Planning Regional-Scale Water-Energy-Food Nexus System Management under Uncertainty: An Inexact Fractional Programming Method

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Abstract

In this study, an inexact fractional programming method is employed for planning the regional-scale water-energy-food nexus (WEFN) system. The IFP cannot only deal with uncertainties expressed as interval parameters, but also handle conflicts among multiple decision stakeholders. The IFP approach is then applied to planning the WEFN system of Henan Province, China. An IFP-WEFN model has been established under consideration of various restrictions related to water and energy availability, as well as food demand. Solutions of the planting areas for different crops in different periods have been generated. The results suggested that there would be a significant increase for vegetable cultivation with an increasing rate of 24.4% and 30% respectively for the conservative and advantageous conditions, followed by the fruit cultivation. In comparison, the planting area of cotton would be decreased with a decreasing rate of 21.2%, and there would also be an explicit decrease for rice cultivation. These results can help generate a desired planting scheme in order to achieve a maximized unit benefit with respect to the water utilization. Comparison between the IFP-WEFN model and the ILP-WEFN model indicates that, even though a slightly lower benefit is obtained from IFP-WENF model, it can result in a higher unit benefit than the planting scheme from ILP-WEFN model. Consequently, the IFP-WEFN model can help decision-makers identify the sustainable agricultural water resources management schemes with a priority of water utilization efficiency.

Keywords: inexact fractional programming; uncertainty; water-energy-food nexus system; decision making; efficiency

1. Introduction

Consumptions of water, energy and food are accelerating due to rapid socio-economic development, booming population, and increasing living standard. Such an issue cannot only be deemed as a general problem of administration but also come into being a large number of intricacies among water, energy and food (Liu et al., 2015). On the one hand, food transport, water treatment, farming, irrigation and water supply require energy to sustain, while water resources can ensure stabilized energy generation, normal crops growth, processing and food production; on the other hand, food can also promote the development of virtual water trade and bioenergy (Liu et al., 2015; Shang et al., 2018). However, the challenge of ensuring water, food and energy demands is expanding accompanied with the urbanization process (Das et al., 2015; Yu et al., 2018). The deterioration of each factor may spread to other components and cause serious consequences. The policy measure and security of water, energy or food may break the fragile balance among the three resources through critical demand and supply mechanism (Keskinen et al., 2016; Owen et al., 2018). Therefore, formulating a high-efficiency and optimal allocation of water, energy and food can both coordinate rapid development of various relevant departments and guarantee social stability and harmony (Martinez et al., 2018; Wang et al., 2018).

Previously, many research works were conducted to explore management strategies of water-energy nexus (WEN), water-food nexus (WFN) and energy-food nexus (EFN). There are lots of studies based on the WEN and water footprint theory (Perrone et al., 2011; Yu et al., 2019). For example, Tsolas et al. (2018) and Liu et al. (2019) employed a graphical and systematic program with the purpose of identifying and eliminating surplus from consumption and productiom of WEN system. Salmoral and Yan (2018) used the theory of virtual water and embedded energy to explore water and energy allocations in the economic system. However, those studies can hardly address extensive uncertainties existing in the water-energy-food nexus (WEFN) system. Recently, some studies have been proposed to reflect various uncertainties in the WEFN system (Perrone et al., 2011; Georgiou et al., 2018; Tsolas et al., 2018; Liu et al., 2019; Yu et al., 2019; Zhang et al., 2018; Fan et al., 2021; Huang and Fan, 2021; Lyu and Fan, 2021). For instance, Hussien et al. (2018) developed a new approach based on risk analysis to address the uncertainties related to demand-supply counterpoise and seasonal changes in the WEFN system. Yu et al. (2019) developed an interval possibilistic-stochastic programming (IPSP) method for planning municipal-scale mixed energy system under multiple uncertainties for the City of Qingdao in Shandong Province, China.

In addition to extensive uncertainties, the management of WEFN system is generally associated to multiple stakeholders which may have contradictory objectives. There have been some studies to address contradictory objectives in the WEFN system through different approaches. For instance, Yue et al., (2021) developed an inexact multi-objective optimization approach for sustainable agricultural energy-water-food nexus (EWFN) management with objectives of social welfare, hydroelectric generation, grain crop production, positive farmland ecosystem service value, and negative farmland ecosystem service value. Sánchez-Zarco et al., (2021) developed a multi-objective mixed integer nonlinear programing model to meet water, energy, and food needs in an arid region involving security assessment. Also, other multi-objective optimization-based studies to tackle multiple objectives in the WEFN system can be found in Yue and Guo (2021), Radmehr et al., (2021), Liu et al., (2022) and so on. In parallel with multi-objective optimization approaches, bi- or multi-level optimization approaches have been developed to reflect multiple objectives from different stakeholders in the WEFN system. For example, Yu et al., (2020a) proposed a multi-level interval fuzzy credibility-constrained programming (MIFCP) method to deal with uncertainties and handle conflicts and hierarchical relationships among multiple decision departments in the WEFN system. Jiang et al. (2019) proposed a three-level optimization-coordination model for optimizing regional irrigation water allocation for multi-stage pumping-water irrigation system. Also, many other studies can be found in Li et al., (2019), Yu et al., (2020b), Zuo et al., (2021), and so on. However, both multi-objective and multi-level optimization approaches may be challenged in dealing with various objectives in the WEFN system such as assigning different weights to different objectives in the multi-objective approaches, and pre-defining the hierarchical structure in the multi-level techniques. Consequently, further studies are still required to explore trade-offs among different objectives in the WEFN system.

Therefore, this paper aims to propose an inexact fractional programming (IFP) method through coordinating interval linear programming (ILP) and fractional programming (FP) into one framework. IFP integrates the unique contribution of each individual technique, in which the ILP would be adopted to deal with various uncertainties and the FP would be employed to reflect conflicting objectives of the studied problem. Moreover, an IFP-WEFN model is developed for planning the WEFN system of Henan Province, China. The obtained results would be able to help the local governor generate desirable planting schemes for different crops with a number of restrictions such as water availability and pollution control, energy availability, and food demand.

2. Methodology

2.1 Interval Linear Programming (ILP)

Interval values are allowed to be incorporated into the optimization process in ILP. All parameters and decision variables in a linear programming can be intervals (Huang et al., 1992). Specifically, an ILP model can be defined as follows:

$$\text{Max} \quad f^{\pm} = C^{\pm} X^{\pm} \tag{1a}$$

Subject to:

$$A^{\pm} X^{\pm} \leq B^{\pm} \tag{1b}$$

$$X^{\pm} \geq 0 \tag{1c}$$

where $A^{\pm} \in \{R^{\pm}\}^{m \times n}$, $C^{\pm} \in \{R^{\pm}\}^{1 \times n}$, $B^{\pm} \in \{R^{\pm}\}^{m \times 1}$, $X^{\pm} \in \{R^{\pm}\}^{n \times 1}$; $R^{\pm}$ denotes a set of interval numbers; $A^{\pm} = (a_{ij}^{\pm})_{m \times n}$, $C^{\pm} = (c_1^{\pm}, c_2^{\pm}, ..., c_n^{\pm})$, $B^{\pm} = (b_1^{\pm}, b_2^{\pm}, ..., b_m^{\pm})^T$ and $X^{\pm} = (x_1^{\pm}, x_2^{\pm}, ..., x_n^{\pm})^T$. An interval number ($a^{\pm}$) is defined as (Huang et al., 1992): $a^{\pm} = [a^{-}, a^{+}] = \{t \in a \mid a^{-} \leq t \leq a^{+}\}$.

An interactive solution algorithm named two-step-method (TSM) was proposed to solve the problem (Huang et al., 1992, 1995; Fan and Huang, 2012; Fan et al., 2009, 2012). Interval solutions can be obtained based on the analysis of detailed interrelationships between the parameters and variables and between the objective function and constraints. The main idea of TSM is to convert the original ILP model into two LP submodels corresponding to the lower and upper bounds of the objective-function value, respectively.

