Optimization model for enhancing water-use efficiency from the perspective of water-energy-food nexus

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Abstract. The water-energy-food (WEF) nexus, which is essential for supporting regional sustainable development, has become a popular research topic. This study proposed an optimization programming framework for improving water-use efficiency from a WEF nexus perspective. Through the incorporation of water rights transfer mechanism, water resources can be flexibly allocated between food and energy sectors. The proposed model could help decision makers to identify the optimal production scales of food and energy production, the potential of water conservation of food production, as well as the investment portfolio of water-saving engineering. The capability of proposed model was illustrated through a case study in Yellow River Basin, north China. Based on the proposed optimization model, the optimal allocation scheme of water resources between food and energy sectors were obtained. A total of 2.34×10^7 m^3 of water would be transferred from food production to energy sector. Compared with state quo, production scales of energy sector, as well as profits of both food and energy sectors would increase rapidly. Optimization results reveal that designed energy production scales proposed by local government and enterprises are attainable as long as there are sufficient water resources available for energy sector.

1. Introduction
Water, energy, and food are essential resources for the development of human beings. They are closely interrelated in many ways [1-3]. For instance, water is required across food and energy production. Agriculture, which is the major source of food production, is the largest water consumer all over the world [4]. Energy production, such as fossil-energy and coal chemicals, highly relies on water resources. The water-energy-food (WEF) nexus has become a popular research topic since Bonne Conference 2011 [5]. Understanding and analyzing the complex interaction of WEF nexus are essential for improving resources efficiency and supporting the sustainable development of WEF systems [6,7].

Optimization techniques have been promoted to tackle WEF nexus problems [8,9]. For instance, Zhang et al developed an integrated modelling framework to satisfy WEF demands with socioeconomic and environmental controls [10]. Udias et al developed a Decision Support System that integrated simulation modules and optimization algorithms to assess the WEF environment nexus [11]. Li et al proposed an integrated model, aimed to optimize
water, energy, and food resources in an agricultural system [12]. In general, researchers are trying to analyze the complex interrelationships among WEF nexus through specific case studies.

Bayannur, located in western Inner Mongolia, China, is faced with growing demands in food and energy with limited water resources [13]. An important commodity grain and oil production base named Hetao irrigation district is located in this city [14]. Meanwhile, Bayannur have developed energy industries, such as coal mining, coal chemical, and energy generation [15]. Water resources become the most important factor restricting regional sustainable development. It is worth noting that Bayannur is the pilot city for water rights transfer policy. Energy sector can obtain transferable water rights through investing water-saving engineering in agricultural irrigation (figure 1). Water rights transfer policy could be an effective way of balancing water resources between food and energy sectors, as well as improving resources utilization efficiencies [16]. However, existing researches still have limitations in tackling such a WEF nexus problem, especially for optimizing the allocation of water resources between food and energy sectors with water rights transfer policy.

![Figure 1](image)

**Figure 1.** Graphical representation of water-energy-food nexus with water rights transfer policy.

Therefore, this study aimed at proposing an optimization programming framework for improving water-use efficiency from a WEF nexus perspective. Through the incorporation of water rights transfer mechanism, water resources could be flexibly allocated between food and energy sectors. The capability of proposed model was illustrated through a case study in Bayannur, north China. Optimal schemes of water resources allocation and production structures of food and energy sectors, as well as the investment portfolio of water-saving engineering could be obtained.

2. Methodology

2.1. Study area and data collection

Bayannur (105°12'-109°53' E, 40°13'-42°28' N) is chosen as the study area (figure 2). Wheat, maize, sunflowers, vegetables, melons, and seed melons are the main crops. Thermal power generation and heat supply are the essential power sources for regional development. Bayannur also has developed coal related industries, including coal washing and coal chemicals. Five kinds of coal chemicals that have high water consumption and high potential
of expanding production scales are selected, namely coke, coal tar, methanol, synthetic ammonia, and urea. The minimum demands and designed production scales of energy products were estimated by historical data and field research.

Four kinds of water-saving engineering are considered in this research, including drip irrigation with groundwater or surface water, shrinking the farmland, and construction of canal lining. Among them, shrinking the farmland means transforming the large farmland into smaller pieces and water-use efficiency can be improved accordingly. The detailed information of water-saving engineering is collected from government documents and field research. Average cost of water-saving engineering over its operational life is viewed as investment fee, since each project has a different life span.

