded in normal year under MD scenario is higher than it in GS-A scenario. It indicates that subsidized trading price of water under GS-A scenario are less or equal to permit holders' opportunity cost. Table S9 suggests that the proposed corn irrigation quotas should respond the temporal and spatial distribution of the precipitation in order to achieve a more adaptable, flexible and sustainable water resources management.

The effectiveness of subsidization policies is disclosed by using system Gross Net Revenue (GNR), which is estimated as the gross revenue minus government subsidy. To compare four policy scenarios (i.e. MD, GS-A GS-B and baseline scenario), the neutral scenario is set to be zero-point as the contrast. It is illustrated that only MD and GS-A scenarios have all positive GNR (shown in Fig. 13), while the baseline scenario is the most "expensive" scenario. Table 2 suggests government subsidies to the trading price of water will be positively enhance water trading. Comparing to direct subsidization policy (i.e. subsidized water price), the indirect subsidization policy will not only reduce the government financial burden, it also provides opportunities for irrigators to gain from the water market.

4.3. Trading limitations and future research

Seasonal water trading is squeezed during the planning horizon due to the development of advanced irrigation technologies as well as the reduced corn growing area. As a result, there is a tradeoff effect between the permanent water trading and seasonal water trading. In the future research, the seasonal water trading will not be limited to a certain kind of crop or irrigation method, and it may also occur between different industries. Moreover, the model assumes that irrigators are willing to trade their water for both long-term and short-term. However, there are many hard-to-quantified factors such as irrigator's willingness-to-trade and irrigation behaviors that influence water sellers from water trading (Wang et al., 2016, 2018). Therefore, more alternatives for irrigators will be considered in the future. In addition, current water trading framework will also be advanced in our future work through integrating Input-Output models to discover the linkage among water consumption, pricing and trading effectiveness for all the water users.

5. Conclusions

A market-based water resources planning model is proposed in this research, which provides a pioneer study integrating system

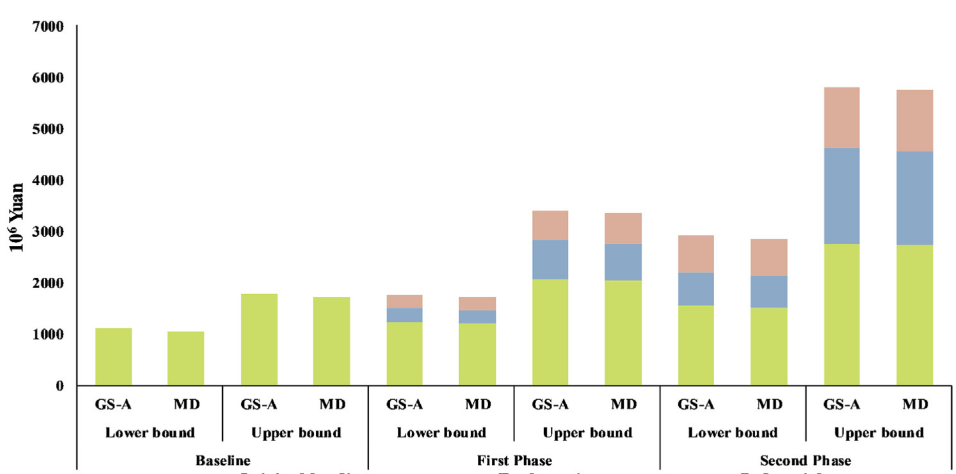
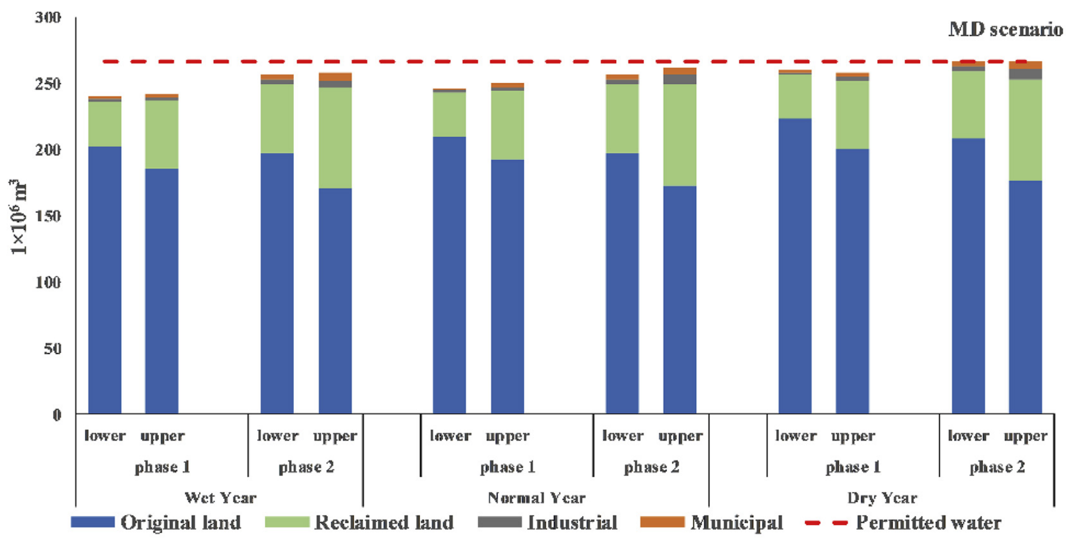


Fig. 10. Gross revenue for GWDS.



