Response to comments

<u>*General Comment*</u>: ***The manuscript has been reviewed by two reviewers, and the authors have, in my view, responded adequately to the issues raised. I have, however, additional comments that were not raised by the reviewers, and which I like to share with the authors, and I invite them to react to these. My comments are quite significant. When the authors submit a revised manuscript I may decide to send it again out for review. The paper addresses an important and interesting issue, namely how to deal with water scarcity taking both blue water transfers and virtual water transfers into account, in a 2-level decision setting, and also taking account of three different water using sectors. Quite a complex setting, and an ambitious undertaking. Given such complexity it is important that the argument is clearly presented and here the manuscript needs to be improved significantly (towards the end of this comment I give details what in my view should be addressed to improve the readability of the paper).***

<u>Response:</u> We would like to thank you and the two reviewers for the valuable comments and suggestions on our manuscript, all of which have assisted us in substantially improving the paper, as detailed in the following responses.

<u>*Comment 1-1:*</u> ***A first comment is that the paper makes no attempt whatsoever to validate the proposed model, or at least to show that model outcomes are plausible; this could have been done, for example by comparing model results with observed data, and discussing similarities and differences.***

<u>Response</u>: Thank you for your observation. As described in the manuscript, the basic idea was that the two-decision maker levels compromise to determine an optimal global solution as it is impossible that both can simultaneously achieve their desired goals. The proposed model was solved using the MATLAB R2017b solver, with the iteration process given in Figure 1. To be specific, the leader makes the first decision, and based on the leader's solution, each follower seeks an optimal solution within the necessary compromise. Then, the followers send their solutions to the leader, who then adjusts their own goals and preferences. The chosen upper level optional solution standard was that the value of the objective function needed to be larger than previous value and the chosen lower level optional solution standard was that one of the objective function values was smaller than the previous objective function value. This iterative process continues until the termination condition is satisfied, which is when the average change in the fitness value

is less than the options or when the algorithm reaches one hundred iterations.

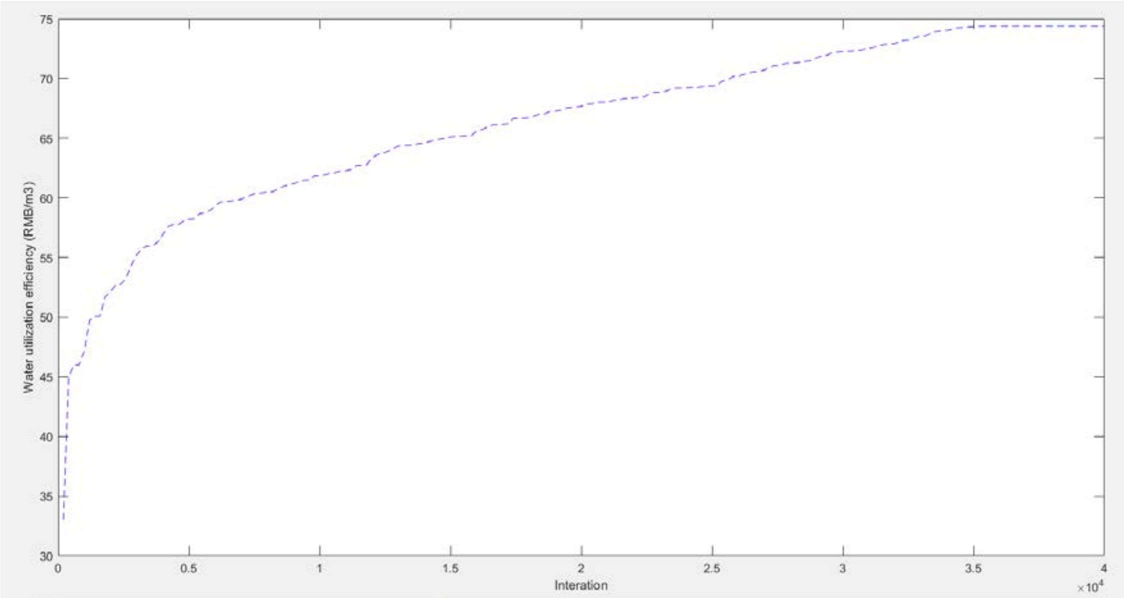


Figure 1 Iteration process for the upper level objective function.

In the revised manuscript, the outcomes were compared with data from a planning report. In **Section 4.3 Optimal Virtual Water Trade**, Figure 5 compares the results from the proposed model with those reported in the Water Resources Planning Report for Bayan Nur, from which it was found that as the Hetao irrigation district was water-scarce, it was most suitable for growing maize, which accounted 182,424 hm^2, with a further 40% devoted to irrigated sunflowers, and 15% to irrigated wheat. In the Water Resources Planning Report of Bayan Nur, a 312,380 hm^2 area was planned for sunflowers, and 124,913 hm^2, 34,073 hm^2 for maize and wheat. In general, the main land use differences were related to the agricultural water usage sector. Economically, the total net import costs were 5.66×10^9 CNY, with the saved water transferred to industrial or domestic sectors totaling about 3.35×10^{11} CNY. Therefore, from both water conservation and economic development perspectives, virtual water imports need to be included because of inter-regional exports and local consumption.

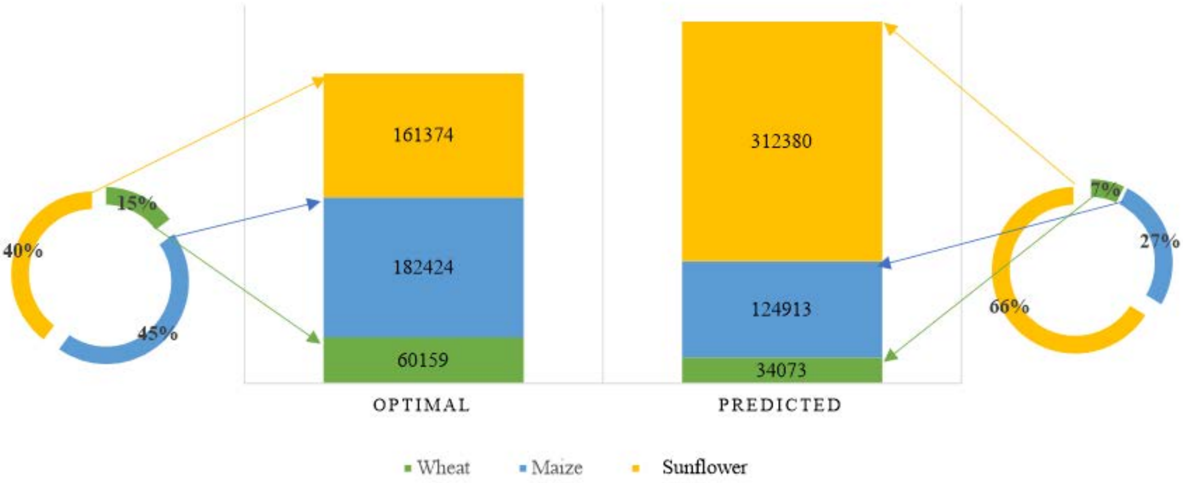


Figure 5. Predicted crop areas in the planning report compared to the optimal values (hm^2)

Comment 1-2: ***Similarly, the authors could have conducted sensitivity analyses to verify how sensitive model results are to changes in input values of certain critical parameters; not for the authors to draw far reaching conclusions, but rather to re-assure the reader of the validity of the model. In the current manuscript the authors have indeed conducted several sensitivity analyses (on water availability, sectoral water demands, prices of import crops and water price), and they draw far reaching conclusions on the outcomes, without even trying to explain these outcomes (see below). But this is not convincing to me. It would be much more convincing to use sensitivity analysis to demonstrate the robustness and plausibility of the model.***

Response: Thank you for your suggestion. In the original manuscript, several sensitivity analyses were included and far reaching conclusions and managerial insights given. In the revised manuscript, based on your suggestion, we have rewritten this section to systematically investigate the allocation responses to changing values in the model's input and drastic changes in the model's structure. Two robustness measures: minimum water utilization efficiency and maximum sectoral vulnerability: were used to assess the optimal solution.

Water availability. The optimal results indicated that with a decrease in available water, the water utilization efficiencies fluctuated slightly, which verified the robustness of the model. When the amount of available water increased, the utilization efficiency fluctuated with an increase in total water consumption, and compared to the water utilization efficiency, the vulnerability values were within an acceptable range. Therefore, it was found that after the blue and virtual water transfers, the water allocation and import/export strategies had the ability to adapt to varying quantities of available water,.

Water demand. With a decrease in the agricultural water demand, the water utilization efficiency improved and total consumption decreased. To monitor the performance and assess the responses to each scenario, Table \ref{tab:com4} indicated that the proposed model was robust to agricultural and industrial sector parameter changes, but was somewhat weaker when domestic water demand changed.

Import prices. When the imported crop import prices changed, there was only a small change in the water utilization efficiency and vulnerability, which also indicated that the proposed model was comparatively robust to changing import prices; however, it was found to be more sensitive to water price variations for sunflowers, followed by maize and wheat.

Water prices. Table 7 indicated that the optimized decision variables were less sensitive to the changes in market prices, and verified that the proposed model had a robustness to market prices.

More content describing the robustness of the proposed model was added in **sub-sections 5.4.1-5.4.4 (Sensitivity analysis)** in the revised manuscript.

Comment 1-3: ***The comparison of model results with scenarios omitting virtual water transfers and blue water transfers and with the two-staged model (section 5.2) is interesting, although it is not clear to me how the proposed model differs from the two-stage model. I would suggest to use this comparison to demonstrate the validity (and value) of the proposed model; rather than to formulate far-reaching conclusions. First the model must be validated before it is used to draw conclusions.***

Response: Thank you for your constructive suggestions. We have added models (C1) and (C2) to the Appendix in the revised paper to elaborate the differences in the models and have rewritten and condensed sections 5.2 and 5.3 to demonstrate the validity (and value) of the proposed model.

In general, the proposed model, and models (C1) and (C2) were all able to solve different realistic problems. Water-scarce areas such as the case study area in northern china have more land and have a duty to provide Southern China with crops. However, planting and crop irrigation strategies have been affected as importing water-intensive crops from other countries has become more common. Therefore, it is vital that water supply system models be developed that can determine the optimal quantities of allocated water and blue and virtual water transfers in hierarchical decision- making structures consisting of a water affairs bureau and water usage sectors. The following paragraphs detail the model differences.

In model (C1), as the crop imports and exports are not considered, the decision variables are X_i, $\mathbf{WTI}$, $\mathbf{WTD}$, x_{1k}. Therefore, the crops are grown only for self-consumption rather than for the development of the agricultural economy. In model (C2), as the blue water transfers from the agricultural sector to the non-agricultural sectors are not considered, the decision variables include X_i, $\mathbf{EM}_k$, $\mathbf{IM}_k$, x_{1k}. Therefore, the water market is ignored, which hinders cooperative economic planning and market regulation development in China.

Given that water utilization efficiency, sectoral vulnerability and water stress are the key indexes for model robustness, it was found that the incorporation of the virtual water and blue water transfers into the traditional bilevel optimization model was able to alleviate water stress, improve water utilization efficiency, minimize sectoral vulnerability and increase system stability. Additional content can be found on **Page 19**.

The main difference between the two-stage optimization model and the proposed model was that a Stackelberg game between a leader and followers was fully considered in the proposed model and there were strategic interactions before the compromised solution was obtained, which were directly included in the solution paradigm and Pseudo code (steps 3 and 4).

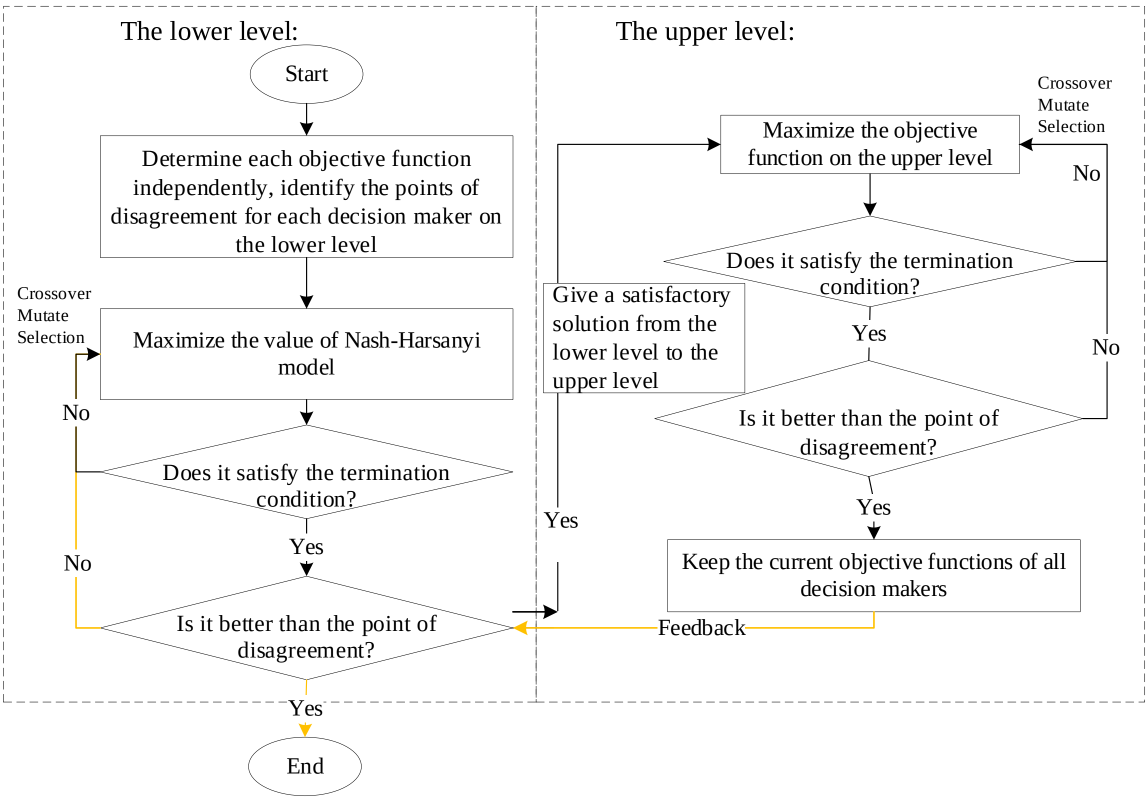


Figure 4. Steps for solving the proposed model

Table B1. Pseudo code for the proposed model.

```
Input: The correlation parameter, disagreement points (dis^U, dis_i^L), bargaining weights (α_i) ;
Output: A satisfactory solution and objective functions for the proposed model;
Step 1: Initialize population, construct fitness functions for the upper objective (Eff) and an auxiliary
fitness function for the Nash-Harsanyi model in the lower level ( ∏_{i=1,2,3} (F_i − dis_i^L)^{α_i} );
Step 2: Randomly generate an initial solution, maximize the fitness function in the lower level
        IF (any lower level objective functions are lower than their disagreement points)
        {generation++;
        population [generation+1]=Select (Mutate(Crossover (parents)))};
        Else: go to step (3);
Step 3: Input the satisfactory solution from step (2), maximize the fitness function in the upper level
        IF (upper level objective function is lower than its disagreement point)
        {generation++;
         population [generation+1]=select (mutate(crossover (parents)))};
        Else: keep the current decision variables and corresponding solutions and go to step (4);
Step 4: Feedback
        IF(the updated lower level objective functions are still better than the disagreement points)
        {IF (generation > Maximum generation )
          {Output all the decision variables
          End loop}}
        Else: go to step (2)
```

Comment 2-1: ***A second comment is that the entire section 5.4 on sensitivity analyses raises more questions than it answers. For example, consider the available water (Table 5): if I understand it well, when there is 10% more water available, less water is allocated to agriculture (X_1), and when there is 15% more water than the base case, more water is allocated to agriculture, and when there is even more water (20% more than the base case) the volume allocated to agriculture is suddenly halved. This begs for an explanation. Similar questions may be raised concerning the water allocated to the domestic sector (X_3).***

Response: Thank you for your detailed comment. We have enriched the explanation for the changes in water use in the discussion on model robustness. In the results, the amount of available water was the main factor regulating and controlling the allocation ratios between the different water users. From the values in the two robustness indexes, the proposed model may not be suitable for solving water allocation problems or blue and virtual water transfers as the imbalance in the market would attract the Chinese interventionist government's attention. In other hydrological environments, there are different water use strategies. For example, when there is 10% more water available through precipitation during a crop growth cycle, there would be less irrigation water needed, which means that less water would be allocated to agriculture. However, if there was 15% more water than the base case, more water would be allocated to agriculture because of an increase in crop exports. Because of Hetao irrigation district’s comparative land advantage (Zhao et al., 2019), it is a suitable place to plant crops if there are enough water resources.