![Study area](image)

**Figure 2. Study area.**

### 2.2. Optimization model

A WEF optimization model with water rights transfer mechanism, called WEFR, was developed in this research. The objective of WEFR was to maximize the net benefits of food and energy production with limited water resources. Decision variables were considered from three aspects, including the cultivation area of every crop, the production amount of every energy product, and the construction scale of every water-saving engineering. Decision variables implemented in WEFR were listed in the text below:

- $AGQ_{ijlm}$: planting area of crop $i$ with irrigation method $j$ and water source $l$ in sub-irrigation district $m$ (hm$^2$);
- $CAL$: canal lining length for water rights transfer (km);
- $TPQ_l$: quantity of thermal power generated with water source $l$ (kwh);
- $HSQ_l$: quantity of heat supply using water source $l$ (kwh);
- $CCQ_l$: quantity of coarse coal used for coal washing with water source $l$ (ton);
- $CIQ_{kl}$: quantity of coal chemical produced with water source $l$ (ton).

The suffixes were identified as:

- $i$: type of crops, $i = 1$ to 6 respectively is wheat, maize, sunflowers, vegetables, melons, and
seed melons; 

$j$ type of irrigation methods, \( j = 1 \) to \( 4 \) respectively is border irrigation, existed drip irrigation, invested drip irrigation, and shrinking the farmland; 

$k$ type of coal chemicals, \( k = 1 \) to \( 5 \) for coke, coal tar, methanol, synthetic ammonia, and urea; 

$l$ type of water sources, \( l = 1 \) and \( 2 \) respectively is surface water and groundwater; 

$m$ type of sub-irrigation districts, \( m = 1 \) to \( 7 \) respectively is Linhe, Wuyuan, Dengkou, Wuqian, Wuzhong, Wuhou, and Hanghou.

2.2.1. Objective function.

\[
\text{Max } F = A + B + C + D + E - G
\]

where \( F \) are the net benefits of WEF system, \( A, B, C, D, \) and \( E \) respectively denote the net benefits of food production, thermal power generation, heat supply, coal washing, and coal chemical production; and \( G \) are the costs of water-saving engineering for water rights transfer.

- Profit from food production:

\[
A = \sum_{i=1}^{j} \sum_{j=1}^{4} \sum_{l=1}^{2} \sum_{m=1}^{5} (AP_iAY_{ij} - AC_{ij})AGQ_{ijlm}
\]

where \( AP_i \) is the cost for crop \( i \) cultivation (yuan / hm\(^2\)); \( AY_{ij} \) is the yield of crop \( i \) under irrigation method \( j \) (kg / hm\(^2\)); and \( AC_{ijl} \) is the cost of cultivation for crop \( i \) under irrigation method \( j \) and water source \( l \) (yuan / hm\(^2\)).

- Profit from thermal power generation:

\[
B = \sum_{l=1}^{5} (TPP - TPC)TPQ_l
\]

where \( TPP \) is the on-grid price for thermal power generation (yuan / kwh); and \( TPC \) is the cost of thermal power generation (yuan / kwh).

- Profit from heat supply:

\[
C = \sum_{l=1}^{5} (HSP - HSC)HSQ_l
\]

where \( HSP \) is the price of heat supply (yuan / kwh) and \( HSC \) is the cost of heat supply (yuan / kwh).

- Profit from coal washing:

\[
D = \sum_{l=1}^{5} (\mu LCP - CCC)CCQ_l
\]

where \( \mu \) is the coal washing rate (%); \( LCP \) is the price for clean coal (yuan / ton); and \( CCC \) is the cost of coal washing (yuan / ton), including the price for coarse coal and the cost of coal washing.

- Profit from coal chemical production:

\[
E = \sum_{k=1}^{K} \sum_{l=1}^{5} (CIP_k - CIC_k)CIQ_{kl}
\]

where \( CIP_k \) is the price for coal chemical \( k \) (yuan / ton); and \( CIC_k \) is the cost of production coal chemical \( k \) (yuan / ton).
Costs of water rights transfer:

\[ G = \text{CAP}_{ Carson} + \sum_{i=1}^{I} \sum_{l=1}^{L} \sum_{m=1}^{M} \text{AGQ}_{jim} \text{ADC}_l + \sum_{i=1}^{I} \sum_{l=1}^{L} \sum_{m=1}^{M} \text{AGQ}_{alm} \text{AFC} \]  

(7)

where \( \text{CAP} \) is the cost of canal lining (yuan / km); \( \text{ADC}_l \) is the investment and maintenance cost of new drip irrigation facilities with water source \( l \) (yuan / hm\(^2\)); and \( \text{AFC} \) is the cost of shrinking the farmland (yuan / hm\(^2\)).