2.2. Factional Programming

A FP model can be an effective tool to deal with ratio optimization problems where the objective function is the quotient of two functions, e.g. cost/evacuee, and cost/time. The method can thus be used for tackling two-objective programming problems without the risk of weighting these objectives. It has been widely used in a number of fields such as resource management, finance, production, and transportation. A FP model can be expressed as follows (Zhu et al. 2014):

$$\text{Max} \quad f(x) = \frac{cx+\alpha}{dx+\beta} \tag{2a}$$

Subject to:

$$x \in S \tag{2b}$$

$$S = [x : Ax \leq b, x \geq 0] \tag{2c}$$

where A is an $m \times n$ matrix, x and b are column vectors with n and m components respectively, c and d are row vectors with n components, α and β are constants. If the denominator is constant in sign for all x on the feasible region, the FP model can be optimized by solving a linear programming program [Charnes and Cooper 1962]. It is also assumed that $dx + \beta > 0$ for all x in S, the objective function is continuously differentiable, and set S is regular, non-empty and bounded.

2.3. Inexact Fractional Programming

The inexact fractional programming (IFP) is developed in this study to deal with controversial objective targets as well as uncertainties existing in WEFN systems. It integrates FP, ILP into a general framework, in which the FP is employed to reflect trade-offs between controversial/conflicting targets, and ILP is used to deal with uncertainty parameters expressed as interval numbers. In general, the IFP model can be expressed as:

$$Max \ f^{\pm} = \frac{\sum_{j=1}^{n} c_j^{\pm} x_j^{\pm} + \alpha^{\pm}}{\sum_{j=1}^{n} d_j^{\pm} x_j^{\pm} + \beta^{\pm}} \tag{3a}$$

Subject to

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \leq b_i^{\pm} \quad i = 1, 2, ..., M \tag{3b}$$

Based on the interactive transform algorithm proposed by Zhu et al. (2014), Model (3) can be transformed into two conventional fractional programming submodels corresponding to the low and upper bound of the objective. The first submodel corresponds to the lower bound (i.e. f^-) of the objective, which is formulated as follows (i.e. Submodel (I)):

$$Max \ f^- = \frac{\sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^- x_j^+ + \alpha^-}{\sum_{j=1}^{k} d_j^+ x_j^- + \sum_{j=k+1}^{n} d_j^+ x_j^+ + \beta^+} \tag{4a}$$

Subject to

$$\sum_{j=1}^{k} | a_{ij}^{\pm} |^+ \ Sign(a_{ij}^{\pm}) x_j^- + \sum_{j=k+1}^{n} | a_{ij}^{\pm} |^- \ Sign(a_{ij}^{\pm}) x_j^+ \leq b_i^- \quad i = 1, 2, ..., M \tag{4b}$$

$$x_j^- \geq 0, \ j = 1, 2 ..., k$$

$$x_j^+ \geq 0, \ j = k+1, k+2, ..., n$$

The second submodel corresponds to the upper bound (f^+) of the objective function, which is formulated as (i.e. Submodel (II)):

$$Max \ f^+ = \frac{\sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1}^{n} c_j^+ x_j^- + \alpha^+}{\sum_{j=1}^{k} d_j^- x_j^+ + \sum_{j=k+1}^{n} d_j^- x_j^- + \beta^-} \tag{5a}$$

$$\sum_{j=1}^{k} | a_{ij}^{\pm} |^- \ Sign(a_{ij}^{\pm}) x_j^+ + \sum_{j=k+1}^{n} | a_{ij}^{\pm} |^+ \ Sign(a_{ij}^{\pm}) x_j^- \leq b_i^+ \quad i = 1, 2, ..., M \tag{5b}$$

$$\sum_{j=1}^{r_i} a_{ij}^- x_j^+ + \sum_{j=r_i+1}^{k} a_{ij}^- x_j^+ + \sum_{j=k+1}^{k+t_i} a_{ij}^- x_{jopt}^+ + \sum_{j=k+t_i+1}^{n} a_{ij}^- x_j^- \leq b_i^+ \quad i = 1, 2, ..., M \tag{5c}$$

$$x_j^+ \geq 0, \ j = 1, 2 ..., k \tag{5d}$$

$$x_j^+ \geq x_{jopt}^-, \ j = 1, 2 ..., k \tag{5e}$$

$$x_j^- \geq 0, \ j = k+1, k+2, ..., n \tag{5f}$$

$$x_j^- \leq x_{jopt}^+, \ j = k+1, k+2, ..., n \tag{5g}$$

In Model (3) and its two submodels (i.e. Submodel (I) numbered as Model (4), Submodel (II) numbered as Model (5)), the former k ($k \le n$) coefficients for $c_j^{\pm}$ and $d_j^{\pm}$ are assumed to be positive (i.e. $0 \le c_j^- \le c_j^+$, and $0 \le d_j^- \le d_j^+$) for a simplicity purpose, and the latter (n - k) coefficients for $c_j^{\pm}$ and $d_j^{\pm}$ are assumed to be negative. Consequently, to get the lower bound (i.e. f^-) of the objective function in Model (3), the former k ($k \le n$) variables (i.e. $x_j^{\pm}$, j = 1, 2, …, k) would get there lower bounds (i.e. x_j^-, j = 1, 2, …, k) correspondingly and the latter variables would get their upper bounds (i.e., x_j^+, j = k + 1, k + 2, …, n) as presented in Equation (4a) (Zhu et al., 2014). For the constraints of Model (3) presented in Constraint (3b), the conservative constraints are to be employed for the submodel corresponding to lower bound (i.e. f^-) of the objective function, and thus b_i^- is adopted in Submodel (I). In comparison, relatively looser constraints (i.e. b_i^+) would be used in the submodel corresponding to lower bound (i.e. f^+) of the objective function as presented in Constraints (5b) and (5c). Detailed proof for the formulation of the two submodels can be found in relevant literatures (Huang, 1995; Fan and Huang, 2012). For Submodel (I), the solutions x_{jopt}^- $(j = 1, 2 ..., k)$ and x_{jopt}^+ $(j = k+1, k+2, ..., n)$ are obtained, which would be used to formulate additional constraints (Equations (14e) and (14g)) in Submodel (II). In addition, r_i and t_i stands for the numbers of $a_{ij}^{\pm} \ge 0$ or $a_{sj}^{\pm} \ge 0$ respectively associated with decision variables $x_j^{\pm}$ $(j = 1, 2 ..., k)$ and $x_j^{\pm}$ $(j = k+1, k+2, ..., n)$ for constraint i or s.

Models (4) and (5) are conventional fraction programming problems, which can be solved through the method proposed by Charnes and Cooper (1962). Thus, the final solutions for Model (3) can be obtained as follows:

$$f^{\pm} = [f_{opt}^-, f_{opt}^+] \tag{6a}$$

$$x_{jopt}^{\pm} = [x_{jopt}^-, x_{jopt}^+] \tag{6b}$$

The IFP-based approaches have been applied for a number of environmental management problems such as planning of regional energy systems (Zhu et al., 2014), agricultural water management (Tan and Zhang, 2018), carbon emission management of urban agglomeration (Cao et al., 2021), allocation of irrigation water resources (Ren et al., 2019), and crop-biomass coproduction management (Ji et al., 2020). In this study, the IFP approach will be applied to support management of a provincial water-energy-food nexus system under consideration of utilization efficiency of water resources.

3. Application

3.1 Overview of the study area

As shown in Figure 1, Henan province is located in the middle-east part of China, which has a largest population over 100 million. Four water systems, including the Yellow River, Huaihe river, Haihe river and Yangtze river, flow across the province with about 1500 tributaries in total. The province has an area of 167×10^3 km^2, accounting for 1.73% of the country's total area. However, the population would account for 7.8% of the country's total population. Henan province is covered with complex terrains and landforms, but about 55.7% of its area is characterized as plains and basins. Such a feature provides favorable conditions for agricultural activities.