When there is 10% more water available, less water is allocated to agriculture and less agricultural water is sold to the non-agricultural sectors. When there is 15% more water than the base case, there is less water being allocated to the domestic sector as rainfall in a planning year has no positive influence on domestic use. In future research, it would be interesting to study the potential impact of an increase in available water on the domestic wastewater reuse rate and domestic water use efficiency (Ding et al., 2012; Li, 2014).

Reference

Zhao D, Hubacek K, Feng K, et al. Explaining the virtual water trade: A spatial-temporal analysis of the comparative advantage of land, labor and water in China. Water research, 2019, 153: 304-314.

Ding G, Liu D, Zheng G et al. Study on factors influencing domestic waste water removal by novel integrated process. Journal of North University of China, 2012, 33(4): 443-447.

Li Yue. Use Efficiency of Domestic Water Resources and Influencing Factors Analysis Based on Stochastic Frontier Analysis (Chinese). Water resources and power, 2014.

Comment 2-2: ***When considering changes in the water price, it is concluded that the price elasticity of water transaction is not linear, as is clearly displayed in Figure 12. But the authors fail to explain why this is so: is this because the model is working as it is supposed to, or may there be something wrong with the model? These are just a few examples on the problematic nature of this section 5.4. As stated in my first comment: I would prefer that the sensitivity analyses are used to validate the model rather than anything else.***

Response: Thank you for your observation. Information has been added to the section on robustness, and some managerial insights about water allocation and water-saving strategies under an uncertain environment have been included after the model validation. In reference to Erfani et al., (2014), the price in this paper was determined as the weighted sum of the willingness price to pay and the reservation sales price. Therefore, depending on the target of the studies, the consideration varies; for instance, this study was established by excluding the internal reason for any price changes. In addition, Figure 12 shows that the water consumption fluctuated with a change in the water market price and had a non-linear trend.

However, this was a different concept to the price elasticity of demand as it was found that the blue water transfer strategies were modified with a change in the water market price.

Reference

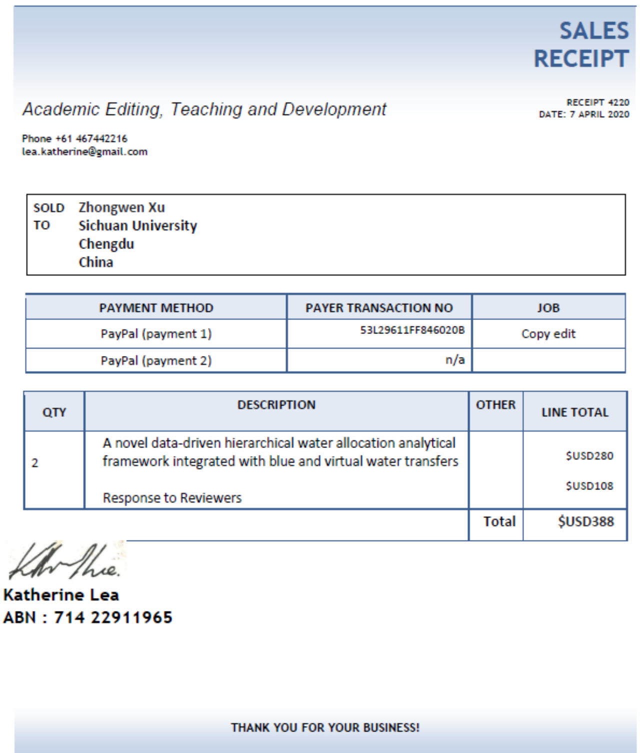
Erfani, T., Binions, O., and Harou, J. J.: Simulating water markets with transaction costs, Water Resources Research, 50, 4726, 2014.

Comment 2-3: ***This also means that the concluding section can be significantly shortened (as the current conclusions spend quite some words on findings from section 5.4).***

Response: Thank you for the suggestion, based on which we shortened and rewrote this section to elaborate the study conclusions.

Comment 3-1: ***The third comment: I find the manuscript not easy to read. In fact it was for me quite cumbersome to read. First, the English is often grammatically incorrect, unclear or oddly formulated. This needs to be addressed. I advise the authors to engage a native English-speaking academic to carefully check the language used.***

Response: Thank you for your suggestion. An academic editor has reviewed and polished the revised manuscript.



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Katherine Lea
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THANK YOU FOR YOUR BUSINESS!

*<u>Comment 3-2</u>: **Second, some figures were for me impossible to interpret. Consider Figure 5: I guess this is a flow diagram indicating the source and destination of the three crops considered; but I couldn't understand it. Figures 8 and 9 I failed to understand at all. The vertical axis of Figure 11 remains a mystery to me. In all figures, the axis should not only have numbers but also the units declared. E.g. what does the negative values in Figure 10d mean?***

<u>Response:</u> Thank you for your suggestions. In the revised manuscript, some figures have been deleted and others have been revised, as follows. The crop proportions for each form: production, imports, exports and consumption: are shown on the left of Figure 6, and the virtual water content is shown on the right of Figure 6 to reflect the amount of embedded water in each crop in each form (production, import, export and consumption). Figure 7 (Figure 9 in the original manuscript) compares the water stress in different scenarios. Figure 7 (B)-(D) details the water stress in each sector and each crop in each of the different scenarios. In Figure 8 (D) (Figure 10 in the original manuscript), the virtual water embedded in the export crops is shown below the X-axis, and the virtual water embedded in the import crops is shown above the X-axis.

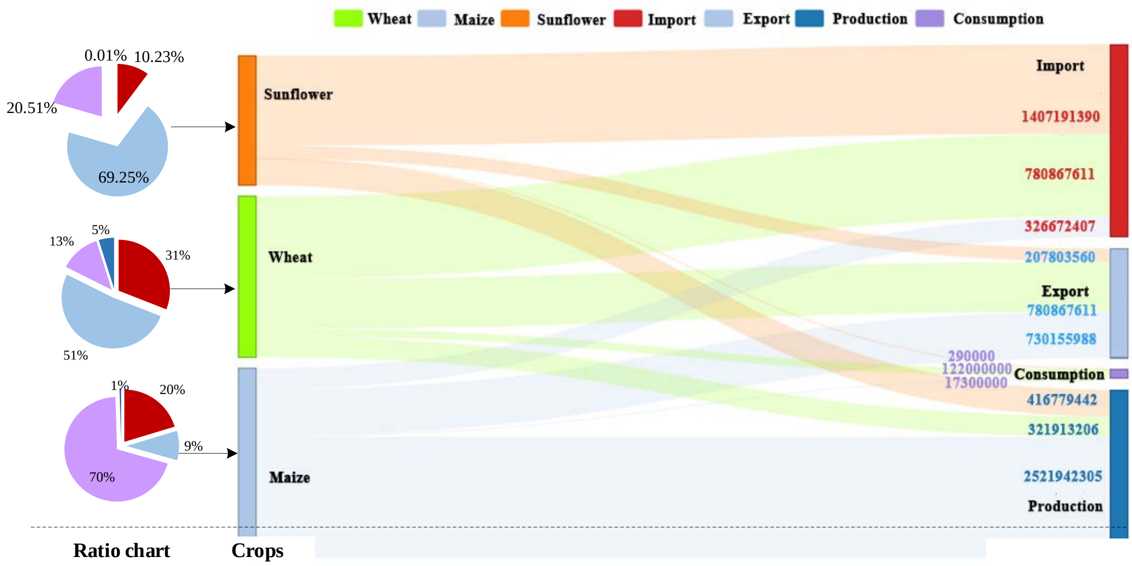

Figure 6 Inter-regional export and international import trade (m^3)

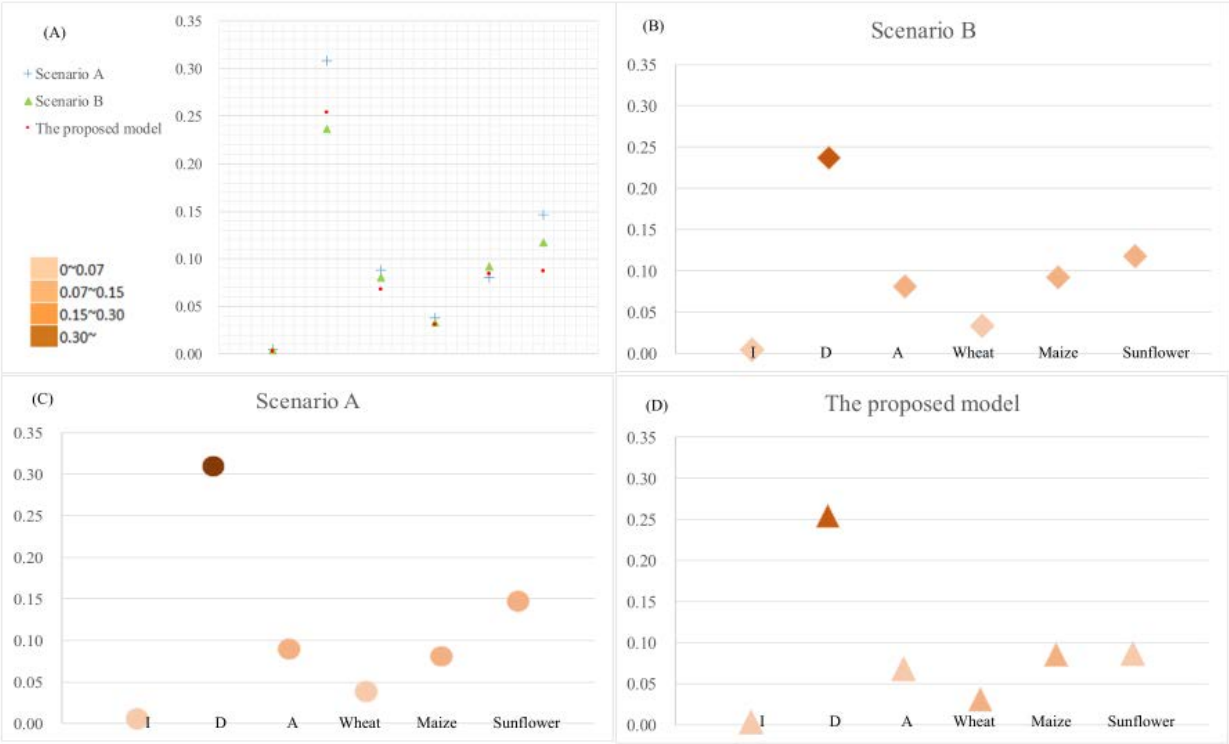

Figure 7. Water stress comparisons. (A) Total water stress; (B) Scenario B water stress; (C) Scenario A water stress; (D) Water stress in the proposed model

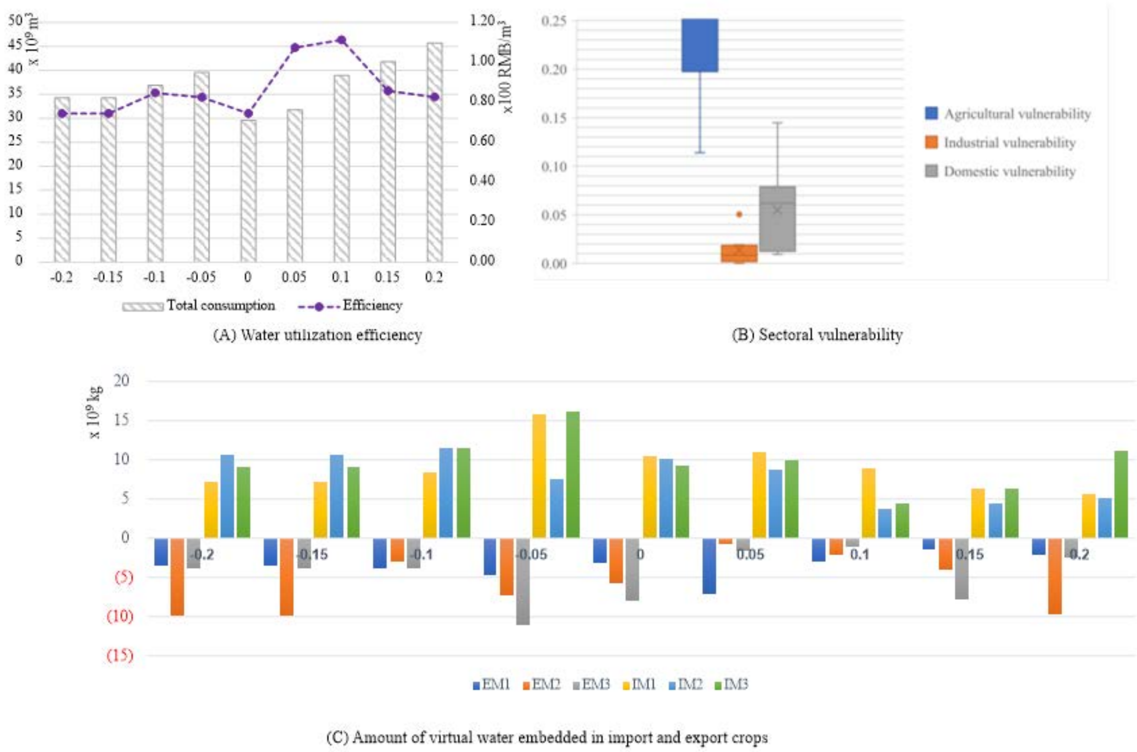

Figure 8. Sensitivity analysis for available water.