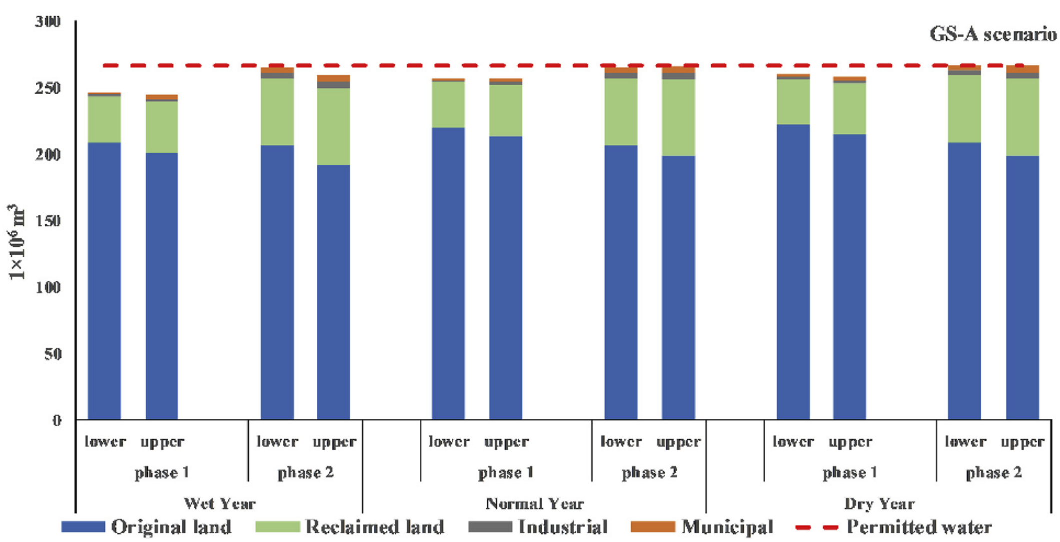


Fig. 11. Water allocation for different consumers.