As a major agricultural province, Henan province is an important production area of wheat, sesame, corn, cotton and soybean in China. In the last few decades, the value of agricultural production has increased gradually. For instance, the total value of agricultural production it has ranged from RMB 0.225×10^{12} (2007) to 0.455×10^{12} (2017), which has a percentage improvement of 102.5％. While it encounters the bottleneck states in recent years, there are RMB 0.450×10^{12} (2015), 0.446×10^{12} (2016), and 0.455×10^{12} (2017). Data show that the trend of sustained growth has vanished and tended to be stable in the future. Therefore, as an vital part of Gross Domestic Product (GDP), it is essential to further increase the output value of agriculture through adjusting crop planting structure under the consideration of various production factors. At present, the main problems of agricultural development in Henan province can be divided into the following aspects.

a) The amount of water resources for irrigation is numerous, while its utilization efficiency is low and leads to serious waste. For instance, the total utilization water amount for agriculture is 10.9×10^9 m^3 in 2017, which accounts for 46.8% of the total water consumption. And the average amount of water applied in Henan province is 2389 m^3/hm^2, which is higher than the level of developed countries and the national average. The main reasons for this state are extensive use of water, imperfect irrigation facilities and lake of unified management.

b) The total energy production decreases with years and the electricity consumption in rural areas has an opposite tendency, which means agricultural electricity distribution needs to be reduced. Specifically, data shows that the total energy production has a decrease ratio of 42.1％ from 2010 to 2017. However, electricity consumption in rural areas has increased from 26.9×10^9 kWh to 32.9×10^9 kWh, which has a ratio improvement of 22.3％.

c) The planting structure of crops is unreasonable and need to plan scientifically. According to the statistical bulletin of 2018, the planting areas of wheat, oil-bearing crops and peanut are 5.74×10^3, 1.46×10^3, and 1.20×10^3 hm^2. Compared with the planting areas in 2017, the increase proportion are 0.4％, 4.6％, and 4.4％, respectively. Conversely, the planting area of corn, cotton and vegetables have decrease proportions of 2.1％, 10.0％, and 0.9％. Data shows that the planting structure of crops would be adjusted under the market regulation, while many factors (e.g., environmental pollution and energy shortage) have been ignored.

d) There have been amounts of consumption for production conditions, which has resulted in serious pollution from non-point sources. As a typical non-point source pollution, many researches have been conducted on the pollution of farmland. Nowadays, pollution sources are mainly divided into three categories (i.e., chemical fertilizer, pesticide, and plastic film), and the consumption of them have a trend of improvement for increasing the agricultural output in the last few years. For instance, the consumption of chemical fertilizer, pesticides, and plastic film were 5.70×10^9, 0.118×10^9, and 0.13×10^9 kg in 2007, while 7.07×10^9, 0.121×10^9, and 0.16×10^9 kg in 2017. The use of three production elements would not only lead to a large emission of nitrogen and phosphorus, but also its residues would pollute the water, soil and air which could break the ecological balance. Although the consumption of them have been decreasing in recent years, its unit consumption still far exceeds the international standard. According to the 13th five-year plan, we will accelerate the transformation of the pattern of agricultural development and implement the “village cleaning project”, which need to strengthen the treatment and repair of major soil pollution, strengthen the prevention and control of non-point source pollution in agriculture, accelerate the comprehensive improvement of rural environment, and ensure the overall stability of soil environmental quality in the province (FPHPEEP, 2017). Therefore, in the overall planning of agricultural development, it is essential to consider agricultural pollution (i.e., the consumption of three production conditions) in order to realize the coordination between planting agriculture and ecological agriculture as well as promote the sustainable development of agriculture.

Place Figure 1 here

3.2 IFP-WEFN modeling formulation

Government departments have formulated relevant documents for controlling pollutant discharge standards in order to mitigate and control environmental pollution caused by agricultural productions. However, for a real-world WEFN system, there are multiple components and multiple uncertainties in association with different decision makers’ preferences. There are many uncertain technical and economic parameters in the production and processing of agriculture. Besides, the management of WEFN system not only considers the profit of the entire WEFN system but also balances the contradiction among agricultural, water and energy resources managers according to different decision-making priorities. Based on the IFP method, an IFP-WEFN model, as presented in Figure 2 is established for planning the WEFN system of Henan province, China.

In the IFP-WEFN model, agriculture activities (i.e. crop cultivation, crop processing, food generation, food transportation) and available resources control (i.e. fertilizer utilization, pesticide utilization, energy consumption for farming, water consumption for irrigation) are considered to achieve a maximized system benefit. In detail, nine crops would be considered in the IFP-WEFN model, including rice, wheat, corn, beans, tubers, oil-bearing, cotton, vegetables and fruits. Also, a planning horizon of 6 years is considered in the developed model, covering 2022-2027. Consequently, the objective of the IFP-WEFN model is to maximize the unit benefit, which is defined as the agriculture profit per water consumption (\$/m^3). The agriculture profits include revenue of crops, and the cost used for the consumption of various resources (e.g., water, fertilizer, electricity, and seed). In addition, the labor cost has not been taken into account.

$$\text{Max } f^{\pm} = \frac{f_1 - f_2 - f_3 - f_4 - f_5 - f_6 - f_7}{f_8} \tag{7a}$$

(1) Revenues of agricultural products

$$f_1 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UW_{t,v}^{\pm} \times UP_{t,v}^{\pm} \tag{7b}$$

(2) Costs for irrigation water

$$f_2 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times AWQ_{t,v}^{\pm} \times UIP_{t}^{\pm} \times \eta \tag{7c}$$

(3) Costs for fertilizers

$$f_3 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCF_{t,v}^{\pm} \times UFP_{t}^{\pm} \times \theta \tag{7d}$$

(4) Costs for pesticides

$$f_4 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCP_{t,v}^{\pm} \times UPP_{t}^{\pm} \times \vartheta \tag{7e}$$

(5) Costs for agricultural films

$$f_5 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCAF_{t,v}^{\pm} \times UPAF_{t}^{\pm} \times \alpha \tag{7f}$$

(6) Costs for electricity consumption

$$f_6 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCE_{t}^{\pm} \times UPE_{t}^{\pm} \tag{7g}$$

(7) Costs for seeds

$$f_7 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UPS_{t,v}^{\pm} \tag{7h}$$

(8) Requirement of water quantity

$$f_8 = \sum_{t=1}^{6}\sum_{v=1}^{9} SA_{t,v}^{\pm} \times AWQ_{t,v}^{\pm} \tag{7i}$$

Based on the current situation and future development strategy, the IFP-WEFN model would consider multifaceted and comprehensive constraints (e.g., limited utilization amount of land and electricity), which could be clearly seen as follows. The constraints can help plan the agricultural development of Henan province, alleviate the contradictions among the development of socio-economic, environmental protection and other aspects, which will ultimately realize the sustainable development. The constraints are:

(1) The excessive exploitation of land for agriculture may lead to negative effects (e.g., ecological environment deterioration and soil erosion), which means cultivated area should be restricted. Constraint 8a limited the minimum and maximum planting area of crops, so as to avoid large fluctuations of the market price of agricultural products. Meanwhile, the total planting area of crops should not exceed the available arable land in planning periods, as shown in constraint 8b.

$$SA_{t,v}^{min\pm} \le SA_{t,v}^{\pm} \le SA_{t,v}^{max\pm}, \ \forall v,t \tag{8a}$$

$$\sum_{v=1}^{9} SA_{t,v}^{\pm} \le TSA_{t}^{\pm}, \ \forall t \tag{8b}$$

(2) As the major sources of agricultural pollution, the utilization amounts of chemical fertilizers, pesticides and plastic films are restricted in constraints 9a, 9b and 9c, respectively.

$$\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCF_{t,v}^{\pm} \times \theta \le TCF_{t}^{\pm}, \ \forall t \tag{9a}$$

$$\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCP_{t,v}^{\pm} \times \vartheta \le TCP_{t}^{\pm}, \ \forall t \tag{9b}$$

$$\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCAF_{t,v}^{\pm} \times \alpha \le TCAF_{t}^{\pm}, \ \forall t \tag{9c}$$

(3) Constraint 10 indicates that the total consumption of water should not exceed the available amount for agriculture in study area. Furthermore, this constraint can optimize the water use structure of crops under a certain amount of water resources, coordinate the contradictions

among water-using departments, and obtain higher economic benefits.

$$\sum_{v=1}^{9} SA_{t,v}^{\pm} \times AWQ_{t,v}^{\pm} \times \eta \leq TWC_{t}^{\pm}, \ \forall t \qquad (10)$$

(4) constraint 11a limits the electricity consumption of agricultural machinery and constraint 11b limits the amount of fossil energy available for power generation, which will help alleviate the contradiction between future energy supply and demand in study area.

$$\sum_{v=1}^{9} SA_{t,v}^{\pm} \times UCE_{t}^{\pm} \leq TAE_{t}^{\pm}, \ \forall t \qquad (11a)$$

$$\sum_{v=1}^{9} CFF_{t,v}^{\pm} \leq AFF_{t}^{\pm}, \ \forall t \qquad (11b)$$

(5) As a large province of population, the total amount of crops yield as well as purchased should guarantee the food security and meet the changing demand structure caused by the improvement of living standards during the planning period, as shown in constraint 12.