Comment 3-3: ***Third, the use of significant numbers, and exponents: in this type of models, parameters may have a maximum of three significant numbers. So declaring values such as 1880616733 doesn't***

make any sense. Why not report it as 1,880 x10^6? Or even better, as 1.88 x10^9. Tables 2 and 3 are difficult to interpret because of different exponents used; why not adhere to the convention and use consistently 10^3, 10^6 and 10^9 and not anything in between?

Response: Thank you for your suggestion. These expressions have been corrected and all others checked in the revised manuscript; for example:

Table 2. Optimal solutions to imported and exported crops

	Agricultural sector		
	Wheat	Maize	Sunflower
Imported crops IM_k (10^9 kg)	1.30	0.327	1.41
Exported crops EM_k (10^9 kg)	0.781	0.730	0.208
Virtual water $VW_k \times IM_k$ (10^9 m^3)	1.21	0.108	2.84
Virtual land IM_k / y_k (hm^2)	242,456	23,630	544,853

Table 3. Optimal water withdrawal results (10^9 m^3)

Sectors	Agricultural sector			Industrial sector	Domestic sector
Initial		X_1		X_2	X_3
water rights		3.05		0.015	1.38
Water	X_{11}	X_{12}	X_{13}		
irrigation	0.300	0.821	0.841		
Water				WTI	WTD
transfer		-1.09		0.014	1.07

Comment 3-4: ***Tables 4, 5, 7 and 8 could benefit if the first column would simply explain what the parameters (X1 etc.) actually mean, including their units. It is also not clear in these table what the final allocated amount of water is (is the volume of water finally and actually allocated to the agricultural sector X1-WTI-WTD; and for industry X2+WTI and for domestic X3+WTD?). Similar, what is the net import (imports minus exports of a certain crop) value of each of the three crops?***

Response: Thank you for your suggestion. We revised the tables, added several rows to elaborate the final used water from the different sectors and the net import value of each of the three crops, and added simple explanations for the parameters (X_1 etc.) in the first column of these tables.

Comment 4-1: ***Fourth, not all variables/parameters are properly introduced in the text (and only later the reader is aware of the existence of annexes), and several parameters/variables have wrong or incomplete units/dimensions. For example, what does the variable theta (eq. 1) physically mean? What***

does it mean if its value increases from 0.5 to say 0.8 and if it decreases to 0.3? Similar for vulnerability F (section 5.4.2). And what does "destroying degree (caused by deficient water withdrawal)" (line 498) mean; and how does it compare/contrast with "economic loss (caused by excess water withdrawal)" (line 499)?

Response: Thank you for your valuable comments. We have reorganized the paper structure and added a more detailed explanation for the parameters' physical meanings, which are highlighted in the revised manuscript.

In this paper, the θ refers to the degree of willingness to pay by the two trading participants; therefore, $\theta = 0.5$ represents an average of willingness to pay by the two trading participants. As θ increases, the price tends towards the buyer's price and as θ decreases, the price tends to the seller's price. The description for vulnerability was also modified from "destroying degree (caused by deficient water withdrawal)" to "demand loss degree", which refers to an inability to satisfy the water demands, and changed "economic loss (caused by excess water withdrawal)"to "supply loss degree", which refers to losses from excess water supplies.

Comment 4-2: ***The correct unit/dimension of ERP_k is not RMB/m^3 but I think it should be RMB/kg. The correct unit/dimension of W_k is not m^3 but m^3/hm^2. All fluxes should have a time dimension, such as Xi = m^3/yr; but also evaporation ET, rainfall R, irrigation w; and even crop consumption (kg per person per year!)). What is the difference between w_k (water irrigation for crop k) and x_{1k} (water irrigated to crop k in the agricultural sector)? What are beta □and P_k (eq. C5)? Why is effective rainfall crop dependent (R_k)? Equation C3 is the well-known Penman equation and need not be reproduced here. A reference would suffice.***

Response: Thank you for your detailed comments. We have corrected the units such as ERP_k, W_k, and added a time dimension to all fluxes. w_k (water irrigation for crop k) is used to predict the agricultural water demand using Equations (A1)-(A4), and x_{1k} (irrigation water for crop k in the agricultural sector) is the decision variable, which is solved using the proposed model. β is the coefficient for efficient rain, and is the proportion of total rain that infiltrates the soil profile and does not contribute to deep percolation, while P_k is the actual rain. The accumulated effective rain for each crop is different because of the different growth periods for each crop.

<u>Comment 5</u>: ***Fifth, what do you mean with the following often repeated sentence: "inter-regional exports and international imports" (lines 475, 478, 504, 521); does this mean that only export between regions within China are considered and not internationally, and that only imports from outside China are considered? If so, why? If not, change the formulation.***

<u>Response:</u> Thank you for your detailed comment. International imports are goods from other countries and reflect the global virtual water trade. Inter-regional exports were also considered as one of the means for providing agricultural food to southern China. Because of its comparative land advantage (Zhao et al., 2019), the Hetao irrigation district has a duty to satisfy the southern China demand for crops. Further, as the Hetao irrigation district is a small typical crop growing area, excess crops are generally exported to other provinces in China rather than being exported to other countries. Therefore, the incorporation of the blue and virtual water transfers varies depending on the target of the studies. In the revised version, we focused on a small irrigation district and characterized the virtual water transfers from an inter-regional export perspective due to the small crop yields. If global data were available in the future, such as all crop yields from all irrigation districts in China as well as information on the demand for crops in other countries, a new optimization model could be established that considers the global virtual water transfers from a global perspective, and explores bilateral trade under changing hydrological conditions.

Reference

Zhao D, Hubacek K, Feng K, et al. Explaining virtual water trade: A spatial-temporal analysis of the comparative advantage of land, labor and water in China. Water research, 2019, 153: 304-314.

<u>Comment 6</u>: ***The paper is very long. Some of the equations and Tables that now appear in the main text can go, together with the Appendices, to Supplementary Materials.***

<u>Response:</u> Thank you for your suggestion. The whole manuscript has been reorganized.

<u>Comment 7</u>: ***The introduction is very long, and can in my view be shortened.***

<u>Response:</u> Thank you for your suggestion. We have condensed the introduction.

Comment 8: ***The paper states that wheat and sunflower need more water compared to maize. I agree that sunflower generally requires more water than maize and wheat; but generally wheat needs a similar volume of water as maize, or slightly less.***

Response: Thank you for your observation. We read several articles, reports and statistical yearbooks and determined that the water requirements were directly affected by the rain and evaporation in an average meteorological year (Herrero and Csterad 1999; Wang et al., 2018). As wheat needs less water than maize, there is less virtual water embedded in wheat. However, due to the yields, more water is allocated to wheat in this irrigation district.

Reference

Herrero J , Casterad M A. Using satellite and other data to estimate the annual water demand of an irrigation district. Environmental Monitoring & Assessment, 1999, 55(2):305-317.

Wang Y, Tang P, Li S et al. The water demand and optimal irrigation schedule of maize in drought years at eastern area of Inner Mongolia. Agricultural research in arid areas, 2018, 036(001):108-114.

Comment 9: ***In Figure 4, I guess that one horizontal arrow pointing from the lower level (left) to the upper level (right) is missing; without it there is no dynamic between both levels.***

Response: Thank you for your comment. We have revised figure 4.

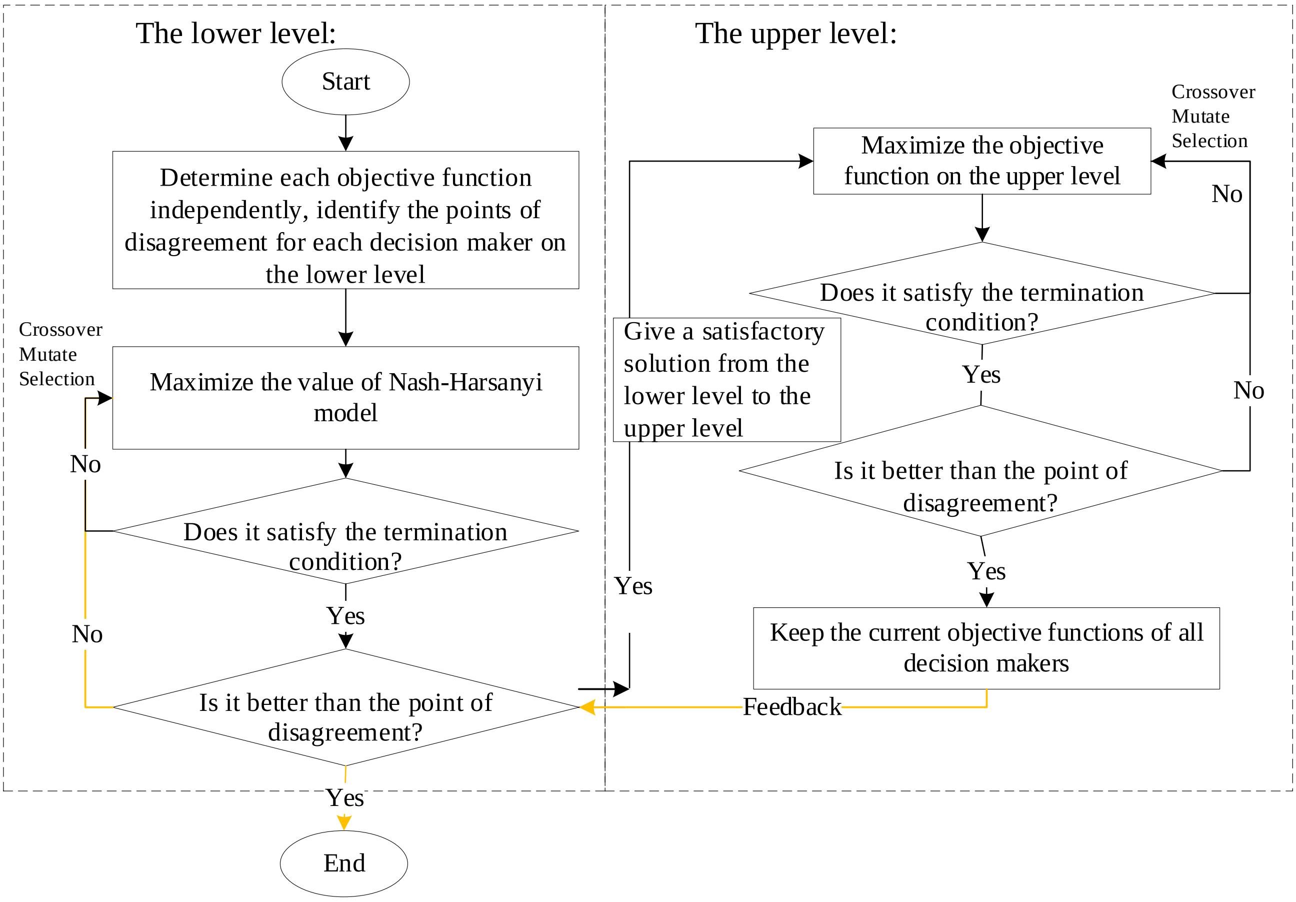

Figure 4. Steps for solving the proposed model

Comment 10: ***Why didn't the authors refer to their own recent publication (Xu, Yao, Zhou, Moudi and Zhang, 2019, in the Journal of Hydrology), since it also uses the Stackelberg approach, but in a different manner? In what ways does it differ?***

Response: Thank you for your suggestion. To solve a water allocation problem that included blue and virtual transfers, this study sought to achieve a Stackelberg-Nash-Harsanyi equilibrium. However, Xu et al. (2019) sought to optimize the water allocation in an irrigation district for water rights transactions based on a Stackelberg-Nash-Cournot equilibrium model. Therefore, the main differences between the two papers are that Xu et al. (2019) did not consider the import or export of crops, which must be included when optimizing a water allocation problem in a water-scarce area as virtual water transfers allows for the redistribution of water resources between countries/regions, which means that water-scarce countries are able to conserve their own water resources, but water-sufficient countries are able to obtain greater economic benefits by selling water-intensive goods. By incorporating the blue and virtual water transfers, the proposed model is able to offers further insights into crop planting and import/export quantities.

A list of all relevant changes

1. Introduction and Conclusion sections have been condensed.

2. An academic editor has been asked to review and polish the revised manuscript.

3. The revised manuscript has been reorganized in order to avoid repetition.

4. Figures have been revised to make them more readable.

5. Tables have been revised to unify the use of significant numbers, and exponents.

6. Sensitivity Analysis section have been rewritten to demonstrate the robustness and plausibility of the model.

A novel data-driven analytical framework on hierarchical water allocation integrated with blue and virtual water transfers

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Abstract. In this study a novel data-driven analytical framework is proposed for cooperative strategies that ensure the optimal allocation of blue and virtual water transfers under different hydrological and economic conditions. A Stackelberg-Nash-Harsanyi equilibrium model is also developed to deal with the hierarchical conflicts between the water affairs bureau and multiple water usage sectors and overcome problems associated with water scarcity and uneven distribution. It was found that cooperative blue and virtual water transfer strategies could save water and improve utilization efficiency without harming sector benefits or increasing the ecological stress. Data-driven analyses were employed to simulate the hydrological and economic parameters, such as available water, crop import price and water market price under various polices. By adjusting the hydrological and economic parameters, it was found that the optimal allocation and transfer strategies were more sensitive to hydrological factors than economic factors. It was also found that cooperative blue/virtual water transfers respond to market fluctuations. Overall, the proposed framework provides sustainable management for physical and virtual water supply systems under future hydrological and economic uncertainties.

1 Introduction

Extreme climatic and hydrological conditions have increased water scarcity pressure. Several Chinese provinces, mostly in northern China, now suffer from severe water scarcity for almost 7 months each year (Zhuo et al., 2016; Cai, 2008), with the relatively high crop provisioning in southern China further aggravating the problems in northern China (e.g., Xinjiang, Heilongjiang, Guangxi, Hunan, Hebei, and Inner Mongolia) (Wang et al., 2014). This pattern has led to a paradox whereby water-intensive crops are being exported from water-insufficient northern China to water-rich southern China, and to enable this crop production, water resources are being transferred from water-rich southern China to water-scarce northern China. However, the South-to-North Water Transfer Project should not be seen as a long-term approach to reduce northern Chinese water shortages(Chen et al., 2017). In the light of the above problems, this paper examined two important issues: blue water transfers to reallocate water between sectors and decrease water usage vulnerability; and virtual water transfers to decrease water stress and modify water use structures under an international trading environment.