2.2.2. Constraints. Water resources constraints.

- Total water resources:

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{m=1}^{M} \text{AGQ}_{jim} \text{AIQ}_{ij} + \text{TPQ}_l \text{TPW}_l + \text{HSQ}_l \text{HSW}_l + \text{CCQ}_k \text{CCW}_k \]

\[ + \sum_{k=1}^{K} \text{CIQ}_k \text{CIW}_k \leq \text{TWQ}_l, \forall l \]

(8)

where \( \text{AIQ}_{ij} \) is irrigation requirement of crop \( i \) under irrigation method \( j \) (m\(^3\) / hm\(^2\)); \( \text{TPW} \) and \( \text{HSW} \) is the water consumption per unit of thermal power generation and heat supply, respectively (m\(^3\) / kwh); \( \text{CCW} \) and \( \text{CIW}_k \) is the water consumption per unit of coal washing and coal chemical \( k \), respectively (m\(^3\) / ton); and \( \text{TWQ}_l \) is the total amount of water \( l \) available for agriculture and energy sectors (m\(^3\)).

- Water resources for food production:

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{m=1}^{M} \text{AGQ}_{jim} \text{AIQ}_{ij} \leq \text{WAQ}_l - \text{WTQ}_l, l = 1 \]

(9)

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{m=1}^{M} \text{AGQ}_{jim} \text{AIQ}_{ij} \leq \text{WAQ}_l, l = 2 \]

(10)

\[ \text{AGQ}_{jim} = 0, l = 1, m = 5,6, \forall i, j \]

(11)

\[ \text{AGQ}_{jim} = 0, l = 2, m = 1,2,7, \forall i, j \]

(12)

\[ \text{AGQ}_{jim} = 0, j = 2, l = 1, \forall i, m \]

(13)

where \( \text{WAQ}_l \) is the available water resources for food sector with water sources \( l \) (m\(^3\)); and \( \text{WTQ}_l \) is the amount of transferable water rights (m\(^3\)). The equations (9) and (10) meant that water used by crop cultivation should be no more than the available agricultural water resources. In particular, available surface water was equal to the total amount of water diverted from the Yellow River subtracted by the amount of water transferred to energy industries. The equation (11) meant that crops in Wuzhong and Wuhou could not utilize surface water for irrigation, and the equation (12) meant that crops in Linhe, Wuyuan, and Hangzhou could not utilize groundwater. The equation (13) meant that existed drip irrigation facilities only could utilize groundwater.

- Water resources for energy industries:

\[ \text{TPQ}_l \text{TPW} + \text{HSQ}_l \text{HSW} + \text{CCQ}_k \text{CCW} + \sum_{k=1}^{K} \text{CIQ}_k \text{CIW}_k \leq \text{WTQ}_l, l = 1 \]

(14)
\[ TPQ_{TPW} + HSQ_{HSW} + CCQ_{CCW} + \sum_{k=1}^{K} CIQ_{CIW_k} \leq WEQ \]  

(15)

where \( WEQ \) is the maximum amount of groundwater available for energy sector (m³); \( TPG, HSQ, CCQ, \) and \( CIQ_k \) is the basic groundwater requirement for thermal power generation, heat supply, coal washing, and coal chemical \( k \), respectively (m³). Since some of the energy companies are located in Wuhou and Whzhong that can only utilize groundwater, the equations (16)-(19) guaranteed the basic groundwater requirements of energy sector.

Water rights transaction constraints:

- Investment of drip irrigation:
  \[ AGQ_{ijlm} = 0, j \geq 3, m = 5, 6, \forall i, l \]  
  (20)

- The proportion of increased water-saving irrigation area constraints:
  \[ \sum_{i=1}^{L} \sum_{l=1}^{L} AGQ_{ijlm} \leq AGN_{i,m}, j \geq 3, \forall m \]  
  (23)

where \( \lambda_i \) is the proportion of water-saving irrigation area in cultivation area of crop \( i \) (%); and \( AGN_{i,m} \) is the minimum cultivation area of crop \( i \) in region \( m \) (hm²).

- Canal lining constraint:
  \[ CAL \leq CAN \]  
  (24)

where \( CAN \) is the length of canal available for lining (km).