$$SA_{t,v}^{\pm} \times UW_{t,v}^{\pm} + PW_{t,v}^{\pm} \geq FD_{t,v}^{\pm}, \ \forall v,t \qquad (12)$$

(6) In order to accord with the reality and guarantee the correctness of results, constraint 13 ensures that the decision variables (i.e., planting area of crops) are non-negative.

$$SA_{t,v}^{\pm} \geq 0, \ \forall v,t \qquad (13)$$

Place Figure 2 here

3.3 Data collection

In this study, the data were mainly extracted from "Statistical Yearbook of Henan Province", "Water Resources Bulletin of Henan Province", "government report", "pertinent literature". The cultivated area of crops in Henan Province from years of 2009-2016 were shown in Table 1 (SBHPNESD, 2017). Table 2 shows the data on the right-hand side of constraints (i.e. consumption of chemical fertilizer, electricity, pesticide, and plastic film) from 2006-2016. These data and other economic data were mainly referred to the statistical yearbooks and the 13th Five-year Plans (SBHPNESD, 2017; FPHPEEP, 2017; HBQTS, 2014; HPWRB, 2017; FEDPHP, 2017; Yu et al., 2020a,b; Zuo et al., 2021). The crop-related parameters having interval values were depicted in Table 3, which are collected from relevant literatures (Li et al., 2019; Zeng et al., 2019; Yu et al., 2020a,b; Zuo et al., 2021).

A planning horizon consisting of six years (i.e., $t = 1, 2, \ldots, 6$) from 2022 – 2027 would be considered in this study. The further data such covering the planning horizon, including the availabilities of water resources (i.e., $TWC_t^{\pm}$), energies (i.e., $TAE_t^{\pm}$ and $AFF_t^{\pm}$), chemical fertilizers (i.e., $TCF_t^{\pm}$), pesticides (i.e., $TCP_t^{\pm}$) and plastic films (i.e., $TCAF_t^{\pm}$), are estimated through regression methods based on these historical data presented in Table 2. Interval solutions would be obtained through the developed IFP-WEFN model, in which the lower bounds would correspond to conservative/demanding conditions (i.e., the lower bound of objective function) whilst the upper bounds would correspond to the advantageous conditions (i.e., the upper bound of objective function).

Place Tables 1-3 here

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4. Result Analysis

Based on the constraints (e.g., environmental protection and limited resource utilization) and the objective of maximum unit benefit, the planting areas of different crops during the planning periods could be obtained by solving the IFP model, as shown in Figure 3 and Table 4. Figure 3 clearly shows crops' planting areas and the corresponding variation trends during the planning periods, which would further help the decision makers to formulate and implement scientific planning schemes. It can be seen that the planting areas for different crops would vary in different planning periods due to the socioeconomic and environmental restrictions. In detail, the planting areas for rice, corn, beans, tubers show a slightly decreasing trend, while in comparison, there would be slightly more planting areas for wheat, oil-bearing crops. For instance, the planting area for rice would be [5248, 5563] km^2 in period 1 and [4916, 5211] km^2 in period 6. This means that the planting area for rice would decrease from 5248 km^2 to 4916 km^2 under the demanding conditions (i.e., corresponding to the lower bound of the objective function), and from 5563 km^2 to 5211 km^2 under advantageous conditions (i.e., corresponding to the upper bound of the objective function), which showed a decreasing rate of 6.8% for both conditions. In comparison, cultivation area for wheat would respectively be [43405, 46010] and [43524, 46136] km^2 in periods 1 and 6, exhibiting an increasing rate of 0.3% for both demanding and advantageous conditions. In addition, it can be found from Figure 3 and Table 4 there would be noticeable increases in the planting areas for vegetables and fruits, while apparent decreasing for the planting area of cotton. The planting area for vegetables would be [14013, 14854] and [18522, 21194] km^2 in periods 1 and 6, leading to increasing rate of 24.4% and 30% for its lower and upper bounds. The cultivation areas for fruit and cotton also respectively present an increasing rate of 9.6% and a decreasing rate of 21.2%. These may be due to the fact that more vegetables and fruits are demanded towards to the healthy life in future. Moreover, as the uncertainty presented in various parameters, the obtained planting areas for the crops also fluctuate within certain ranges. These results can help decision makers make tradeoff between advantageous and conservative conditions.

Place Figure 3 and Table 4 here

In study area, the contradiction between water-using departments is increasingly prominent due to the acceleration of industrialization, wasteful use of irrigation water, and improvement of living standards. Specifically, the water utilization would increase during the whole planning horizon, in which the water demand would be [1.01, 1.03] × 10^{11} m^3 in period 1 and [1.06, 1.09] × 10^{11} m^3 in period 6, showing increasing rates of 4.3% and 6.2% for its lower and upper bounds. Figure 4 presents the water demands for all crops in different time periods. We can notice that the significant increase for water demand occurs in period 3. This may be attributed to the noticeable increase in the planting area for vegetables, as shown in Figure 3(h).

Place Figure 4 here

Figure 5 depicts the detailed proportion for water demand by different crops in different planning periods. It can be seen that the wheat would utilize most irrigation water with a proportion more than 40%, followed by the vegetables being allocated around 18% in period 1 but more than 22% after period 2. Moreover, the irrigation consumption amounts for rice, corn and oil-bearing crops have similar proportions around 10%. For the water allocation proportions for specific crops in different planning periods, it is noticed that all water allocation proportions except vegetables and fruits, would show a slightly decreasing trend even though the cultivation areas for wheat and oil-bearing crops would increase during the planning horizon. For instance, the water allocation proportion for wheat would be 43.2% in period 1 and [40.3%, 41.1%] in period 6. This would mainly be attributed to the significant increase for water consumption for vegetables, in which its water allocation proportion increases from 18.7% in period 1 to [23.5%, 24.9%] in period 6. In terms of the proportion for water demand from fruits, it would slightly increase due to the increasing cultivation area in periods 1 and 2, but would decrease due to the competitive demand from vegetables. Moreover, even though there are visible uncertainties in the planting areas for different crops in different periods, these uncertainties would not significantly influence the water allocation proportions, leading to limited fluctuation ranges for the proportion values.

Place Figure 5 here

In addition to water resources to support crop growing, energies such as electricity or fossil energy are required in agricultural activities such as machinery and irrigation. Figure 6 presents the energy utilizations for different crop cultivation in different time periods in which the purple and red bars respectively represent the energy allocation proportions under the demanding (i.e., lower bound of the objective function) and advantageous (i.e., the upper bound of the objective function) conditions. It is noticed that cultivation of wheat would be the prioritized energy user which would consume more than 35% energies allocated to all agricultural activities. This is similar with the utilization of water resources. However, even through less than 10% water resources would be distributed to corn cultivation, this kind of crop would utilize more than 20% of energies just followed the energy consumption of wheat cultivation. This is because that the energy utilization is directly associated with the cultivation areas for different crops and corn would have the second largest planting area as presented in Table 4. Due to this fact, the energy usage pattern is different from the water utilization which is affected by both water availabilities as well as the unit water consumption for different crops.

Place Figure 6 here

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5. Discussion

The objective of the IFP-WEFN model is to achieve a maximized unit benefit for the agriculture department with respect to the water consumption, which is different from traditional WEFN model aiming to maximize the total benefit of the agricultural department. Table 5 presents the planting crop areas for different crops in different time periods generated from an ILP-WEFN model. The planting scheme from ILP-WEFN model would be different from that generated by the IFP-WEFN model. For instance, the planting areas for vegetables from the ILP-WEFN model would be [16518, 17394] and [15453, 18551] km^2 in periods 1 and 2, while in comparison the planting areas from IFP-WEFN model would respectively be [14013, 14854] and [14089, 14934] km^2 in periods 1 and 2. This suggests that maximizing the total system benefit would not necessarily lead to a maximum unit benefit.