District irrigation in many countries usually involves two different hierarchical structures: a water affairs bureau and water usage sectors. Previous studies have employed stochastic dynamic, multi-objective programming models to resolve the conflicting objectives in water allocation problems (Zeng et al., 2017; Xu et al., 2018, 2019). However, these models have neglected dynamic feedback mechanisms possibly existing in different hierarchical structures, resulting in solutions that do not maximize benefits at the system scale. Instead, game theory, which originated with the pioneering work of (Neuman and Morgenstern, 1944), was a successful alternative tool used for analyzing strategic interactions among different hierarchical decision makers (Madani, 2010; Ye et al., 2018). We recall some typical game-theoretical models from water resource management relating to our work, as shown in Table 1. In a water allocation context, consider the conflict of two hierarchical stakeholders through strategic interaction is vital, hence Stackelberg game is used to solve water allocation problem having stakeholders in different position.

However, as there are multiple followers, a major problem is equitably and sustainably allocating the limited water resources to the various water use sectors: agricultural, industrial, domestic and ecological: and deciding whether any excess water can be transferred to other sectors. Under government guidance, regional sector usage managers have the right to reallocate/sell their surplus water to other sector managers, with the transfer prices decided through negotiations between the transfer participants (Dai et al., 2017; Ahmadi et al., 2019; Wang, 2018). Multi-objective programming has been extensively used to resolve water allocation conflicts of competing water usage sectors (Sedghamiz et al., 2018a; Brown et al., 2015). Nash (1953) proposed a 2-player bargaining game for cooperative resource sharing, after which Harsanyi (1959, 1963); Sedghamiz et al. (2018b) generalized the Nash solution from a 2-player bargaining game to an n-players game, which was more suitable for the multiple stakeholder non-cooperative situation. In this paper, during the water transfer process, a n-person Nash-Harsanyi bargaining model is developed, which also considers the water withdrawal and reallocation process among sectors. To the best of our knowledge, there have been few studies that have applied game theory to resolve two different conflicts within an irrigation district that include a leader (water affairs bureau) in the dominant position and multiple followers (water usage sectors), or developed a suitable a bilevel model to solve the problem.

Blue water transfers allow for water transfers between sectors, and virtual water transfers (embedded in the crops) (Zhuo et al., 2016) allow for water transfers between countries. Therefore, it is possible that importing water-intensive goods (particularly crops) rather than producing them domestically could conserve water resources and drive economic development in the exporting countries (Shtull-Trauring and Bernstein, 2018; Jiang and Marggraf, 2015). Virtual water, which was first introduced by Allan (1993) refers to the water embedded in a product in a virtual form Liu et al. (2009). Virtual water transfers, therefore, allow for the redistribution of water resources between countries, which means that water-scarce countries can conserve their own water resources while water-sufficient countries can obtain greater economic benefits by selling their surplus water (Liu et al., 2015a, b) to water-scarce countries. In this study, blue and virtual water are jointly considered within an irrigation district to completely resolve water scarcity problems. As an increase in crop imports could lead to a decrease in local production, which could significantly reduce local agricultural incomes, and an increase in crop exports could lead to local water and ecological stress, determining the optimal blue and virtual water transfers is of great importance. While there have been several studies on the evolution of the virtual water trade (Lamastra et al., 2017; Duarte et al., 2016; Chen et al., 2017), its influence (Mohammadikanigolzar et al., 2014) and its determinants (Zhuo et al., 2016), no comprehensive systematic method has been developed to determine optimal virtual water transfers.

Therefore, to provide a new, unstructured alternative to sectoral water demand satisfaction, the first objective is to determine an optimal blue/virtual water transfer and water allocation strategy. In addition to accurately quantifying the blue water transfers between the sectors, this paper also determines the optimum imported crop quantity to conserve farmer enthusiasm in the importing country and the optimum exported crop quantity to ensure water sufficiency in the exporting country. The second innovation in this paper is the use of game theory within a bilevel framework to determine the blue/virtual water transfers and sectoral water allocations, which has rarely been applied to irrigation district analyses. Previous research in this area and the analysis techniques applied are given in Table 1. Because this problem cannot be modelled using conventional methods, a novel Stackelberg-Nash-Harsanyi equilibrium model model is developed that jointly considers the blue/virtual water transfers and the sectoral water allocations within a hierarchical decision making structure. In this way, equilibrium can be achieved through the strategic interactions between the water affairs bureau and the water usage sectors, with the competing water usage sectors not only making sustainability decisions that target their own benefits, but also allowing blue water transfers to improve overall water usage system efficiency.

Table 1. Literature review

Articles	Problem statement	Methodologies	Difference in technical strategy point
Dai et al. (2017)	The compensation mechanism for agricultural water transfer	Classification theory	
Jiang and Marggraf (2015)	Assessing the virtual water transfer in agricultural products between Germany and China	Statistic analysis	Ignoring quantitative analysis
Shtull-Trauring and Bernstein (2018)	Analyzing virtual water transfer on a country level	Statistic analysis	
Ahmadi et al. (2019)	Optimizing Beheshtabad Water Transfer Project	Both cooperative and non-cooperative approaches	
Fu et al. (2018)	Water allocation	Two-stage model considering Nash-Harsney equilibrium model	Ignoring virtual/blue water transfers and hierarchical strategic interaction
Xu et al. (2018)	Water allocation	Multi-objective programming model	
Sedghamiz et al. (2018b)	Water and crop area allocation	Leader-follower game	
Sedghamiz et al. (2018c)	Water management with the presence of executive managers in top-level and the agricultural sectors in low-level as leader and followers	Two-level optimization model	Ignoring virtual/blue water transfers and conflict at the lower level
Guo et al. (2012)	Solving the multi-reservoir operation problem in inter-basin water transfer supply project	A bilevel model	
Sedghamiz et al. (2018a); Wang et al. (2008)	The objectives consist of equity maximization, benefit maximization	Multi-objective programming model	Ignoring virtual/blue water transfers, strategic interaction and the objective of sustainable development

As is known, bilevel optimization techniques are intrinsically complex to solve referring to Hossein et al. (2018); Wei et al. (2017)'s research results. In regard to a solution, Eichfelder (2010) presented several new solutions for general multi-objective bilevel optimization problems using an optimistic approach. In other studies, different methods such as particle swarm optimization and artificial neural networks have been used to solve bilevel water exchange decision-making problems in eco-industrial parks (Ramos, 2016), and product engineering (Liu et al., 2017b). However, these techniques have seldom been applied to practical water allocation cases due to their complexity. In this paper, a bargaining weights method, a Nash-Harsanyi solution method, and a genetic algorithm (GA) are combined to solve the proposed model.

Overall, the main results and contributions in this study are summarized as follows:

Contribution 1: By incorporating blue and virtual water transfers, the developed model further relieves water scarcity stress, offers insights into crop planting and import/export quantities, and allows for the application of different strategies based on changing hydrological and market conditions. Overall, therefore, the model has positive effects on the water stress index, water usage efficiency and sectoral vulnerabilities, and saves water and land through its consideration of international transactions. Water usage efficiency between the three sectors was found to increase because of the crop planting plan modifications, blue water transfers.

Contribution 2: A novel game-theory model based on the Stackelberg game and Nash-Harsanyi equilibrium was developed to resolve the "leader-followers" and "competing followers" conflicts through strategic interaction. It was found that the total consumption using a two-stage optimization model was generally higher than when using our proposed model, and was therefore detrimental to water conservation.

2 Study area and water trading background

2.1 Study area

The Hetao irrigation district has been facing a contradiction between North-South crop export requirements and water scarcity. Chinese irrigation districts, which produce more than 75% of the grain consumed in China, have become increasingly important in ensuring both China's food security and its socioeconomic development (Wang et al., 2005). As studies on small and specific irrigation districts have proved to be more significant than national studies in resolving water scarcity problems, the Hetao irrigation district was chosen as the case study area to: (1) optimize the agricultural, domestic and industrial sector water withdrawals in a planning year; (2) optimize the virtual water quantities to be imported and exported under the international trading environment; and (3) optimize the blue water quantities to be transferred under a water market environment. This study therefore provides water reallocation perspectives, assists in alleviating local water scarcity, and promotes sustainable socio-economic-environmental development.

The Hetao irrigation district (Fig. 1) is an agricultural production and trade area in western Inner Mongolia, China (40°13'-42°28'N, 105°12'-109°53'E) that has five counties (Dengkou, Hanghou, Linhe, Wuyuan, and Qianqi) and an irrigated area of 5.74×10^3 km^2, the water for which comes mainly from the Yellow River. The main problems facing the Hetao irrigation district are continually increasing water requirements and severely constrained freshwater resources. The agricultural activities

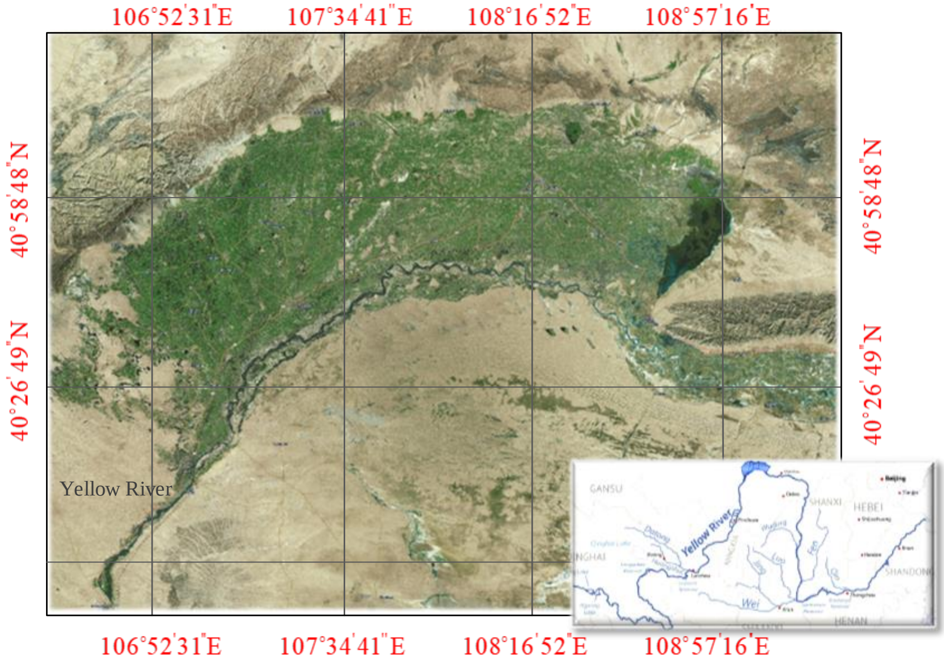

Figure 1. Hetao irrigation district longitude-latitude projection image ©Google Maps

in this region consume approximately 93% of the total regional water consumption (Feng et al., 2012), and while it has a continental monsoon climate, there is little and erratically distributed rain (130-215 mm with 70% falling in July, August, and September) and an annual evaporation of 2100-2300 mm (Liu et al., 2015a, b; Wang et al., 2005). As the Hetao irrigation district is close to several port cities, key crops are imported from Russia and other countries, which helps relieve some of the water consumption stress.

2.2 Water trading background

The water trading environment considers both blue and virtual water trading. Blue water is the surface or groundwater that evaporates during production processes, while virtual water is the volume of water needed to produce a certain commodity (Allan et al., 1993). After each sector (e.g., domestic, industrial or agricultural) has been granted initial water withdrawal rights, blue water can be directly transferred from one sector to another using conveyance infrastructure. Virtual water, which is calculated based on the crops exports or import volume sums, is indirectly transferred from one country to another embedded in the traded crops. In this study, three crops are considered: wheat, maize and sunflowers.

Water pricing is a key component of current water policy reforms in China as it is believed that reasonable pricing reform can guide water transfers; that is, reasonable transaction prices can control water use and market participation. Generally, water rights trading takes place between two participants, who together negotiate a suitable price. Therefore, in this study, the unit price of the water trade is based on the buyer's willingness to pay and the seller's reservation sales price (Erfani et al., 2014).

Therefore, the price is determined as the weighted sum of the willingness to pay the price and the reservation sales price, that is, the negotiated price, as follows;

$$\mathrm{PTI} = \theta p_1 + (1-\theta) p_2, \quad \mathrm{PTD} = \theta p_1 + (1-\theta) p_3, \tag{1}$$

where $\theta, 0 \leq \theta \leq 1$ is the degree of willingness to pay by the two trading participants, or the decision makers, p_i is the water price set by the leader for water withdrawal, PTI is the price of the water transferred to the industrial sector, and PTD is the price of the water transferred to the domestic sector.

3 Methods

3.1 Notations

The following notations are used to develop the model.

Indexes:

k : crop indicators, $k = 1$ for wheat, $k = 2$ for maize, $k = 3$ for sunflower

i : water usage indicator, $i = 1$ for agricultural sector, $i = 2$ for industrial sector, $i = 3$ for domestic sector, $i = 4$ for ecological sectors

Parameters:

p_i : water price set by the leader for sectoral water uses, RMB/m^3

ERW_i : economic return per unit of water consumption in sectors, $i = 1, 2, 3$, RMB/m^3

ERP_k : economic return from agricultural products exports, $i = 1$, where $\mathrm{ERP}_k = \mathrm{ERW}_k \times VW_k$, RMB/kg^3

c_k : economic costs because of agricultural products imports, RMB/kg

TC : transaction cost per unit of water resource from agricultural sector to industrial or domestic sectors, RMB/m^3

μ : the irrigation coefficient, which presents the utilization effectiveness of irrigation water

A : total available area for crop planting, hm^2

ϕ_{ind} : the gross industrial output value, RMB

R_k : effective rainfall, mm/day

β : coefficient for efficient rainfall

P_k : actual rainfall, mm/day

ϖ_k : crop k consumption per unit in the Hetao irrigation area, kg/(person $\cdot$ year)

Auxiliary variables (continuous variables)

AW : maximum volume of available water in Hetao irrigation district, m^3/yr

PTI : price of water transfers to industrial sector, RMB/m^3

PTD : price of water transfers to domestic sector, RMB/m^3

θ : the degree of willingness to pay of the two trading participators, if $\theta = 0.5$, it means the average of willingness to pay of the two trading participators

w_k : water irrigation for crop k, m^3/yr

W_k represents the blue and green water components in crop k, $m^3/(hm^2 \cdot yr)$

y_k represents the crop yield per unit of irrigation area, $kg/(hm^2 \cdot yr)$

l_k : total yield of crop k, kg/yr)

VW_k : virtual water content of crop k, m^3/kg

A_{1k} : area allocated to crop k, hm^2/yr

d_i : water demand of sectors, $i = 1, 2, 3, 4$, m^3/yr

d_{1k} : water demand of crops in agricultural sector, $k = 1, 2, 3$, m^3/yr

ϕ_{pop} : per capita disposable income, RMB

POP: population in the Hetao irrigation area

Decision variables (continuous variables)

X_i : initial water rights in sectors, $i = 1, 2, 3, 4$, determined by the upper-level decision maker, m^3/yr

EM_k: quantity of products exports, determined by the upper-level decision maker, kg/yr

IM_k: quantity of products imports from international trade, determined by the upper-level decision maker, kg/yr

WTI : water transfer from agricultural sector to industrial sector, determined by the lower-level decision makers, m^3/yr

WTD : water transfer from agricultural sector to domestic sector, determined by the lower-level decision makers, m^3/yr

x_{1k} : water irrigated to crop k in the agricultural sector, determined by the lower-level decision maker, $\sum_{k=1}^{3} x_{1k} = X_1 - WTI - WTD$, m^3/yr

3.2 Bilevel water allocation system framework

Fig. 2 gives a complete description of the four steps covered in this study. First, the water allocation system stakeholders are identified, after which the conceptual water allocation framework is constructed (Fig. 3). The proposed model is then applied to a real-world case study and decisions made on the water allocations, crop irrigation, international imports, inter-regional exports and blue water transfer quantities. Finally, to determine the most appropriate approach for future water sustainability, multiple scenarios are examined.