Total amount of water saved from crop cultivation:

\[ CALWSL + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{l=1}^{L} AGQ_{ijlm} WSD_{ij} = WSQ \]  

(25)

where \( WSL \) is the amount of water saved through lining per unit length of canal (m³ / km); \( WSD_{ij} \) is the amount of water saved through converting the irrigation method of crop \( i \) from border irrigation into water-saving irrigation method \( j \) (m³/hm²); and \( WSQ \) is the total amount
of water saved in crop cultivation (m$^3$).

- Total amount of transferable water rights:
  \[ WTQ = \beta WSQ \]  
  \[ (26) \]

where $\beta$ is conversion coefficient denoted the proportion of transferable water in the total amount of saved water (%).

Production constraints
- Crops production constraints:
  \[ AD^\text{min}_i \leq \sum_{j=1}^{I} \sum_{l=1}^{L} \sum_{m=1}^{M} AGQ_{ijlm} AY_j \leq AD^\text{max}_i, \forall i \]  
  \[ (27) \]

where $AD^\text{min}_i$ is the minimum demand of crop $i$ (kg); and $AD^\text{max}_i$ is the maximum demand of crop $i$ (kg).

- Cultivation area constraints:
  \[ \sum_{l=1}^{L} \sum_{m=1}^{M} AGQ_{ijlm} \leq AGTL \]  
  \[ (28) \]

\[ \sum_{l=1}^{L} \sum_{m=1}^{M} AGQ_{ijlm} \leq AGLR_m, \forall m \]  
  \[ (29) \]

\[ \sum_{j=1}^{J} AGQ_{ijlm} \leq AGDI_{im}, j = 2, \forall i, m \]  
  \[ (30) \]

\[ \sum_{j=1}^{J} \sum_{l=1}^{L} AGQ_{ijlm} \geq AGN_{im}, \forall i, m \]  
  \[ (31) \]

\[ \sum_{j=1}^{J} \sum_{l=1}^{L} AGQ_{ijlm} \leq \gamma_m AGLR_m, l = 1, m = 3, 4 \]  
  \[ (32) \]

where $AGTL$ is the amount of arable land (hm$^2$); $AGLR_m$ is the arable land in region $m$ (hm$^2$); $AGDI_{im}$ is the existed drip irrigation area of crop $i$ in region $m$ (hm$^2$); and $\gamma_m$ is the conversion coefficient that denotes the proportion of surface water irrigated area in region $m$. Since parts of arable land of Dengkou and Wuqian only use groundwater, equation (32) meant that surface water irrigated area in these regions should be no more than arable land that could utilize surface water.

- Production demand in energy industries
  \[ TPD^\text{min} \leq \sum_{l=1}^{L} TPQ_l \leq TPD^\text{max} \]  
  \[ (33) \]

\[ HSD^\text{min} \leq \sum_{l=1}^{L} HSQ_l \leq HSD^\text{max} \]  
  \[ (34) \]

\[ CCD^\text{min} \leq \sum_{l=1}^{L} CCQ_l \leq CCD^\text{max} \]  
  \[ (35) \]
$$CID_{i}^{\min} \leq \sum_{l=1}^{L} CIQ_{il} \leq CID_{k}^{\max}, \forall k$$ (36)

$$\sum_{l=1}^{L} CIQ_{il} = \delta \sum_{l=1}^{L} CIQ_{il}$$ (37)

$$\eta \sum_{l=1}^{L} CIQ_{il} \leq \sum_{l=1}^{L} CIQ_{il}$$ (38)

where $TPD_{\min}$ and $TPD_{\max}$ respectively is the minimum and maximum demand for thermal power generation (kwh); $HSD_{\min}$ and $HSD_{\max}$ respectively is the minimum and maximum demand for heat supply (kwh); $CCD_{\min}$ is the minimum demand for coarse coal (ton); $CCD_{\max}$ is the production scale for coal washing (ton); $CID_{k}^{\min}$ and $CID_{k}^{\max}$ respectively is the minimum and maximum demand for coal chemical $k$ (ton); $\delta$ is the proportion of coal tar production in input coke (%); and $\eta$ is the consumption rate of ammonia producing per unit of urea (%).