Place Table 5 here

Figure 7 shows the total benefit of the agricultural department obtained from the IFP-WEFN and ILP-WEFN models. The results show that the total benefit from IFP-WEFN model would slightly lower than that from ILP-WEFN model. In detail, the total benefit obtained from IFP-WEFN model would range within [2.32, 2.84] × 10^{12} RMB, while the total benefit from ILP-WEFN model fluctuates within [2.35, 2.85] × 10^{12} RMB. This is due to the difference in the objective for those two models. Figure 8 presents the unit benefits obtained from the IFP-WEFN and ILP-WEFN models. Conversely with the total benefit, the unit benefit from IFP-WEFN model would higher than that from ILP-WEFN model. The unit benefit of IFP-WEFN model would range within [37.1, 44.1] RMB/m^3, while the unit benefit from ILP-WEFN model would change within [36.5, 43.4] RMB/m^3 due to the uncertainties in model parameters. These results indicate that the planting scheme from IFP-WEFN model would be more appropriate with a priority of water utilization efficiency, while the scheme from ILP-WEFN model would be adopted for a purpose of maximizing the system benefit.

Place Figures 7 and 8 here

In this study, the contradictory objectives between system benefits and water consumption were reflected through a fractional objective. Compared with traditional ILP-WEFN model, the proposed IFP-WEFN model would give priority to the unit system benefit with respect to water utilization rather than the total system benefit. Therefore, higher unit benefits would be generated by the IFP-WEFN model (i.e., [37.1, 44.1] RMB/m^3) which can enhance the utilization efficiency of water resources. This is particularly meaningful for Henan Province which is one of the most water scarce regions in China. Moreover, the introduction of fractional programming into the IFP-WEFN model can also have merits in tackling contradictory objectives than other relevant approaches such as bi-level or multi-level programming methods in: i) avoiding priority pre-specification among those two objectives and ii) relative simple solution procedures (Xu et al., 2022).

6. Conclusions

In this study, an inexact fractional programming (IFP) method has been adopted to provide management strategies for the complex water-energy-food nexus (WEFN) system. An IFP-WEFN model has been formulated for planning the WEFN system of Henan Province. Solutions of the planting areas for different crops under different periods have been generated in order to achieve a maximized unit benefit with respect to the water utilization.

The solutions obtained from the IFP-WEFN model is subject to maximizing the utilization efficiency of water resources, which would tend to approach sustainable water resources management. The results indicated that, among the nine crops, the planting areas for rice, corn, beans, tubers, and cotton would decrease, while the other four crops, namely wheat, oil-bearing crops, vegetables, and fruits, would have more planting areas. More specifically, the planting area for vegetables would significantly increase, leading to a noticeable decrease in the planting area for cotton. Moreover, the water demand for most crops would decrease over the planning horizon, due to the remarkable increase for the water demand from the vegetables. Compared with the IFP-WEFN model, the ILP-WEFN model merely consider the total system benefit and thus leads to a different planting scheme for the Henan province. The results suggest that the unit benefit from IFP-WEFN model would higher than that from ILP-WEFN model, even through the total benefit from ILP-WEFN model is slightly lower.

The obtained results for the IFP-WEFN model can support further planting schemes in Henan province. From a perspective of sustainable water resources management, the Henan province is recommended to reduce the cultivation area for rice and corn but at the same time increase wheat planting to satisfy the local demand of cereals. In addition, due to the realization of the healthy life, more fruits and vegetables will be needed which lead to increasing trends for the cultivation areas of these two crops especially after 2023. Correspondingly, some crops would be less planted due to the limited availability of arable lands, in which the plant area of cotton would be decreased most significantly.

The IFP-WEFN model could deal with contradictions among various objectives under uncertainty. However, in real-world WEFN management problems, the flow of natural surface water may be affected by a variety of factors from climate, topographic, and other aspects, showing various uncertainties in different formats such as fuzzy sets and random variables. Therefore, further studies are required to deal with multiple uncertainties in the WEFN system. Besides, only one water resource (i.e. surface water) were considered in this study. Consequently, further studies are required to include other water resources such as groundwater, diverted water, and reclaimed water, as well as to reveal the effect of consumption change of water for agriculture to other consumption. Such a challenge can be addressed through integrating factorial analysis method into the IFP-WEFN model.

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Appendix A. Nomenclatures for parameters and variables

±	The interval value with lower and upper bounds
t	Planning period, t = 1 is 2022, 2 is 2023, 3 is 2024, 4 is 2025, 5 is 2026, 6 is 2027
v	Variety of crops, v = 1 is rice, 2 is wheat, 3 is corn, 4 is beans, 5 is tuber, 6 is oil-bearing crops, 7 is cotton, 8 is vegetables, 9 is fruits
α	Actual utilization coefficient of agricultural film
η	Effective utilization proportion of irrigation water
θ	Effective utilization coefficient of chemical fertilizer
ϑ	Effective utilization coefficient of spraying pesticide
$AFF_{t}^{\pm}$	Available fossil fuels in period t (kWh)
$AWQ_{t,v}^{\pm}$	Agricultural water requirement quota to crop v in period t (m^3/km^2)
$UCAF_{t,v}^{\pm}$	unit consumption of agricultural film (kg/km^2)
$UCF_{t,v}^{\pm}$	Unit consumption of chemical fertilizers to crop v in period t (kg/km^2)
$UCP_{t,v}^{\pm}$	Unit consumption of pesticides to crop v in period t (kg/km^2)
$UPE_{t}^{\pm}$	Unit price of electricity for agricultural machinery in period t (RMB ¥/kWh)
$CFF_{t,v}^{\pm}$	Consumption of fossil fuels to crop v in period t (kWh)
$UFP_{t}^{\pm}$	Unit price of chemical fertilizer in period t (RMB ¥/kg)
$UPP_{t}^{\pm}$	Unit price of pesticides (RMB ¥/kg)
$FD_{t,v}^{\pm}$	Food demand of crop v in period t (kg)
$ITW_{t}^{\pm}$	The total water consumption for agricultural irrigation in period t (m^3)
$TWC_{t}^{\pm}$	The maximum allowable total agricultural irrigation water consumption (m^3)
$UW_{t,v}^{\pm}$	Output of crop v in period t (kg/km^2)
$UP_{t,v}^{\pm}$	Unit price of crop v in period t (RMB ¥/kg)
$UCE_{t}^{\pm}$	Unit electricity consumption of agricultural machinery in period t (kWh/km^2)
$TAE_{t}^{\pm}$	Total available electricity for agricultural machinery in period t (kWh)
$PW_{t,v}^{\pm}$	Purchased amount of crop v in period t (kg)
$UPAF_{t}^{\pm}$	Unit price of agricultural films in period t (RMB ¥/km^2)
$SA_{t,v}^{\pm}$	Sown areas of crop v in period t (km^2)
$SA_{t,v}^{min\pm}$	The minimum sown areas of crop v in period t (km^2)
$SA_{t,v}^{max\pm}$	The maximum sown areas of crop v in period t (km^2)
$UPS_{t,v}^{\pm}$	Unit price of seeds to crop v in period t (RMB ¥/km^2)
$TCF_{t}^{\pm}$	Total limited consumption of chemical fertilizers in period t (kg)
$TCP_{t}^{\pm}$	Total limited consumption of pesticides in period t (kg)
$TEM_{t}^{\pm}$	The total energy consumption for agricultural machinery in period t (kWh)

$TCAF_t^{\pm}$	Total limited consumption of agricultural films in period t (kg)
$TSA_t^{\pm}$	Total available sown areas in period t (km^2)
$UIP_t^{\pm}$	Irrigation water price in period t (RMB ¥/m^3)

Appendix B. Abbreviation

FP	Fractional programming
GDP	Gross domestic product
ILP	Interval parameter programming
IFP	Inexact fractional programming
WEFN	Water-energy-food nexus

References

Cao R., Huang G.H., Chen J.P., Li Y.P., (2021). A fractional multi-stage simulation-optimization energy model for carbon emission management of urban agglomeration. Science of The Total Environment, 774, 144963.

Charnes A., Cooper W.W., (1962). Programming with linear fractional functionals. Naval Research Logistics, 9(3-4)181 – 186.

Das B., Singh A., Panda S.N., Yasuda H.S., (2015). Optimal land and water resources allocation policies for sustainable irrigated agriculture. Land Use Policy, 42, 527-537.

Fan Y.R., Huang G.H., (2012). A Robust Two-Step Method for Solving Interval Linear Programming Problems within an Environmental Management Context. Journal of Environmental Informatics, 19(1), 1-9.