Driven by a traditional water resource management process (Harsanyi, 1963), this study constructs a bilevel framework that has one leader, the water affairs bureau, and multiple followers, the water usage sectors, as shown in Fig. 3. Two games are included in the framework: a Stackelberg game between the leader and followers in which the water affairs bureau (the leader) takes the leading role in allocating the water resources, moves first and has complete information about the followers' possible reactions, and the water usage sectors (the followers), who react after being given the leader's strategy; and a Nash-Harsanyi bargaining solution between multiple followers in which the n followers make corresponding decisions based on the leader's decisions (Fu et al., 2018).

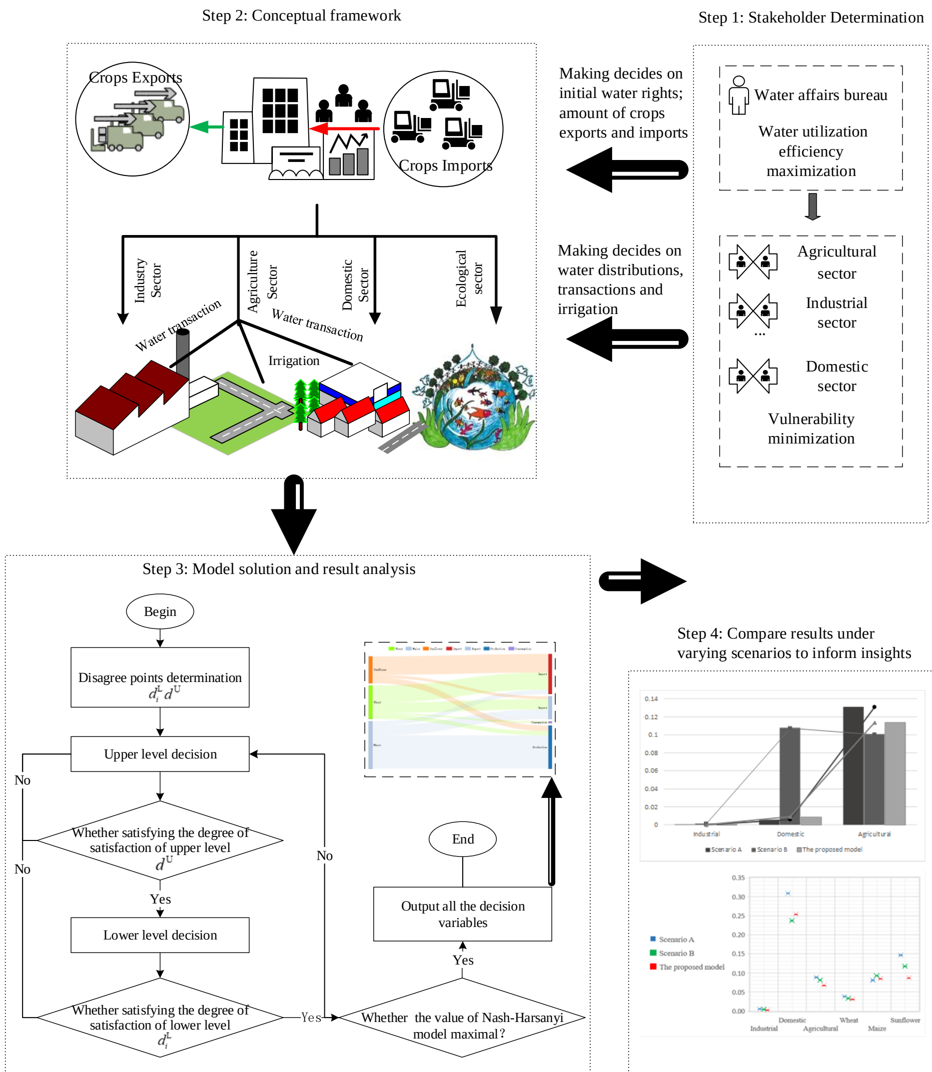

Figure 2. Four steps in the water allocation plan and future solutions

The following section outlines the mathematical model formulation. As water resource management allocation in Chinese irrigation districts usually involves a single leader and several followers, it is suitable for a Stackelberg-Nash-Harsanyi equilibrium model application. The model was developed based on the following assumptions:

Assumption 1: Regions with water deficits can import agricultural products from neighboring countries that have surplus water.

Assumption 2: The water market is available for all sectors, with the water trading prices being defined as the average willingness to pay of the participants.

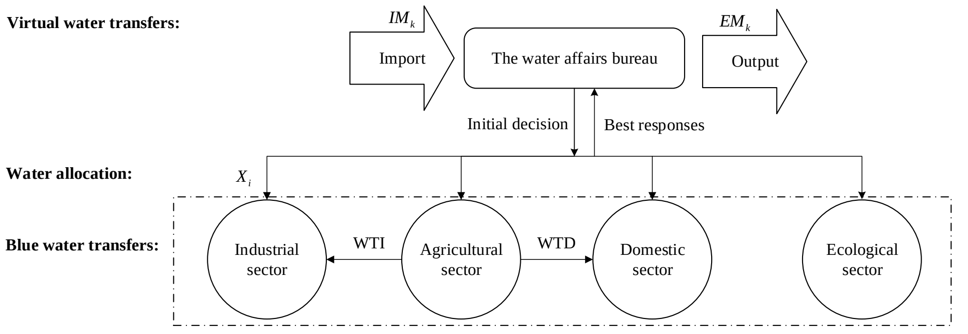

Figure 3. Bilevel water allocation system framework

Assumption 3: In semiarid and arid regions, as the water is scarce relative to the available land, it is assumed that land availability does not constrain crop decisions.

3.3 Objective functions

To ensure both economic benefits and water demand satisfaction in the different sectors, the water affairs bureau seeks to maximize the water resource system's water utilization efficiency, as shown in Eq. (2). To achieve economic development, the leader also needs to determine the crop quantities to be exported or imported, and the followers need to independently minimize their own vulnerabilities.

Under a water-scarce environment, the leader focuses more on water utilization efficiency. Therefore, fractional linear programming model (2) is employed to reflect the water utilization efficiency, in which the imported crops and the water transfer costs are considered when determining total economic benefits.

$$\max \mathrm{Eff} = \frac{\mathrm{Re}}{\mathrm{Cons}} \tag{2}$$

$$\begin{aligned} \mathrm{Re} &= \mathrm{Income} - \mathrm{Cost}, \\ &= \left(\sum_{k=1}^{3}(\mathrm{ERP}_k \times \mathrm{EM}_k) + \mathrm{WTI} \times \mathrm{PTI} + \mathrm{WTD} \times \mathrm{PTD} - \sum_{k=1}^{3}(p_1 \times x_{1k})\right) + (X_2 \times \mathrm{ERW}_2 + \\ &\quad \mathrm{WTI} \times \mathrm{ERW}_2 - \mathrm{PTI} \times \mathrm{WTI} - p_2 \times X_2) + X_3 \times \mathrm{ERW}_3 + \mathrm{WTD} \times \mathrm{ERW}_3 - \mathrm{PTI} \times \mathrm{WTD} \\ &\quad - p_3 \times X_3) - \sum_{\mathrm{k}=1}^{3}(c_k \mathrm{IM}_k) - \mathrm{TC} \times (\mathrm{WTI} + \mathrm{WTD}), \end{aligned} \tag{3}$$

$$\mathrm{Cons} = (\sum_{k=1}^{3} x_{1k} + \mathrm{WTI} + \mathrm{WTD}) + X_2 + X_3, \tag{4}$$

where Re is the total economic returns from the agricultural, industrial and domestic sectors, as shown in Model (3). $\left(\sum_{k=1}^{3}(\mathrm{ERP}_k \times \mathrm{EM}_k) + \mathrm{WTI} \times \mathrm{PTI} + \mathrm{WTD} \times \mathrm{PTD} - \sum_{k=1}^{3}(p_1 \times x_{1k})\right)$, $(X_2 \times \mathrm{ERW}_2 + \mathrm{WTI} \times \mathrm{ERW}_2 - \mathrm{PTI} \times \mathrm{WTI} - p_2 \times X_2)$ and $(X_3 \times \mathrm{ERW}_3 + \mathrm{WTD} \times \mathrm{ERW}_3 \; - \mathrm{PTI} \times \mathrm{WTD} - p_3 \times X_3)$ represents the economic returns in the different sectors. $\mathrm{ERW_k}$ is the economic return per unit of water consumed by the crops, $\mathrm{ERP_k}$ is the economic return from the agricultural product exports, where $\mathrm{ERP_k} = \mathrm{ERW_k} \times \mathrm{VW}_k$. In addition, $\sum_{\mathrm{k}=1}^{3}(\mathrm{ERP_k} \times \mathrm{EM}_k)$, $\sum_{\mathrm{k}=1}^{3}(c_k \times \mathrm{IM}_k)$ and $\mathrm{TC} \times (\mathrm{WTI} + \mathrm{WTD})$ are respectively the export returns, import costs and transaction costs, where c_k is the economic cost due to agricultural product imports, and TC is the transaction cost per unit of water resource unit transferred from the agricultural sector to the industrial or domestic sectors.

The lower-level decision makers are the water usage sectors' managers that independently minimize their own vulnerabilities. Vulnerability is related to the water demand and the water supply, and is the extent to which the water allocation system can or cannot cope with water scarcity or water abundance (floods). In this way, the allocation strategy is expected to have the ability to meet the "water demands" while avoiding the waste of water. And thus, the vulnerability, which is denoted as $F, F \geq 0$, is assessed from the demand loss degree (F^{DD}) and the supply loss degree (F^{EL}), as shown in Eqs. (5-15). An F equal to 0 means that the water resource system is stable in the planned period. When F has a value greater than 0, this reflects poor management and water allocation and therefore greater vulnerability.

Agricultural sector: $\min F_1$ (5)

$$F_1 = \omega^{\mathrm{DD}} F_1^{\mathrm{DD}} + \omega^{\mathrm{EL}} F_1^{\mathrm{EL}}, \tag{6}$$

$$F_1^{\mathrm{DD}} = \frac{1}{3} \frac{\sum_{k=1}^{3} \max\left((d_{1k} - x_{1k}), 0\right)}{\sum_{k=1}^{3} d_{1k}}, \tag{7}$$

$$F_1^{\mathrm{EL}} = \frac{1}{3} \frac{\sum_{k=1}^{3} \max\left((x_{1k} - d_{1k}), 0\right)}{\sum_{k=1}^{3} d_{1k}}. \tag{8}$$

$$F_2 = \omega^{\mathrm{DD}} F_2^{\mathrm{DD}} + \omega^{\mathrm{EL}} F_2^{\mathrm{EL}}, \tag{9}$$

$$F_2^{\mathrm{DD}} = \frac{\max\left(d_2 - (X_2 + \mathrm{WTI}), 0\right)}{d_2}, \tag{10}$$

$$F_2^{\mathrm{EL}} = \frac{\max\left(((X_2 + \mathrm{WTI}) - d_2), 0\right)}{d_2}. \tag{11}$$

Domestic sector: $\min F_3$ (12)

$$F_3 = \omega^{\mathrm{DD}} F_3^{\mathrm{DD}} + \omega^{\mathrm{EL}} F_3^{\mathrm{EL}}, \tag{13}$$

$$F_3^{\mathrm{DD}} = \frac{\max\left(d_3 - (X_3 + \mathrm{WTD}), 0\right)}{d_3}, \tag{14}$$

$$F_3^{\mathrm{EL}} = \frac{\max\left(((X_3 + \mathrm{WTD}) - d_3), 0\right)}{d_3}. \tag{15}$$

where ω^{DD} and ω^{EL} are the weights for the demand loss degree and supply loss degree in the different sectors, $\omega^{\mathrm{DD}}+\omega^{\mathrm{EL}}=1$.

3.4 Model constraints

Specific constraints reflect the real-world practice management rules and behaviors. The objective function (2) is subject to constraints (16)-(19), and constraint (21) characterizes the feasible region on the lower level.

3.4.1 Available water constraint

The water withdrawals for the three sectors cannot exceed the initial water in the irrigation district.

$$\sum_{\mathrm{i}=1}^{4} X_i \leq \mathrm{AW} \tag{16}$$

3.4.2 Price constraint

The benefits need to be considered when deciding on internal sectoral transactions. When the water demand in the industrial or domestic sectors is greater than the available water withdrawal, the water usage sector needs to buy water from the water market; conversely, a manager can sell extra water in the water market if such water trading leads to greater benefits than using the water to irrigate crops. Nevertheless, the transaction price cannot exceed the water withdrawal price.

$$p_1 < \mathrm{PTI} < p_2, \quad p_1 < \mathrm{PTD} < p_3 \tag{17}$$

3.4.3 Ecological water requirements

To guarantee sustainable development in the whole river basin, the minimum ecological water requirements must be satisfied across the whole river basin.

$$X_4 \geq e \tag{18}$$

3.4.4 Export and import balance equation

The annual export volume plus the grain consumption should be smaller than the total grain yield plus the annual import volume. Eq. (19) is the import-export balance equation, $\mathrm{POP}\varpi_k$ is the total consumption in the irrigation area, POP is the Hetao irrigation area population, ϖ_k is the annual crop k consumption per unit in the Hetao irrigation area, and l_k is the crop yield, which is determined based on the water allocated to the different crops on the lower level.

$$\mathrm{EM}_k + \mathrm{POP}\varpi_k \leq l_k + \mathrm{IM}_k \tag{19}$$

$$l_k = y_k \frac{x_{1k}}{W_k} \tag{20}$$

3.4.5 Planting area constraint

The land area allocated to the different crops in a given cropping season must not exceed the total cultivatable area (denoted by A) in that season, as shown in constraint (21), in which $A_k = \frac{X_k}{W_k}$.

$$\sum_{k=1}^{3} A_k \leq A \tag{21}$$

3.5 Solution procedure

There are two types of games in this solution procedure: the game between the leader and the followers, and the game between the followers. The leader makes virtual water or blue water transfer decisions, and the followers decide on their own rights to water withdrawal and irrigation. Therefore, a compromised solution is needed between the upper- and lower-level decision makers. Fig. 4 illustrates the four steps for the Stackelberg-Nash-Harsanyi bargaining process, and Table B1 in the Appendix shows a pseudo code for solving Stackelberg-Nash-Harsanyi bargaining process.