Non-negative constraints

$$AGQ_{ijl} \geq 0, \forall i, j, l$$ (39)

$$TPQ_{l} \geq 0, \forall l$$ (40)

$$HSQ_{l} \geq 0, \forall l$$ (41)

$$CAL \geq 0$$ (42)

$$CCQ_{l} \geq 0, \forall l$$ (43)

$$CIQ_{il} \geq 0, \forall k, l$$ (44)

3. Result analysis

3.1. Food production

Agriculture is the predominant activity of food production. It is also the largest water consumer in study area, with a great potential of saving irrigation water resources. The optimal crops planting patterns obtained from WEFR are shown in figure 3. In general, total cultivation area would be $7.49 \times 10^5$ hm$^2$. Maize would be the most popular crop, taking up 45% of the total cultivation area. Sunflowers would have the second largest planting area, accounting for 30% of the total cultivation land. The following would be sunflowers, wheat, vegetables, and seed melons. Melons would have the least cropping area. Though have a similar cultivation method, seed melons would have a larger planting area than melons.
Figure 4 illustrates the optimal cropping patterns of every sub-irrigation district. It would be obvious that planting maize and sunflowers would be popular among all these districts. The total planting areas of maize and sunflowers would take up more than 50% of cultivation area in every district. Apart from maize and sunflowers, melons would be the best choice for Dengkou and Wuhou, accounting for 25% of total planting area. Planting vegetables would be recommended in Wuzhong, where vegetables occupying 27% of cultivation area. In terms of total cultivation area, Wuhou would have the least cultivation area, similar with the current cultivation habits.

3.2. Energy industries
The quantity of thermal power generation and heat supply would be 9.98 and 3.80×10⁹ kwh, respectively. In terms of coal related industries, coal washing would have the largest production scale of 2.40×10⁷ ton. Methanol would have the largest production scale among all chemical products. Subsequent to coke would be urea, followed by synthetic ammonia and coal tar. The proportion of optimal production scales in the design production scales of every energy product is shown in figure 5. Except for coke and urea, production scales of other energy industries would meet the designed production scales.
3.3. Water resources

Food sector would consume more water than energy sector. In detail, food and energy sector would respectively consume $3.49 \times 10^9$ and $4.67 \times 10^7$ m$^3$ of water. Most of the groundwater would be used for crops irrigation. While a small portion of groundwater would be used in energy sector, which was not sufficient enough to support its production. Surface water would become the major irrigation water source for crops cultivation, accounting for 80.61% of agricultural water consumption. Additionally, a total of $2.34 \times 10^7$ m$^3$ of surface water would be delivered to energy sector through the policy of water rights transfer. Surface water would become the main source for energy sector, accounting for 50.19% of total water used. Except that coal tar and methanol would solely rely on groundwater, all of the energy products would use mixed water resources for production. Though costs of transferring surface water would be higher than utilizing groundwater, energy industries would gain higher profit with transferred water.

3.4. Water rights transfer

From the perspective of economy, canal lining would be the most economic water-saving engineering, followed by shrinking the farmland, drip irrigation with groundwater, and drip irrigation with surface water. The contribution of every water-saving engineering is shown in figure 6. Such results were obtained from automatic optimization of WEFR, considering complex tradeoffs among economic and physical constraints. Shrinking the farmland would be the most popular project due to the lower investment cost. It would contribute 38.57% of transferable water rights. In total, drip irrigation would contribute 54.14% to the transferable water resources. Proportion of drip irrigation with groundwater would be higher than that with surface water. Groundwater irrigation is economic than those of surface water, since surface water delivered from the Yellow River has higher sediment content. Canal lining would contribute 7.28% for saved transferable water. The optimal length for canal lining would be 320 km, already equivalent to the length of canal that can be lined restricted by corresponding constraints.

Figure 5. The proportion of designed production scales obtained from WEFR and base year.
Figure 6. Contribution of every water-saving engineering in saving transferable water resources.

Figure 7. Breakdown of water-saving irrigation methods by crops.

The total project area of water-saving engineering would take up 4.40% of total cultivation area. Figure 7 illustrates the breakdown of water-saving irrigation methods by crops. Sunflowers, maize, seed melons, and melons would take up 50.12, 41.27, 6.58, and 2.03% of reconstructed farmland, respectively. In terms of invested drip irrigation with groundwater, sunflowers would become the most popular crop. Planting area of maize would be 3,402 hectares, only 170 hectares less than sunflowers. Seed melons, wheat, melons, and vegetables would respectively take up 10.64, 3.18, 2.70, and 1.46% of cultivation area irrigated by invested drip irrigation with groundwater. Maize would take up about 81.32% of cultivation area under invested drip irrigation with surface water, while vegetables and melons would respectively account for 11.68 and 7.01%. Wheat, sunflowers, and seed melons would not be recommended to utilize drip irrigation method with surface water.