Fan Y.R., Huang G.H., Li Y.P., (2012). Robust interval linear programming for environmental decision making under uncertainty. Engineering Optimization 44 (11), 1321-1336.

Fan Y.R., Huang G.H., Li Y.P., Cao M.F., Cheng G.H., (2009). A fuzzy linear programming approach for municipal solid-waste management under uncertainty. Engineering Optimization 41 (12), 1081-1101.

Fan Y.R., Yu L., Shi X., Duan Q.Y., (2021). Tracing uncertainty contributors in the multi-hazard risk analysis for compound extremes, Earth's Future 9 (12), e2021EF002280

Georgiou S., Acha S., Shah N., Markides C.N., (2018). A generic tool for quantifying the energy requirements of glasshouse food production. Journal of Cleaner Production, 191, 384-399.

FEDPHP (The 13th Five-year Energy Development Plan of Henan Province), (2017). Henan Provincial Bureau of Statistics (HPBS). http://www.zhoukou.gov.cn/Article/Index?Id=19718

FPHPEEP (The 13th Five-year Plan of Henan Province for Ecological and Environmental Protection), (2017). The People’s Government of Henan Province. http://www.puyang.gov.cn/ztzl/zt/show.asp?id=111475&class=992

HBQTS (Henan Bureau of Quality and Technical Supervision), (2014). Agricultural Basic Water Quota of Henan Province. http://slt.henan.gov.cn/2019/12-30/1242083.html

HPWRB (Henan Provincial Water Resources Bulletin), (2017). Henan Provincial Department of Water Resources. http://slt.henan.gov.cn/bmzl/szygl/szygb/

Huang G.H., Baetz B.W., and Patry G.G. (1992). A grey linear programming approach for municipal solid waste management planning under uncertainty. Civil Engineering Systems, 10, 123-149.

Huang G.H., Baetz B.W., and Patry G.G., (1995). Grey integer programming: An application to waste management planning under uncertainty. European Journal of Operational Research, 83, 594-620.

Huang K., Fan Y.R., (2021). Parameter uncertainty and sensitivity evaluation of copula-based multivariate hydroclimatic risk assessment. Journal of Environmental Informatics, 38(2), 131-144. doi:10.3808/jei.202100462

Hussien W.A., Memon F.A., Savic D.A., (2018). A risk-based assessment of the household water-energy-food nexus under the impact of seasonal variability. Journal of Cleaner Production, 171, 1275-1289.

Ji L., Zheng Z., Wu T., Xie Y., Liu Z., Huang G., Niu D., (2020). Synergetic optimization management of crop-biomass coproduction with food-energy-water nexus under uncertainties. Journal of Cleaner Production, 258, 120645

Jiang Y., Xiong L., Yao F., Xu Z., (2019). Optimizing regional irrigation water allocation for multi-stage pumping-water irrigation system based on multi-level optimization-coordination model. Journal of Hydrology X, 4, 100038. https://doi.org/10.1016/j.hydroa.2019.100038

Keskinen M., Guillaume J.H.A., Kattelus M., Porkka M., Räsänen T.A., Varis O., (2016). The water-energy-food nexus and the transboundary context: insights from large Asian rivers. Water, 8(5), 193.

Li M., Fu Q., Singh V.P., Ji Y., Liu D., Zhang C.L., Li T.X., (2019). An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty. Science of the Total Environment, 651, 1416–1434

Liu D.D., Guo S.L., Liu P., Xiong L.H., Zou H., Tian J., Zeng Y.J., Shen Y.J., Zhang J.Y., (2019). Optimisation of water-energy nexus based on its diagram in cascade reservoir system. Journal of Hydrology, 569, 347-358.

Liu J., Mooney H., Hull V., Davis S.J., Gaskell J., Hertel T., Lubchenco J., Seto K.C., Gleick P., Kremen C., Li S.X., (2015). Systems integration for global sustainability. Science, 347(6225), 1258832.

Liu S.K., Lin Z.E., Chiueh P.T., (2022). Improving urban sustainability and resilience with the optimal arrangement of water-energy-food related practices, Science of The Total

Environment, 812, 152559. https://doi.org/10.1016/j.scitotenv.2021.152559

Lyu X.D., Fan Y.R., (2021). Characterizing impact factors on the performance of data assimilation for hydroclimatic predictions through multilevel factorial analysis. Journal of Environmental Informatics, 38(1), 68-82. doi:10.3808/jei.202100463

Martinez P., Blanco M., Castro-Campos B., (2018). The water-energy-food nexus: a fuzzy-cognitive mapping approach to support nexus-compliant policies in Andalusia (Spain). Water, 10(5), 664.

Owen A., Scott K., Barrett J., (2018). Identifying critical supply chains and final products: An input-output approach to exploring the energy-water-food nexus. Applied Energy, 210, 632-642.

Perrone D., Murphy J., Hornberger G.M., (2011). Gaining perspective on the water-energy nexus at the community scale. Environmental Science & Technology, 45(10), 4228-4234.

Radmehr R., Ghorbani M., Ziaei A.N., (2021). Quantifying and managing the water-energy-food nexus in dry regions food insecurity: New methods and evidence. Agricultural Water Management, 245, 106588. https://doi.org/10.1016/j.agwat.2020.106588

Ren C., Yang J., Zhang H., (2019). An inexact fractional programming model for irrigation water resources optimal allocation under multiple uncertainties. PLoS ONE 14(6): e0217783

Salmoral G., Yan X.Y., (2018). Food-energy-water nexus: a life cycle analysis on virtual water and embodied energy in food consumption in the Tamar catchment, UK. Resources, Conservation and Recycling, 133, 320-330.

Sánchez-Zarco, X.G., González-Bravo, R., Ponce-Ortega, J.M., (2021). Multi-objective Optimization Approach to Meet Water, Energy, and Food Needs in an Arid Region Involving Security Assessment. ACS Sustain. Chem. Eng., 9, 4771–4790. https://doi.org/10.1021/acssuschemeng.0c09322

SBHPNESD (Statistical Bulletin of Henan Province on National Economic and Social Development), (2017). Henan Provincial Bureau of Statistics. http://www.ha.stats.gov.cn/tjfw/tjcbw/tjnj/

Shang Y.Z., Hei P.F., Lu S.B., Shang L., Li X.F., Wei Y.P., Jia D.D., Jiang D., Ye Y.T., Gong J.G., Lei X.H., Hao M.M., Qiu Y.Q., Liu J.H., Wang H., (2018). China's energy-water nexus: assessing water conservation synergies of the total coal consumption cap strategy until 2050. Applied Energy, 210, 643-660.

Tan Q., Zhang T., (2018). Robust fractional programming approach for improving agricultural water-use efficiency under uncertainty. Journal of Hydrology, 564, 1110-1119.

Tsolas S.D., Karim M.N., Hasan M.M.F., (2018). Optimization of water-energy nexus: a network representation-based graphical approach. Applied Energy, 224, 230-250.

Wang X., Daigger G., Lee D.J., Liu J.X., Ren N.Q., Qu J.H., Liu G., Butler D., (2018), Evolving wastewater infrastructure paradigm to enhance harmony with nature. Science Advance, 4(8), q210

Xu Y., Tan J., Wang X., Li W., He X., Hu X., Fan Y., (2022). Synergetic management of water-energy-food nexus system and GHG emissions under multiple uncertainties: An inexact fractional fuzzy chance constraint programming method. Agricultural Water Management, 262, 107323. https://doi.org/10.1016/j.agwat.2021.107323

Yu L., Li Y.P., Huang G.H., Fan Y.R., Yin S., (2018). Planning regional-scale electric power systems under uncertainty: A case study of Jing-Jin-Ji region, China. Applied Energy, 212, 834-849.

Yu L., Li Y.P., Huang G.H., (2019). Planning municipal-scale mixed energy system for stimulating renewable energy under multiple uncertainties-the city of Qingdao in Shandong Province, China. Energy, 166, 1120-1133.

Yu L., Xiao Y., Zeng X.T., Li Y.P., Fan Y.R., (2020a). Planning water-energy-food nexus system management under multilevel and uncertainty. Journal of Cleaner Production, 251, 119658.