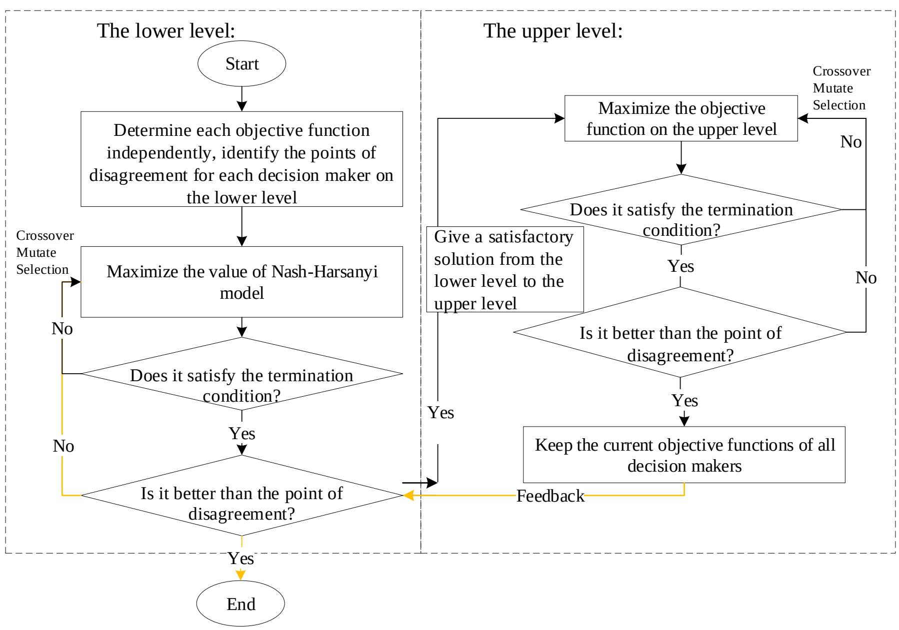

Figure 4. Steps for solving the proposed model

Step 1: Determine the disagreement points (dis^U, dis_i^L) and the bargaining weights (α_i) for the decision makers on each level, and randomly generate an initial solution.

Step 2: Maximize the value $\prod_{i=1,2,3} \left(F_i - dis_i^L\right)^{\alpha_i}$ by selecting the level objective functions that are better than the respective disagreement points, determine if the termination condition is satisfied, and if yes, go to *Step 3*; otherwise, continue to add generations.

Step 3: Maximize the upper-level objective function on the premise that it is better than the disagreement point, determine if the termination condition is satisfied, and if yes, output all decision variables, and go to *Step 4*; otherwise, continue to add generations.

Step 4: Determine whether the lower level objective function is still better than the disagreement points, and if yes, end the loop; otherwise go back to *Step 2*.

Combined with the practical problem described in this paper, the vector for the disagreement points is defined as the maximum vulnerability for the followers and the minimum water utilization efficiency from the leader. Specifically, the disagreement point is calculated as follows:

The the leader's individual best and least solutions obtained by the GA method are $(X_i, \mathrm{EM_k}, \mathrm{IM_k}, \mathrm{WTI}, \mathrm{WTD}, x_{1k}; \mathrm{Eff}^{\max})$ and $(X_i', \mathrm{EM_k'}, \mathrm{IM_k'}, \mathrm{WTI}'$,
WTD', x_{1k}'; $\mathrm{Eff}^{\min}$), where

$$\mathrm{Eff}^{\max} = \max \mathrm{Eff}(\mathrm{X_i}, \mathrm{EM_k}, \mathrm{IM_k}, \mathrm{WTI}, \mathrm{WTD}, x_{1k}) \tag{22}$$

$$\mathrm{Eff}^{\min} = \min \mathrm{Eff}(\mathrm{X_i'}, \mathrm{EM_k'}, \mathrm{IM_k'}, \mathrm{WTI}', \mathrm{WTD}', x_{1k}') \tag{23}$$

Similarly, the best and least solutions of the followers are $(X_i'', \mathrm{EM_k''}, \mathrm{IM_k''}, \mathrm{WTI}'', \mathrm{WTD}'', x_{1k};\ F_i^{\min})$ and $(X_i''', \mathrm{EM_k'''}, \mathrm{IM_k'''},$ $\mathrm{WTI}''', \mathrm{WTD}''', x_{1k}'''$; $\mathrm{F_i^{max}}$), respectively, where

$$F_i^{\min} = \max F_i(X_i'', \mathrm{EM_k''}, \mathrm{IM_k''}, \mathrm{WTI}'', \mathrm{WTD}'', x_{1k}) \tag{24}$$

$$F_i^{\max} = \min F_i(X_i''', \mathrm{EM_k'''}, \mathrm{IM_k'''}, \mathrm{WTI}''', \mathrm{WTD}''', x_{1k}''') \tag{25}$$

The lower tolerance limits ($\mathrm{Eff}^{\min}, \mathrm{F_i^{max}}$) for achieving the goal levels of the leader and follower can be defined as disagreement points (denoted as dis^U, dis_i^L) for the decision makers on each level. Then, the additional constraints for each level are added so that each objective function value is better than the disagreement point respectively (Eff $>$ dis^{U} with $F_i < dis_i^L$), namely, the disagreement point presents the worst result that the decision maker was unwilling to accept.

The bargaining weights, which reflect each follower's degree of importance are defined based on water demand elasticity. For the demand principle, the formula for calculating the water demand elasticity level is $\delta_i = 1 - \frac{d_i}{\Sigma d_i^L}$, and then each follower's bargaining weight under demand principle is calculated as $\alpha_i = \frac{\delta_i}{\Sigma \delta_i}$. In this study, the disagreement points dis^U and $dis_{i,i=1,2,3}^L$ are set to 33 and 0.3, respectively. The bargaining weights $\alpha_{i,i=1,2,3}$ are respectively defined as $0.3,\ 0.4,\ 0.3$. The solving algorithm is coded in MATLAB R2017a.

4 Data and Results

4.1 Economic parameters

The main data sources are based on the Bayna Noaoer Yearbook, the Hetao irrigation district statistical data and some published papers. The outputs for each sector per unit of water (ERW_i) are $\mathrm{ERW}_1 = 2.34$ RMB/m^3, $\mathrm{ERW}_2 = 109.96$ RMB/m^3, and

$\text{ERW}_3 = 131.17$ RMB/m^3 (Liu, 2016). From "http://price.h2o-china.com/" and the Development and Reform Commission and Department of Water Resources' agricultural water price adjustment programs, the price of water is determined to be $p_1 = 0.103$, $p_2 = 3.85$, and $p_3 = 4.40$ in 2020. The prices of crops (wheat, maize and sunflower) imported from other countries are determined according to the average import prices of agricultural crops over the years, that is, $c_1 = 2.58$, $c_2 = 1.50$, and $c_3 = 4.10$ RMB/kg. The water transfer price, θ, is set equal at 0.5; and the water transfer prices are PTI $= 1.98$ and PTD $= 2.25$. The transfer cost TC $= 1.00$ RMB/m^3 based on "http://cwex.org.cn/lising/". The consumptions of each crop ($\sum_{k=1}^{3} \text{POP}_k \varpi_k$) in 2020 are predicted to be 1.22×10^8, 1.73×10^7 and 2.90×10^5 kg respectively.

4.2 Hydrological parameters and water demand analysis

Using the data extracted from the BayanNur Water Resources Bulletin from 2012-2015 and based on the Eqs. (A4)-(A7), η is 0.574, and K^D is 6.9×10^6 ($R^2 = 0.978$), ϑ is -0.858, and K^I is 8.9×10^{16} ($R^2 = 0.835$). μ is the irrigation coefficient, which presents the utilization effectiveness of irrigation water, and its value is 0.487 in 2020 (Wang et al., 2017; Wang, 2017). Three representative crops (wheat, maize and sunflower) are chosen because these crops constitute a large share of the total production in the area. The water demand and virtual water content of these crops are calculated based on Eqs. (A4)-(A7). Water demand in each sector is predicted respectively, $d_1 = 3.50 \times 10^9$, $d_2 = 4.53 \times 10^7$, and $d_3 = 1.94 \times 10^9$. Moreover, the annual water demand in the ecological sector for sediment scouring will to be 1.64 $\times10^8$ m^3 in 2020 (Wang et al., 2017; Wang, 2017). More initial data are present in the Appendix D.

4.3 Optimal virtual water trade

This study considers both the inter-regional and international transactions (virtual water transfers) and then incorporates and quantifies water transfers in the form of virtual water when optimizing the import and export process. Table 2 shows the optimal amounts of inter-regional export and international import trade, and verifies the corresponding saved irrigation water (the virtual water embedded in imported crops) and area (the virtual land that would have been planted if crops had not been imported).

Table 2. Optimal solutions to imported and exported crops

	Agricultural sector		
	Wheat	Maize	Sunflower
Imported crops IM_k (10^9 kg/yr)	1.30	0.327	1.41
Exported crops EM_k (10^9 kg/yr)	0.781	0.730	0.208
Virtual water $\text{VW}_k \times \text{IM}_k$ (10^9 m^3)	1.21	0.108	2.84
Virtual land IM_k/y_k (hm^2)	242,456	23,630	544,853

From $\text{VW}_k \times \text{IM}_k$, the total virtual water in the imported crops was calculated as 4.16×10^9 m^3, which would save 75.64% of the total available water in this area. The quantification of the land savings calculated by IM_k/y_k, is also shown in Table 2. A comparison with the national 2020 land-use planning is shown in Fig. 5. The results illustrate the differences between the optimal solutions from the proposed model and the expected national land use planning. Specifically, if international imports were allowed, the total land needed for crops could be reduced by 16.7%, and to satisfy the wheat, maize and other food crop requirements, the land needed for growing sunflowers would decrease significantly. Therefore, the results clearly reflect the water use and land-use planning differences and how optimizing previous planting structures can improve water utilization efficiency.

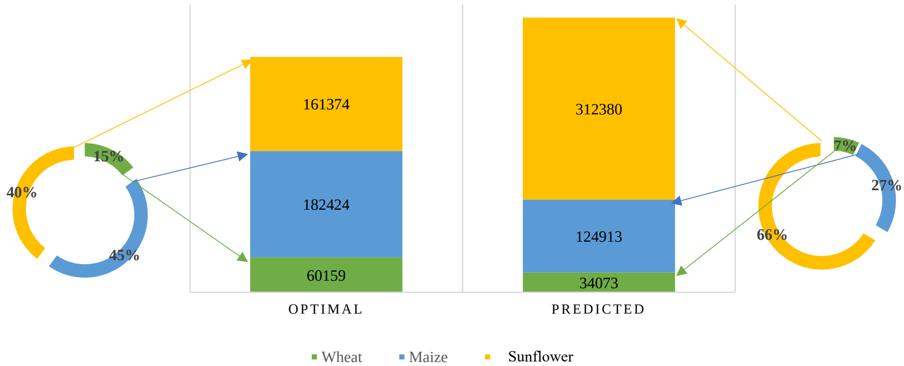

Figure 5. Predicted crop areas in planning report compared with optimal values (hm^2)

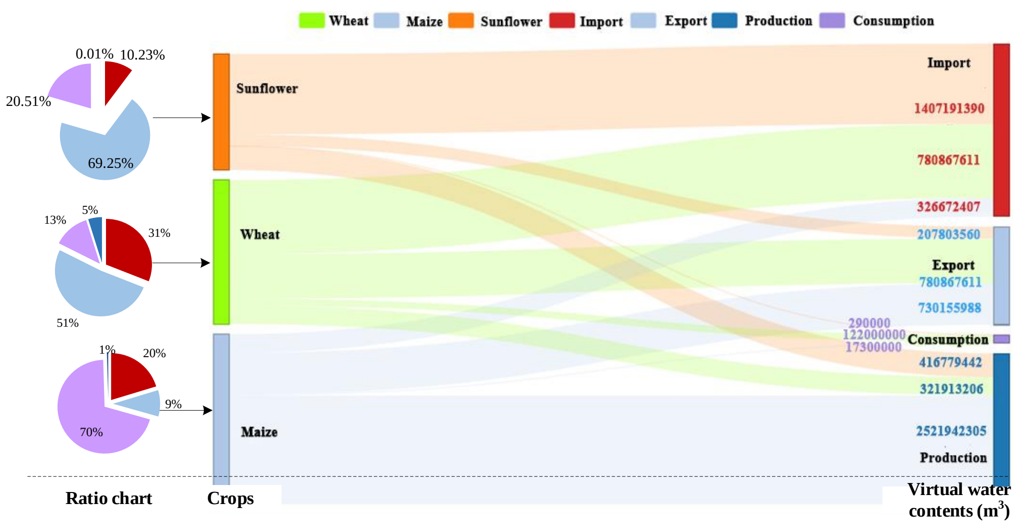

Figure 6. The amount of inter-regional export and international import trade (m^3)

The crop proportions for each form (production, import, export and consumption) are shown on the left of Fig. 6, and the virtual water content is shown on the right. As can be seen, as the crop consumption in this district is far less than the crops produced, particularly sunflowers, the surplus crops from the Hetao irrigation area can be sold to southern China. The light blue rectangle shows the total water embedded in the exported sunflower, wheat and maize, and the red rectangle shows the total water embedded in the imported sunflower, wheat and maize.

4.4 Irrigation, industrial and domestic water consumptions and blue water transfers

Certain differences should be allowed when supplying limited water to sectors. As the model also maximizes the overall water utilization efficiency from the perspective of the system, an equilibrium between the multiple sectors is not always exactly equal when seeking to satisfy the water demand of each sector.

Table 3. Optimal water withdrawal results (10^9 m^3)

Sectors	Agricultural sector			Industrial sector	Domestic sector
Initial		X_1		X_2	X_3
water rights		3.05		0.015	1.38
Water	X_{11}	X_{12}	X_{13}		
irrigation	0.300	0.821	0.841		
Water				WTI	WTD
transfer		-1.09		0.014	1.07

Table 3 gives an example of a compromised solution to water allocations, transfers, and crop irrigation. More initial water is allocated to the agricultural sector, followed by the domestic sector and the industrial sector, which conforms to actual practices. Through the water market (blue and virtual water transfers), blue water is transferred from the agricultural sector to the industrial or domestic sector: 13.6×10^6 m^3 of water is transferred from the agricultural sector to industrial sector and 1.07×10^9 m^3 of water is transferred from the agricultural sector to domestic sector: which improves the objective functions on both the upper and lower levels.