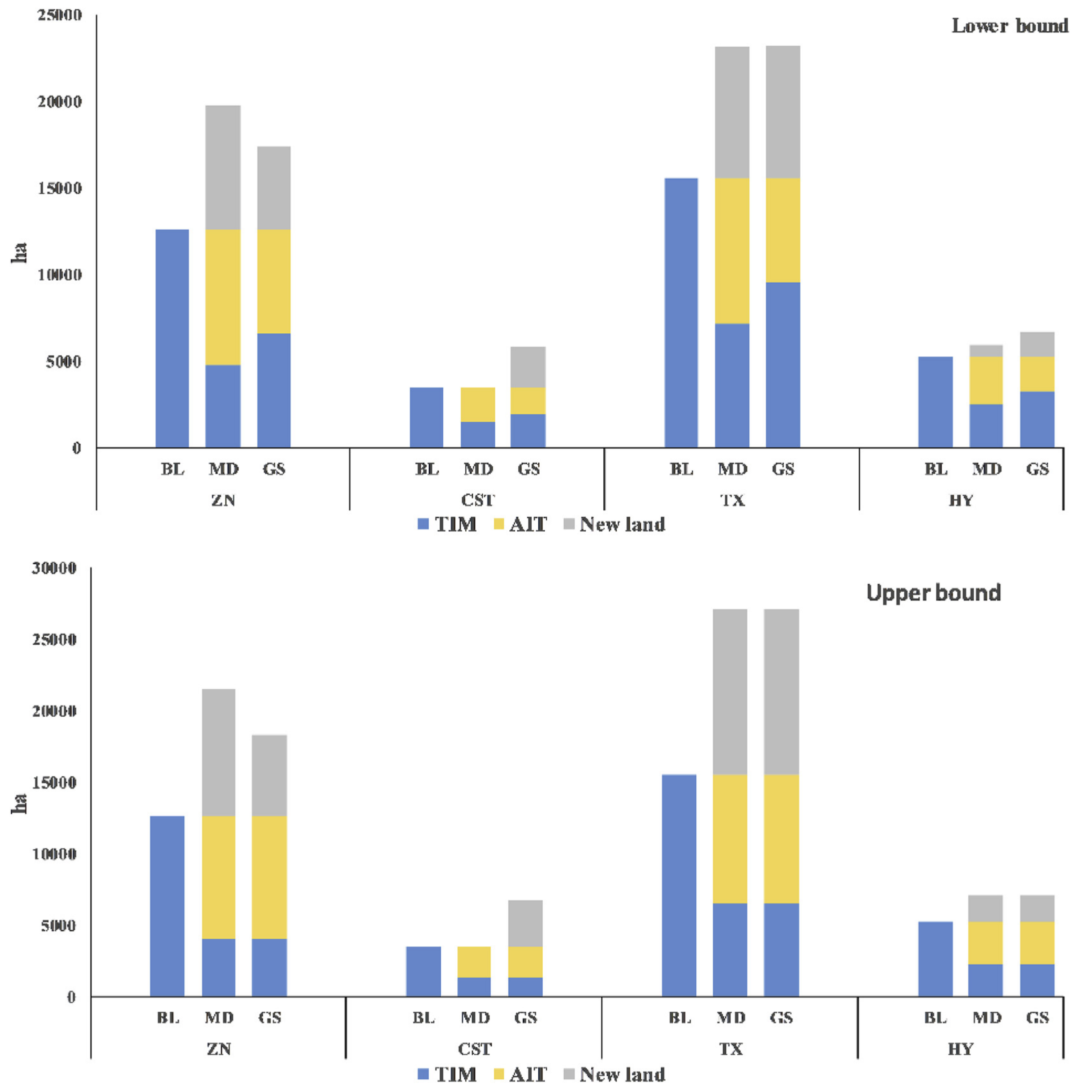


Fig. 12. Farmland area at the end of second phase.

Table 2
Government subsidies under different scenarios.

Scenario	Phase 1 (10^6 Yuan)	Phase 2 (10^6 Yuan)
GS-A	[68.3, 88.6]	[67.1, 72.1]
GS-B	[86.3, 111.2]	[76.0, 80.5]
Baseline	[92.0, 95.1]	[95.8, 101.1]
Neutral	0.0	0.0
MD	0.0	0.0

optimization, technological innovation and water trading. The analytical solutions provide in-depth information for decision makers to achieve a drought resilient and resources sustainable cropping pattern. Permanently conserved water will meet the industrial and municipal sectors' water demand via long-term water trading. Temporally conserved water will increase the system flexibility and shift the water to higher social gains. The improved water use efficiency will facilitate local cleaner production with less application of fertilizer and energy consumed for pumping water.

By integrating the crop yield simulation functions and DI practice, the model allows seasonal water trading, which will help irrigators to manage their licensed water and change their irrigation attitude from 'irrigate as much as possible' to 'think before irrigate'. Owing to the adaptation of innovative irrigation technology, the regulated trading prices of water will become less attractive to water permit holders. To keep water permit holders incentivized all the time, the trading price of water should keep pace with the growth of opportunity cost of water. The revealed relationship between government subsidy and generated revenue will help design of subsidization policies and reduce the government's financial burden, hence promote sustainability.

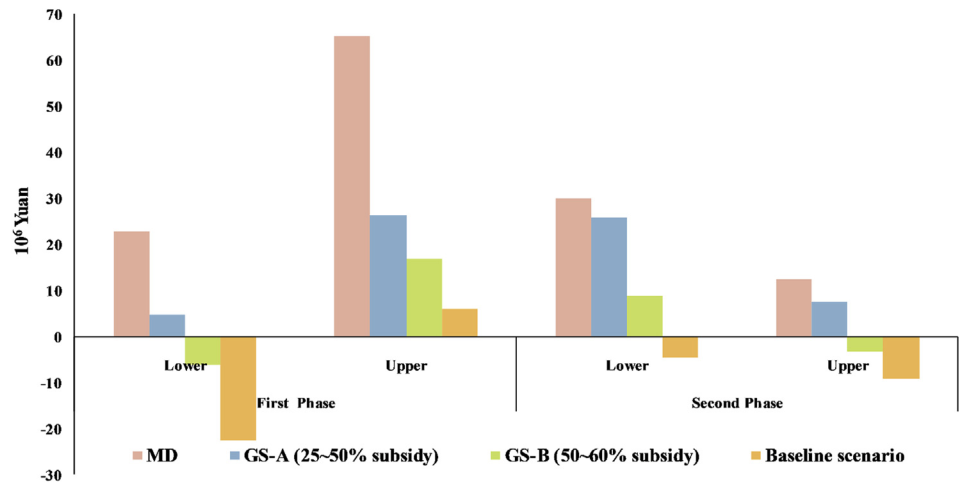


Fig. 13. Comparing GNRs of four scenarios (setting neutral scenario as zero point).

Acknowledgement

This research was supported by the National Key Research and Development Plan (2016YFC0502800, 2016YFA0601502), the Natural Sciences Foundation (51520105013, 51679087), the National Bureau of Asian Research and 111 Programs (2013CB430401, B14008) and the Natural Sciences and Engineering Research Council of Canada. We appreciate Ningxia water conservancy for offering related data and help, and we also appreciate reviewers and editors for their careful reading of our manuscript and constructive comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.05.379.

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