Yu L., Li Q.W., Jin S.W., Chen C., Li Y.P., Fan Y.R., Zuo Q.T., (2020b). Coupling the two-level programming and copula for optimizing energy-water nexus system management – A case study of Henan Province. Journal of Hydrology, 586, 124832. https://doi.org/10.1016/j.jhydrol.2020.124832

Yue Q., Guo P., (2021). Managing agricultural water-energy-food-environment nexus considering water footprint and carbon footprint under uncertainty. Agricultural Water Management, 252, 106899. https://doi.org/10.1016/j.agwat.2021.106899

Yue Q., Wu H., Wang Y., Guo P., (2021). Achieving sustainable development goals in agricultural energy-water-food nexus system: An integrated inexact multi-objective optimization approach. Resources, Conservation and Recycling, 174, 105833. https://doi.org/10.1016/j.resconrec.2021.105833

Zeng X.T., Zhang J.L., Yu L., Zhu J.X., Li Z., Tang L., (2019). A sustainable water-food-energy plan to confront climatic and socioeconomic changes using simulation-optimization approach. Applied Energy, 236, 743–759.

Zhang F., Zhang C.L., Yan Z.H., Guo S.S., Wang Y.Z., Guo P., (2018). An interval nonlinear multiobjective programming model with fuzzyinterval credibility constraint for crop monthly water allocation. Agricultural Water Management, 209, 23-133.

Zhu H., Huang W.W., and G. H. Huang, (2014). Planning of regional energy systems: An inexact mixed-integer fractional programming model, Applied Energy, 113, 500-514

Zuo Q., Wu Q., Yu L., Li Y., Fan Y., (2021). Optimization of uncertain agricultural management considering the framework of water, energy and food. Agricultural Water Management, 253, 106907.

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Table 1. Planting area of crops (10^3 km^2) (Yu et al., 2020; Zuo et al., 2021)

Crops	2009	2010	2011	2012	2013	2014	2015	2016
Rice	6.11	6.28	6.38	6.48	6.41	6.50	6.56	6.55
Wheat	52.63	52.80	53.23	53.40	53.67	54.07	54.25	54.66
Corn	28.95	29.46	30.25	31.00	32.03	32.84	33.44	33.17
Beans	5.30	5.13	5.06	5.20	5.04	4.54	4.14	4.16
Tubers	3.15	3.06	2.99	3.12	3.02	3.48	3.54	3.49
Oil-bearing	15.41	15.64	15.79	15.74	15.90	15.98	16.01	16.25
Cotton	5.37	4.67	3.97	2.57	1.87	1.53	1.20	1.00
Vegetables	16.92	17.04	17.20	17.30	17.46	17.26	17.52	17.72
Fruits	3.33	3.42	3.29	3.31	3.36	3.26	3.25	3.51

Table 2. Consumption of agricultural production conditions (Yu et al., 2020; Zuo et al., 2021)

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Consumption of chemical fertilizer by 100％ effective component (10^9 kg)	5.40	5.70	6.02	6.29	6.55	6.74	6.84	6.96	7.06	7.16	7.15
Electricity consumption in rural areas (10^9 kWh)	18.88	22.34	23.74	25.78	26.94	28.18	29.00	30.54	31.32	32.10	31.72
Consumption of pesticides (10^6 kg)	111.6	118	119.1	121.4	124.9	128.7	128.3	130.1	129.9	128.7	127.1
Plastic film use for agriculture (10^6 kg)	118.4	126.6	130.7	141.4	147.0	151.6	155.2	167.8	163.5	162.0	163.1

Table 3. Crop-related parameters (Yu et al., 2020; Zuo et al., 2021)

Parameters	Rice	Wheat	Corn	Beans	Tubers	Oil-bearing	Cotton	Vegetables	Fruits
Cost of crops (RMB ¥/kg)	[3.82, 3.98]	[3.68, 3.83]	[2.63, 2.73]	[9.80,10.20]	[2.45, 2.55]	[9.80, 10.20]	[5.88, 6.12]	[0.98, 1.02]	[1.47, 1.53]
Cost of seeds (10^3 RMB ¥/km^2)	[48.76, 49.75]	[92.35, 94.22]	[73.88, 75.37]	[1.48, 1.51]	[66.49,67.84]	[258.6, 263.8]	[44.33, 45.22]	[29.55, 30.15]	[110.8, 113.1]
Pesticide demand of crops (10^3 kg/km^2)	[1.45, 1.54]	[1.45, 1.54]	[1.45, 1.54]	[0.362, 0.384]	[0.145, 0.154]	[0.145, 0.154]	[7.24, 7.69]	[1.45, 1.54]	[1.49, 1.56]
Fertilizer demand of crops (10^3 kg/km^2)	[73.13, 76.12]	[73.13, 76.12]	[73.13, 76.12]	[36.57, 38.06]	[36.57, 38.06]	[36.57, 38.06]	[73.13, 76.12]	[146.3, 152.2]	[146.3, 152.2]
Water demand of crops (10^3 m^3/km^2)	[360.1, 375.1]	[172.8, 180.0]	[64.8, 67.5]	[115.2, 120.0]	[144.0, 150.0]	[86.4, 90.0]	[72.0, 75.0]	[230.4, 240.0]	[124.8, 130.0]

Table 4. The planting schemes for different crops from the IFP-WEFN model (unit: km^2)

	t =1	t=2	t=3	t=4	t=5	t=6
Rice	[5248, 5563]	[5088, 5393]	[5046, 5348]	[4998, 5298]	[4953, 5250]	[4916, 5211]
Wheat	[43405, 46010]	[43438, 46045]	[43457, 46064]	[43478, 46086]	[43498, 46108]	[43525, 46136]
Com	[26751, 28356]	[26491, 28081]	[26332, 27912]	[26182, 27752]	[25985, 27544]	[25844, 27395]
Beans	[3309, 3508]	[3299, 3497]	[3262, 3458]	[3230, 3424]	[3203, 3395]	[3168, 3358]
Tubers	[2835, 3005]	[2810, 2978]	[2756, 2921]	[2734, 2898]	[2718, 2882]	[2672, 2832]
Oil-bearing Crops	[19210, 20362]	[19253, 20408]	[19321, 20480]	[19354, 20515]	[19379, 20542]	[19405, 20570]
Cotton	[960, 1018]	[918, 973]	[891, 945]	[865, 917]	[834, 884]	[792, 840]
Vegetables	[14013, 14854]	[14089, 14934]	[17937, 20567]	[18062, 20702]	[18298, 20958]	[18528, 21204]
Fruits	[3905, 4140]	[4200, 4452]	[4232, 4486]	[4292, 4550]	[4318, 4577]	[4320, 4579]

Table 5. The planting schemes for different crops from the ILP-WEFN model (unit: km^2)

	t =1	t=2	t=3	t=4	t=5	t=6
Rice	[7822, 7822]	[7632, 7632]	[5046, 5348]	[4998, 5298]	[4953, 5250]	[4916, 5211]
Wheat	[43405, 46010]	[45475, 47429]	[43457, 46064]	[43478, 46086]	[43498, 46108]	[43525, 46136]
Com	[26751, 32160]	[26491, 28081]	[26332, 27192]	[26182, 27752]	[25985, 27544]	[25844, 27395]
Beans	[3309, 3508]	[3299, 3497]	[3262, 3458]	[3230, 3424]	[3203, 3395]	[3168, 3358]
Tubers	[2835, 3005]	[2810, 2978]	[2756, 2921]	[2734, 2898]	[2718, 2882]	[2672, 2832]
Oil-bearing Crops	[19210, 20362]	[19253, 20408]	[19321, 20480]	[19354, 20515]	[19379, 20542]	[19405, 20570]
Cotton	[960, 1018]	[918, 973]	[891, 945]	[865, 917]	[834, 884]	[792, 840]
Vegetables	[16518, 17394]	[15453, 18551]	[17937, 20567]	[18062, 20702]	[18298, 20958]	[18528, 21204]
Fruits	[3905, 4140]	[4200, 4452]	[4232, 4486]	[4292, 4550]	[4318, 4577]	[4320, 4579]