The agricultural sector has the largest gap between water supply and demand, followed by the industrial sector; however, the water demand in the domestic sector is satisfied. We analyze the reason is that more water-intensive crops are imported. In addition, with more sunflower being imported, saved water is allocated to sectors whose water utilization efficiency is higher. Overall, the above analysis verifies that the proposed model not only assists in optimizing water resource allocations but also assists in land use planning based on water utilization efficiency maximization and vulnerability minimization. Therefore, it is suggested that when there is insufficient water, blue water can be transferred to the industrial and domestic sectors from the agricultural sectors to enhance water utilization efficiency and achieve greater economic benefits, and virtual water imported to save irrigation water consumption.

5 Discussion

This section explores the reasons why virtual and blue water transfers should be conducted together and the effects available water, market prices and import prices have on the water allocations in the different sectors under future uncertainty.

5.1 Main reasons for water stress

Before developing long-term future water plans, it is vital to determine which sector is the largest contributor to regional water stress. A blue water scarcity index can be calculated from a production perspective, as shown in Eq. (26). BWS_1, BWS_2 and BWS_3 respectively represent blue water scarcity in the agricultural, industrial and domestic sectors). $X_2+\mathrm{WTI}, X_3+\mathrm{WTD}$, and $\sum_{\mathrm{k}=1}^{3} x_{1k}$ are chosen to represent the blue water consumption. Liu et al. (2017a) concludes that water stress in an area is low if the ratio of the water consumption to availability is less than 0.07, is medium if the ratio is 0.15-0.3 and is high if the ratio is greater than 0.3, as shown in Table **??**.

$$\mathrm{BWS} = \frac{\sum_{\mathrm{k}=1}^{3} x_{1k} + X_2 + \mathrm{WTI} + X_3 + \mathrm{WTD} + X_4}{\mathrm{AW} + \sum_{\mathrm{k}=1}^{3} \mathrm{VW}_k \times \mathrm{IM}_k} \tag{26}$$

$$\mathrm{BWS}_1 = \frac{\sum_{\mathrm{k}=1}^{3} x_{1k}}{\mathrm{AW} + \sum_{\mathrm{k}=1}^{3} \mathrm{VW}_k \times \mathrm{IM}_k} \tag{27}$$

$$\mathrm{BWS}_2 = \frac{X_2 + \mathrm{WTI}}{\mathrm{AW} + \sum_{\mathrm{k}=1}^{3} \mathrm{VW}_k \times \mathrm{IM}_k} \tag{28}$$

$$\mathrm{BWS}_3 = \frac{X_3 + \mathrm{WTD}}{\mathrm{AW} + \sum_{\mathrm{k}=1}^{3} \mathrm{VW}_k \times \mathrm{IM}_k} \tag{29}$$

The BWS in the Hetao irrigation district is 0.47 after the optimization, indicating high water stress, with the BWS values for the agricultural, industrial, and domestic sectors being 0.068, 0.003, and 0.254, which indicates that the domestic sector is the largest contributor to the regional water stress. Analysis indicates that the main reason for these results is that an increase in the population, and therefore more water being needed for daily needs.

5.2 The importance of coalitional utilization of blue and virtual water transfers

Virtual water and blue water transfers have a significantly positive effect on water allocation systems. Previous research has not optimized water allocation problems by simultaneously incorporating virtual and blue water transfers. The following discusses the importance of including virtual water transfers (in terms of international imports and inter-regional exports) and blue water transfers from four perspectives: objective functions, total water consumption, import/export structures, and water stress.

Scenario A: Comparison to model (C1) without considering virtual water transfers.

Scenario B: Comparison to model (C2) without considering blue water transfers.

Three compromise solutions are shown in Table 4. As can be seen, the proposed model has the highest water utilization efficiency, followed by Scenario A, with the lowest being Scenario B, which proves that blue water transfers improve water utilization efficiency. Specifically, when blue water transfers are included, both agricultural and industrial sector vulnerabilities are reduced; however, the virtual water transfers have a positive effect on the industrial and domestic sector vulnerability but not on agricultural sector vulnerability. Therefore, the analysis indicates that the inclusion of water transfers enables greater water consumption in sectors that use less water to produce greater economic benefits, which is in line with the conclusions in Liu and Yang (2012)'s research, that virtual water transfers potentially reduce the degree of crop self-sufficiency.

Table 4. Comparison results under different scenarios

	Scenario A	Scenario B	Proposed model	Two-stage model
Decision variables				
Initial water right X_1 (10^9 m^3/yr)	3.21	2.17	3.05	3.08
Initial water right X_2 (10^6 m^3/yr)	24.2	40.4	15.2	34.3
Initial water right X_3 (10^9 m^3/yr)	1.32	2.12	1.38	0.793
Water transfer WTI (10^6 m^3/yr)	18.5	-	13.6	4.49
Water transfer WTD (10^9 m^3/yr)	1.11	-	1.07	0.778
Crops export EM_1 (10^9 kg/yr)	-	0.260	0.781	0.115
Crops export EM_2 (10^9 kg/yr)	-	1.11	0.73	0.583
Crops export EM_3 (10^9 kg/yr)	-	0.633	0.208	0.456
Crops import IM_1 (10^9 kg/yr)	-	1.14	1.30	0.482
Crops import IM_2 (10^9 kg/yr)	-	0.799	0.327	0.751
Crops import IM_3 (10^9 kg/yr)	-	1.04	1.41	0.697
Agricultural use (10^9 m^3/yr)	2.08	2.17	1.97	3.08
Industrial use (10^6 m^3/yr)	42.7	40.4	28.8	34.3
Domestic use (10^9 m^3/yr)	2.43	2.12	2.45	0.793
Net IM_1 (10^9 kg/yr)	-	0.880	0.519	0.367
Net IM_2 (10^9 kg/yr)	-	-0.311	-0.403	0.168
Net IM_3 (10^9 kg/yr)	-	0.407	1.20	0.241
Objective values				
Lower level				
Agricultural sector	0.131	0.100	0.114	0.417
Industrial sector	0.000200	0.00112	0.000100	0.00800
Domestic sector	0.00560	0.107	0.00920	0.000100
Upper level (RMB/m^3)	71.9	66.7	74.4	111

Compared with Scenario A, the total water consumption calculated using the proposed model decreased from 4.55×10^9 to 4.45×10^9 m^3. Specifically, the industrial and agricultural sectors receive fewer initial water rights, the domestic sector receives more initial water rights, and the blue water transfer value declines from 1.13×10^9 to 1.09×10^9 m^3. Therefore, the proposed model is able to appropriately reduce the water transfer quantities and thereby minimize the ecological and economic losses. In comparison, in Scenario B, the total water consumption calculated using the proposed model increases from 4.33×10^9 to 4.45×10^9 m^3. Specifically, the international import and inter-regional export structures change, with greater quantities of wheat

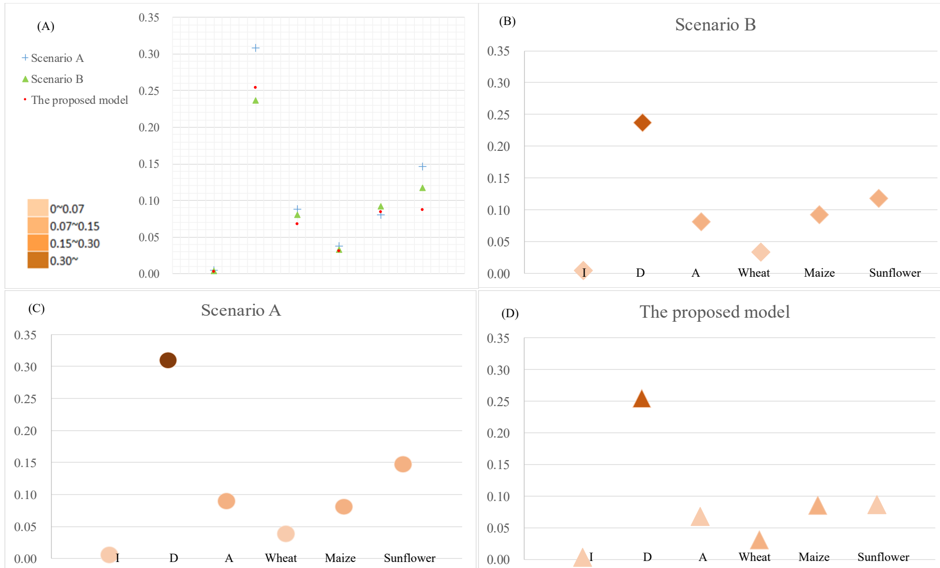

Figure 7. Water stress comparisons. (A) Total water stress; (B) Scenario B water stress; (C) Scenario A water stress; (D) Water stress in the proposed model

and sunflowers and lesser quantities of maize being imported, and greater quantities of wheat and lesser quantities of sunflower and maize being exported to neighboring regions. In general, when the blue water transfers are considered, there is a positive effect on water utilization efficiency and a reduction in sector vulnerability.

The water stress under different scenarios is then calculated, as shown in Fig. 7. Fig. 7 (A) shows the degree to which the water stress is relieved after the optimization, with the water stress under Scenario A being greater than the water stress under the other two scenarios, which indicate that the inclusion of virtual water transfers can alleviate water stress. The water stress values in the different sectors are then compared, as illustrated in Fig. 7 (B-D), which indicate that the consideration of blue water transfers decreases industrial and agricultural sector consumption stresses and the inclusion of virtual water transfers decreases water stress in all sectors. Therefore, as shown, both virtual water and blue water transfers should be considered in future water management planning.

5.3 Importance of the hierarchical strategic interaction

One of the most widely used water resource allocation models has been the two-stage optimization model. In comparison, the Stackelberg game between the leader and followers in this study is fully considered as the strategic interactions are considered before the final determination of the compromise solution. Therefore, to further illustrate the superiority of the proposed model, it is compared with a two-stage model that has the same objective functions for each stage decision maker, the results for which are shown in Table 4.

As can be seen, the total consumption determined using the two-stage optimization model is mostly higher than in the proposed model. In the first stage of the two-stage optimization model, the initial water rights and virtual water transfers for the sector users are determined by maximizing the water utilization efficiency, and following the decisions in the first stage, in the second stage, the followers decide on their water withdrawal and blue water transfer quantities based on the asymmetric Nash-Harsanyi game model. The comparison of the amount of inter-regional exports and international imports indicate that the trade scale is squeezed, which is not suitable for a region that sends grain from northern China to southern China. In addition, the increase in sector vulnerability could result in unsustainable irrigation district development.

Because the proposed model includes the strategic interactions, this cannot be ignored by the decision makers. Generally, the main reason for the strong discriminatory power in the developed model is that as it is able to deal with the conflicts between the leader and followers, it can produce a more realistic water allocation strategy.

5.4 Sensitivity Analysis

The extended Fourier amplitude sensitivity test (EFAST) is used to analyze the allocation results when the crop import prices, available water, or water demand change, with the solutions being assessed using two robustness measures: minimum water utilization efficiency and maximum sectoral vulnerability.

5.4.1 Future uncertainty down to changing available water

Available water is affected by precipitation, which in turn reflects a wet or a dry hydrological environment. In this section, to assist decision makers understand the overall water allocation and utilization strategies, the available water is assumed to increase/decrease by a 20% interval.

To quantify the available water sensitivity and determine the reactions to varying the model parameters, several scenarios are conducted and tested, the optimal responses and objective function values from which are shown in Figs. 8. As can be seen, when the amount of available water decreases, the water utilization efficiencies fluctuate slightly, thus verifying the model robustness. When the amount of available water increases, the utilization efficiency fluctuates with an increase in total water consumption, and in both cases, the vulnerability values are within an acceptable range. Therefore, the results indicate that after considering the blue and virtual water transfers, water allocation and import/export strategies could be used to adapt to varying available water quantities.

5.4.2 Future uncertainty down to sectoral water demand

Policies that encourage water-conserving irrigation techniques, improve resident water conservation awareness, focus on the construction of water reuse schemes, better manage water use mechanisms, and expand water conservation investments could reduce water demand in each sector by 10 to 20%. Therefore, in this section, seven scenarios are analyzed, including one with no change (the results from the proposed model). To monitor the performance and assess the actions relevant to each scenario, the results presented in Table 5 are analyzed. If there is a decrease in agricultural water demand, water utilization efficiency

(A) Water utilization efficiency

(B) Sectoral vulnerability

(C) Amount of virtual water embedded in import and export crops

Figure 8. Sensitivity analysis of available water. (in Fig. 8 (C) virtual water embedded in export crops are shown below the X-axis, while virtual water embedded in import crops are shown above the X-axis)

would improve, and total consumption would decrease. As can be seen in Table 5, the proposed model demonstrates robustness when the agricultural and industrial sectors parameters change, but the robustness is weak when the domestic water demand changes.

Table 5. Objective values and total consumption for the 10% and 20% reductions in water demand

		Agricultural (-10%)	Industrial (-10%)	Domestic (-10%)
Vulnerability F_1	0.00006	0.00030	0.00474	0.00162
Vulnerability F_2	0.00920	0.04632	0.15199	0.02506
Vulnerability F_3	0.11382	0.26058	0.14329	0.13170
Efficiency (RMB/m^3)	74.40	95.42	77.48	57.68
Total consumption (10^9 m^3/yr)	4.61	3.90	4.07	3.02
		Agricultural (-20%)	Industrial (-20%)	Domestic (-20%)
Vulnerability F_1	0.00006	0.00002	0.00030	0.00460
Vulnerability F_2	0.00920	0.06672	0.03920	0.03719
Vulnerability F_3	0.11382	0.11124	0.11939	0.11469
Efficiency (RMB/m^3)	74.40	59.99	72.24	38.93
Total consumption (10^9 m^3/yr)	4.61	3.09	4.23	2.93

The parametric sensitivity analysis information could be useful when deciding on future water conservation and sustainable development investments. For example, modifying irrigation frequency and adopting a single irrigation strategy could be operative policies to reduce irrigation quantities while achieving acceptable crop yields. In line with Zou and Liu (2014)'s research and the results from the proposed model, it can be seen that there is an "inverse U-shaped relationship" between industrial water demand, industrial added value and the industrial water recycling rate. Water conservation in the industrial sector is observed to have a positive effect on economic development only when the industrial added value/water recycling rate has surpassed a certain value, which indicates that any reductions in industrial water demand should be accompanied by industrial structural adjustments and industrial water-recycling rate improvements. The suggested strategies for the domestic sector include incentive policies to encourage households to reduce domestic water consumption and policies to guarantee sustainable water utilization and reduce total consumption.

5.4.3 Future uncertainty down to import crop prices

Imported crop prices are increased/decreased by 10% and input into the model to analyze the effect on water allocation, withdrawal and transfer processes. Table 6 shows the optimal solution for water use and net imports, from which it can be seen that with a price change in the importing crops, there are minimal changes in the water utilization efficiency and vulnerability, which indicates that the proposed model is comparatively robustness to import price changes; however, it is more sensitive to the virtual water price variations for the sunflowers, followed by the maize and the wheat.