Figure 8 illustrates the implementation of water-saving engineering in every sub-irrigation district. Investment of drip irrigation with surface water would be popular in Linhe, Wuyuan, and Hanghou. Drip irrigation with groundwater would be implemented in Dengkou and Wuqian, since groundwater could only be used in these districts. Shrinking the farmland would be implemented in every district. Among all sub-irrigation districts, Wuqian would have the largest project area. This is mainly because Wuqian had the largest cultivation area and could utilize groundwater for irrigation. Linhe would have the second largest project area,
followed by Wuyuan, Dendkou, and Hanghou.

Figure 8. Implementation of water-saving irrigation methods in every sub-irrigation district.

3.5. Economic benefits

The economic benefits of WEF system would be 4.38×10^{10} yuan. The benefits of food and energy sectors and the costs for water rights transfer are shown in figure 9. In general, energy would be the major profitable sector. Economic benefits of coal chemical would be 1.8×10^{10} yuan, ranking the highest. Economic benefits of food production would be slightly lower than coal chemical, followed by coal washing industry. Thermal power generation and heat supply would have the least profit. The costs of water rights transfer would be 1.63×10^8 yuan, merely taking up 0.63% of economic benefits of energy sector. Therefore, investment in agricultural water-saving engineering would not be a burden to energy industries in terms of economic.

4. Discussion
The optimal scheme obtained from the WEFR were compared to those from the base year (2015). If the optimal solution of WEFR would be adopted, profits of WEF system would have an enormous growth (figure 9). Profits of food and energy sector would increase by 9.23 and 375.72%, respectively. Specifically, a significant increase could be observed in coal
chemicals, of which the benefits would be 6.49 times the benefits in base year. Benefits of coal washing would be 5.38 times the current level. Allocation schemes of water resources would be optimized as well. According to the base year data, water resources used in energy sector only accounted for 0.74% of total amount of water used in WEF system. While this proportion would increase to 1.32% if the optimal scheme obtained from WEFR applied.

In terms of food production, the total amount of water used for irrigation would increase by 12.37%. It has to be noted that such an increase in agricultural water resources were obtained due to the relaxation of water-related constraints. Though it would increase the profit of agriculture to some extent, the preferences of cultivating crops and investment in water-saving projects suggested by WEFR would not be affected. In terms of crops planting area, comparing to the base year, cultivation areas of maize, vegetables, and melons would increase while those of wheat, sunflowers, and seed melons would decrease (figure 3). Furthermore, water-use efficiency would be improved with the implementation of water-saving engineering. Compared with base year, cultivation areas with water-saving irrigation methods would increase by 79.20%.

With the implementation of water rights transfer, more water would be available for energy sector. If the status quo remains, energy sector should continue to produce with relatively small production scales. In comparison, water available for energy industries of WEFR would increase by 100.12%, providing a large space for energy industries to expand production scales. The production scale of every product would have an enormous increase when compared with that of base year (figure 5). For instance, methanol would rapidly expand from 2% of production scale to the designed production scale. Such increases imply that the designed energy production scales proposed by local government and enterprises are attainable as long as there are sufficient water resources available for energy sector.

5. Conclusions
An optimization model WEFR was developed to support sustainable development of regional WEF nexus. Through the incorporation of water rights transfer mechanism, WEFR could help decision makers to optimize the allocation of water resources between food and energy sectors. Results of WEFR could provide food sector with optimal crops planting patterns. It could also guide energy sector to optimize the production scales of energy products and investment portfolio for water-saving engineering.

The developed WEFR was applied to a case study in Bayannur City, north China. In terms of food production, maize and sunflowers would be the main crops for cultivation. Food sector would still be the largest consumer of surface water and groundwater. In terms of energy sector, coal washing would have the largest production scale. Almost all energy products would meet the designed production scales, except for coke and urea. A total of 2.34×10^7 m³ of surface water would be delivered to energy sector through the policy of water rights transfer. Water rights transfer is proved effective for enhancing the sustainable development of WEF system. Compared with base year, food and energy sectors would gain higher profits. Water-saving irrigation area would increase by 79.20%. Moreover, the production scales of energy products would have enormous increases. Such increases imply that the designed energy production scales proposed by local government and enterprises are attainable as long as there are sufficient water resources available for energy sector.

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