Table 6. Optimal results under varying import crops' prices

	No change	Wheat import price		Maize import price		Sunflower import price	
	0	-10%	10%	-10%	10%	-10%	10%
Agricultural use (10^9 m^3/yr)	1.96	1.73	2.23	1.62	2.3	1.94	2.32
Industrial use (10^6 m^3/yr)	28.7	29.6	26.7	28.9	25.2	30.8	27.5
Domestic use (10^9 m^3/yr)	2.46	2.41	2.20	2.27	1.85	2.35	2.12
Net IM_1 (10^9 kg/yr)	0.519	0.588	0.697	0.651	0.590	0.810	0.758
Net IM_2 (10^9 kg/yr)	-0.403	-0.383	-0.394	0.0240	-0.029	-0.717	-0.361
Net IM_3 (10^9 kg/yr)	1.20	1.07	1.28	0.816	-0.068	0.919	0.586
Vulnerability F_1	0.0001	0.1130	0.1168	0.0905	0.1138	0.1263	0.1788
Vulnerability F_2	0.0092	0.0006	0.1321	0.0008	0.0001	0.0012	0.0004
Vulnerability F_3	0.1138	0.0001	0.0003	0.1203	0.0092	0.0321	0.0455
Water utilization efficiency (10^9 m^3/yr)	74.4	72.5	73.1	66.6	74.4	59.9	59.9

5.4.4 Future uncertainty down to market prices

We define the parameter θ as 0.5, which presents the average of willingness to pay of the two trading participators, and then we obtain an optimal solution to water use and transfers. We probe deeper by changing the values of θ and analyze the effects of blue water transfer price on solutions. An increase in θ indicates a higher willingness to buy at the buyer's price, and decrease in θ indicates a higher willingness to trade at the seller's price. Table 7 indicates that the optimized decision variables are less sensitive to a change in the market prices, and further verifies that the proposed model is robust to market prices.

Table 7. Optimal solutions under varying water market prices

	$\theta = 0.15$	$\theta = 0.30$	$\theta = 0.50$	$\theta = 0.65$	$\theta = 0.80$
Agricultural use (10^9 m^3/yr)	1.74	2.29	1.96	1.78	1.75
Industrial use (10^6 m^3/yr)	26.7	38.2	28.7	55.3	61.5
Domestic use (10^9 m^3/yr)	2.02	2.26	2.46	1.32	1.35
Net IM_1 (10^9 kg/yr)	0.813	0.675	0.517	0.304	0.225
Net IM_2 (10^9 kg/yr)	-0.347	-0.220	-0.403	-0.569	0.824
Net IM_3 (10^9 kg/yr)	0.053	0.224	1.2	0.371	0.862
Vulnerability F_1	0.1168	0.0905	0.1138	0.1263	0.1788
Vulnerability F_2	0.1321	0.0008	0.0001	0.0012	0.00044
Vulnerability F_3	0.0003	0.1203	0.0092	0.0321	0.0455
Water utilization efficiency(10^9 m^3/yr)	73.2	66.7	74.4	59.9	59.9

6 Conclusions

In this study, a novel model based on Stackelberg-Nash-Harsanyi game theory was proposed to analyze a water reallocation problem that included water transfers and crop transactions. To describe the realistic water allocation, withdrawal and transaction processes, a bilevel framework with one leader and multiple followers was employed in which the water affairs bureau was in the leader position and multiple water usage sectors were in the follower positions. Vulnerability, which included the demand loss degree (caused by deficient water withdrawal) and supply loss degree (caused by excess water withdrawal), was the lower level objective, with the water utilization efficiency across the whole system being maximized on the upper level. Blue and virtual water transfers, which are mechanisms that can essentially relieve uneven water distribution, were included in this study based on the idea that blue water can be reallocated to industrial and domestic sectors to develop water-saving agriculture and that virtual water in crops can be quantified to optimize inter-regional exports and international imports.

To verify the feasibility and practicality of the developed model, a real-world application was conducted in the Hetao irrigation district in northern China. It was found that the water demand in the domestic sector was first satisfied, followed by the agricultural and industrial sectors, with the blue water transfers providing an opportunity for each sector to achieve efficient water utilization, and the virtual water transfers providing a new opportunity for water conservation and land use. To be specific, some initial water rights were transferred from the agricultural sector to the industrial and domestic sectors, and key crops, and particularly water-intensive crops (e.g., wheat and sunflower), were imported from other countries rather than being grown domestically. To demonstrate the superiority of the developed model, two comparative scenarios were considered: one without virtual water transfers and the other limiting blue water transfers. The analysis in Scenario A highlighted the importance of virtual water transfers in alleviating water usage stress, and the analysis in Scenario B verified that blue water transfers reduced the vulnerability in each sector and demonstrated how inter-regional exports, international imports and blue water transfers could result in higher water utilization efficiencies in all three sectors.

Several scenarios also assessed changes in the environment and water-conservation strategies, including one without no changes (the results from the proposed model). These sensitivity analyses not only proved the robustness of the proposed model, but also determined the potential adjustments that could be made in water usage sector allocation strategies to alleviate regional water stress, eliminate the negative impacts caused by the crop trade, ensure regional food security, and develop sustainable irrigation.

This work focused on water allocation in a bilevel framework and conducted a case study in an irrigation district. Given that we explored only one leader and multiple followers, there are possibilities for multiple leaders and multiple followers in future research. Further, a macroscopic analysis between China and foreign countries could also be interesting.

Appendix A: Water demands computation

A1 Virtual water content

This study provides detailed quantitative information on crop imports and exports. The principle for assessing the virtual water content (denoted by $\mathrm{VW}_k, k = 1,2,3$, $\mathrm{m}^3\ \mathrm{kg}^{-1}$) of a food was proposed by the Food and Agriculture Organization (FAO) as the amount of water per unit of food that is consumed during the production process Zeng et al. (2012), as shown in Eq. (A1).

$$\mathrm{VW}_k = \frac{W_k}{y_k} = \frac{10(\mu \times w_k + R_k)}{y_k}, \tag{A1}$$

where effective rainfall over the crop-growing period is denoted as R_k (mm) and irrigated water is denoted as w_k (mm). μ is the irrigated coefficient, which presents the utilization effectiveness of irrigation water. W_k ($\mathrm{m}^3/\mathrm{hm}^2$), calculated by $10(\mu \times w_k + R_k)$, presents the water components in crop k, which consist of effective irrigated water and rainfall. The value of 10 is used to convert mm to $\mathrm{m}^3/\mathrm{hm}^2$. y_k ($\mathrm{kg}\ /\mathrm{hm}^2$) represents the crop yield per irrigation area unit. As rainfall is an additional supplement for crop water demands, in addition to evapotranspiration (ET), water irrigation quantities are somewhat influenced by the effective rainfall in different seasons in addition to evapotranspiration (ET), as shown below.

$$ET_k = kET_0, \tag{A2}$$

$$w_k = \frac{(ET_k - R_k)}{\mu}, R_k = \beta P_k. \tag{A3}$$

The accumulated ET over the crop-growing period, shown in Eq. (A2). ET_0 is the reference evapotranspiration of a standard crop, which can be calculated by the FAO Penman-Monteith function (Allan, 1998; Su et al., 2014). β is the coefficient for efficient rain, which presents the proportion of total rainfall that infiltrates into the soil profile and does not contribute to deep percolation, while P_k is the actual rainfall (Patwardhan et al., 1990).

A2 Agricultural water demand

Agricultural water demand is the sum of the crops' demand for water, as calculated in Eqs. (A4) and (A5), for which several representative crops were chosen.

$$d_{1k} = w_k A_k, \tag{A4}$$

$$d_1 = \sum_{k=1}^{3} d_{1k}, \tag{A5}$$

where d_{1k} is the water demand of crops in the agricultural sector, and A_k is the area allocated to crop k.

A3 Domestic water demand

Domestic water demand includes all water consumed in a given period for all residential purposes, e.g., in-house water use for kitchens, laundry and baths, and outside uses in gardens. The domestic water demand can be determined based on population and income growth projections (Cai, 2002; Young and Haveman, 1985). From many studies on water demand, it was concluded that per capita disposable income was a key influence on water demand; therefore, a power function between water demand and water price was determined.

$$d_3 = K^D \phi_{pop}^{\eta}, \tag{A6}$$

where K^D is a constant, ϕ_{pop} is the per capita disposable income, and η is the demand income elasticity coefficient.

A4 Industrial water demand

The projection of industrial water demand depends upon income (gross industrial output value). Through the data obtained from the BayanNur Water Resources Bulletin, future industrial water demand is projected as follows:

$$d_2 = K^I \phi_{ind}^{\vartheta} \tag{A7}$$

where K^I is the constant, ϕ_{ind} is the gross industrial output value, and ϑ is the demand income elasticity coefficient.

A5 Ecological water demand

The water demands for environmental protection and ecological systems are assumed to be constant at the present stage of the study, and these values are determined by the local government based on the consideration of current water use and climate change.

Appendix B: Pseudo code

A pseudo code for solving Stackelberg-Nash-Harsanyi bargaining process is shown in Table B1.

Table B1. Pseudo code for the proposed model.

```
Input: The correlation parameter, disagreement points (dis^U, dis_i^L), bargaining weights (α_i);
Output: A satisfactory solution and objective functions for the proposed model;
Step 1: Initialize population, construct fitness functions for the upper objective (Eff) and an auxiliary
fitness function for the Nash-Harsanyi model in the lower level ( ∏_{i=1,2,3} (F_i − dis_i^L)^{α_i} );
Step 2: Randomly generate an initial solution, maximize the fitness function in the lower level
        IF (any lower level objective functions are lower than their disagreement points)
        {generation++;
        population [generation+1]=Select (Mutate(Crossover (parents)))};
        Else: go to step (3);
Step 3: Input the satisfactory solution from step (2), maximize the fitness function in the upper level
        IF (upper level objective function is lower than its disagreement point)
        {generation++;
         population [generation+1]=select (mutate(crossover (parents)))};
        Else: keep the current decision variables and corresponding solutions and go to step (4);
Step 4: Feedback
        IF(the updated lower level objective functions are still better than the disagreement points)
        {IF (generation > Maximum generation )
          {Output all the decision variables
          End loop}}
        Else: go to step (2)
```

Appendix C: Comparative models

$$
\max\ \text{Eff} = \frac{\text{Re}}{\text{Cons}}
$$

$$
s.t.\begin{cases}
\sum_{i=1}^{4} X_i \le \text{AW} \\
p_1 < \text{PTI} < p_2 \\
p_1 < \text{PTD} < p_3 \\
X_4 \ge e \\
\text{POP}\varpi_k \le l_k \\
\min\ F_1 \\
s.t.\begin{cases}
\sum_{k=1}^{s} A_k \le A, A_k = \frac{X_{1k}}{W_k} \\
x_{ik} > 0
\end{cases} \\
\min F_2 \\
s.t. X_2 > 0 \\
\min F_3 \\
s.t. X_3 > 0
\end{cases}
\tag{C1}
$$

$$
\max \ \mathrm{Eff} = \frac{\mathrm{Re}}{\mathrm{Cons}}
$$

$$
s.t. \begin{cases}
\sum\limits_{\mathrm{i}=1}^{4} X_i \leq \mathrm{AW} \\
X_4 \geq e \\
\mathrm{EM}_k + \mathrm{POP}\varpi_k \leq l_k + \mathrm{IM}_k \\
\min F_1 = \omega^{\mathrm{DD}} F_1^{\mathrm{DD}} + \omega^{\mathrm{EL}} F_1^{\mathrm{EL}} \\
s.t. \begin{cases}
F_1^{\mathrm{DD}} = \frac{1}{3} \frac{\sum\limits_{k=1}^{3} \max((d_{1k} - x_{1k}), 0)}{\sum\limits_{k=1}^{3} d_{1k}} \\
F_1^{\mathrm{EL}} = \frac{1}{3} \frac{\sum\limits_{k=1}^{3} \max((x_{1k} - d_{1k}), 0)}{\sum\limits_{k=1}^{3} d_{1k}} \\
\sum\limits_{k=1}^{s} A_k \leq A, A_k = \frac{X_{1k}}{W_k} \\
x_{ik} > 0
\end{cases} \\
\min F_2 = \omega^{\mathrm{DD}} F_2^{\mathrm{DD}} + \omega^{\mathrm{EL}} F_2^{\mathrm{EL}} \\
s.t. \begin{cases}
F_2^{\mathrm{DD}} = \frac{\max(d_2 - X_2, 0)}{d_2} \\
F_2^{\mathrm{EL}} = \frac{\max(X_2 - d_2, 0)}{d_2} \\
X_2 > 0
\end{cases} \\
\min F_3 = \omega^{\mathrm{DD}} F_3^{\mathrm{DD}} + \omega^{\mathrm{EL}} F_3^{\mathrm{EL}} \\
s.t. \begin{cases}
F_3^{\mathrm{DD}} = \frac{\max(d_3 - X_3, 0)}{d_3} \\
F_3^{\mathrm{EL}} = \frac{\max(X_3 - d_3, 0)}{d_3} \\
X_3 > 0
\end{cases}
\end{cases} \tag{C2}
$$

Appendix D: Data collection

535 The main input data and sources are shown in Tables D1.

Table D1. Overview of input variables, data sources and determination

Input variable	Source	Determination
Water demand in each sector	BayanNur Water Resources Bulletin	Predicted by Eqs. (A4)-(A7)
Output in each sector per unit of water	Published paper Liu (2016)	
Consumption of each crop per capita	Bayna Noaoer yearbook	Average value from years 2012-2015
Irrigation coefficient	Published paper Wang (2017)	–
The price of water	Published paper Wang (2017)	–
Prices of imported agricultural crops	Wind database, FAO database.	Calculated by average annual import price of each crop based on data for the period 2012-2015
Consumptions of each crop yearly	Bayna Noaoer yearbook, Bayannur water resources bulletin	Calculated by $\sum_{k=1}^{3} \mathrm{POP}_k \varpi_k$
Prices of blue water transfers	Published paper: Erfani et al. (2014)	Calculated by Eq. (1)
Transfer cost	Website China water exchange (http://cwex.org.cn/lising/)	Average value
The hydrologic data	Inner Mongolia Statistical Yearbook, Bayna Noaoer yearbook, China Meteorological Data Sharing Service System, Published paper Wang (2017)	–
Agricultural data	Hetao Irrigation District Agricultural Statistical Data, Published paper Wang (2017)	–

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Acknowledgements. The main data sources for the solution are based on the Bayna Noaoer yearbook, Hetao irrigation district statistical data, BayanNur Water Resources Bulletin and some published papers. Table D1 provides a general overview of the input variables, data sources and determination in this study. Some are cited from the website and published papers directly, and others are predicted by relative equations based on historical data.

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