Graphical abstract

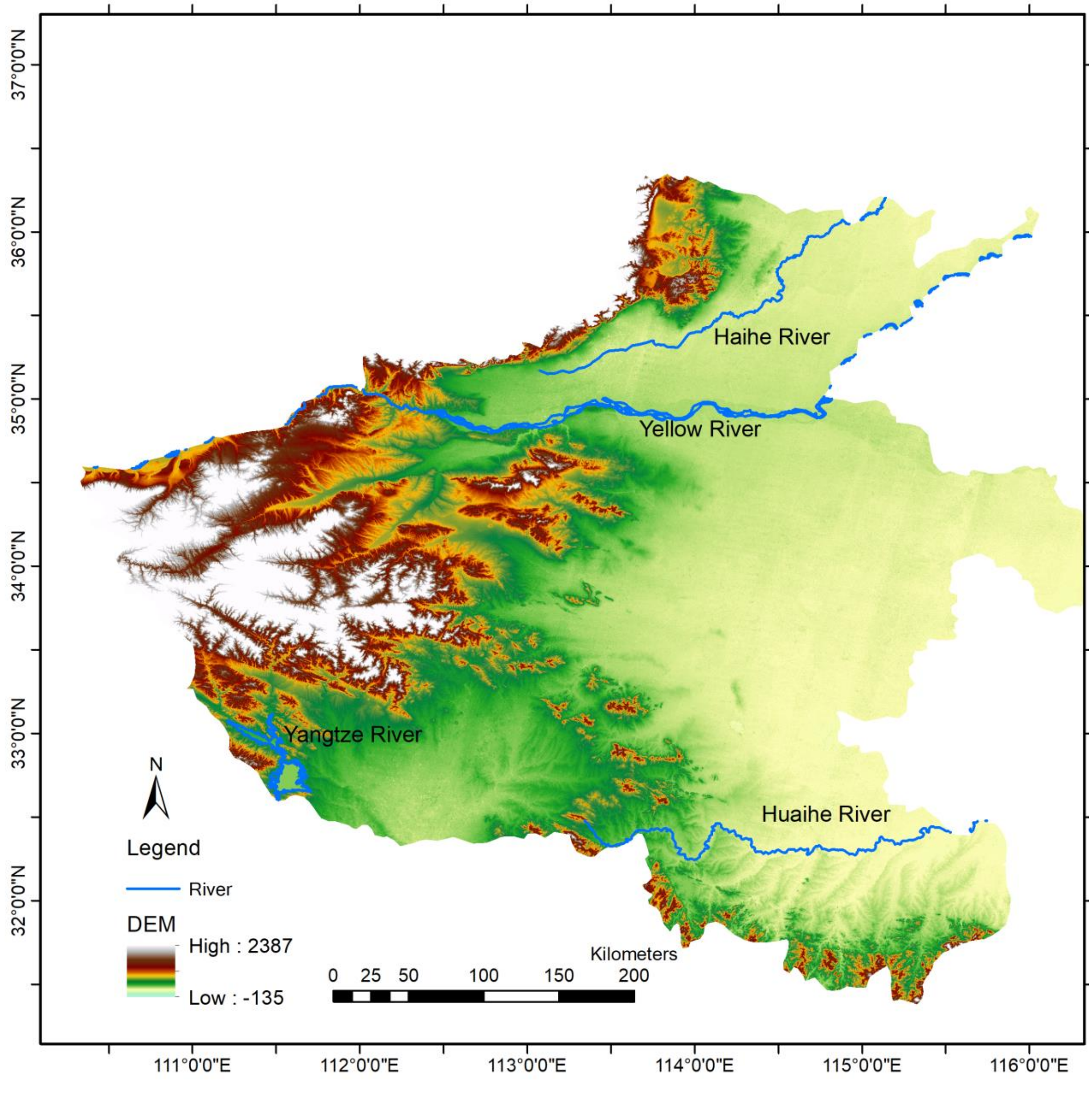
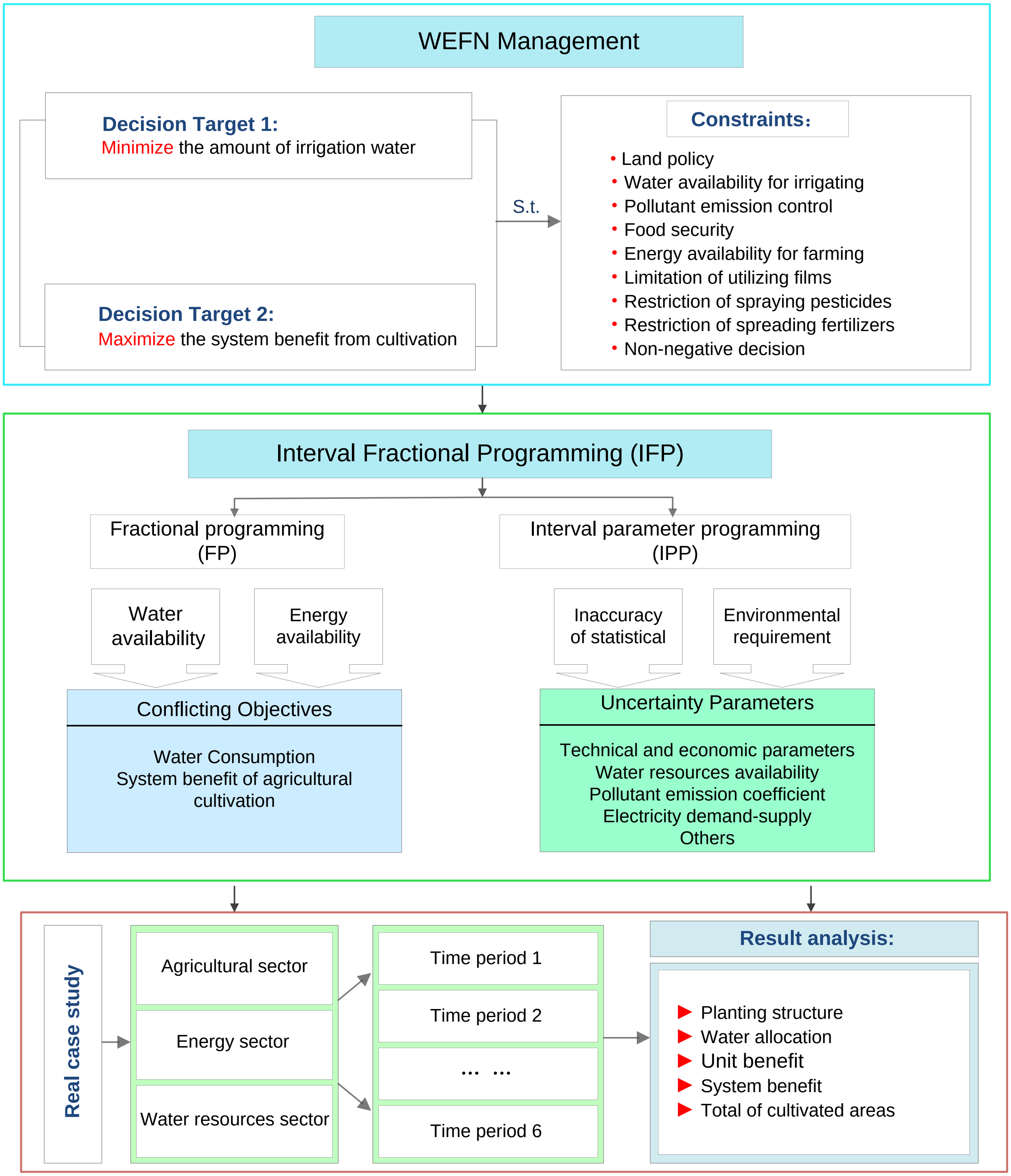


Figure 1. The study area



WEFN Management

Decision Target 1:
Minimize the amount of irrigation water

Decision Target 2:
Maximize the system benefit from cultivation

S.t.

Constraints:

- Land policy
- Water availability for irrigating
- Pollutant emission control
- Food security
- Energy availability for farming
- Limitation of utilizing films
- Restriction of spraying pesticides
- Restriction of spreading fertilizers
- Non-negative decision

Interval Fractional Programming (IFP)

Fractional programming (FP)

Interval parameter programming (IPP)

Water availability

Energy availability

Inaccuracy of statistical

Environmental requirement

Conflicting Objectives

Water Consumption
System benefit of agricultural cultivation

Uncertainty Parameters

Technical and economic parameters
Water resources availability
Pollutant emission coefficient
Electricity demand-supply
Others

Real case study

Agricultural sector
Energy sector
Water resources sector

Time period 1
Time period 2
… …
Time period 6

Result analysis:

- Planting structure
- Water allocation
- Unit benefit
- System benefit
- Total of cultivated areas

Figure 2. The framework of IFP-WEFN model

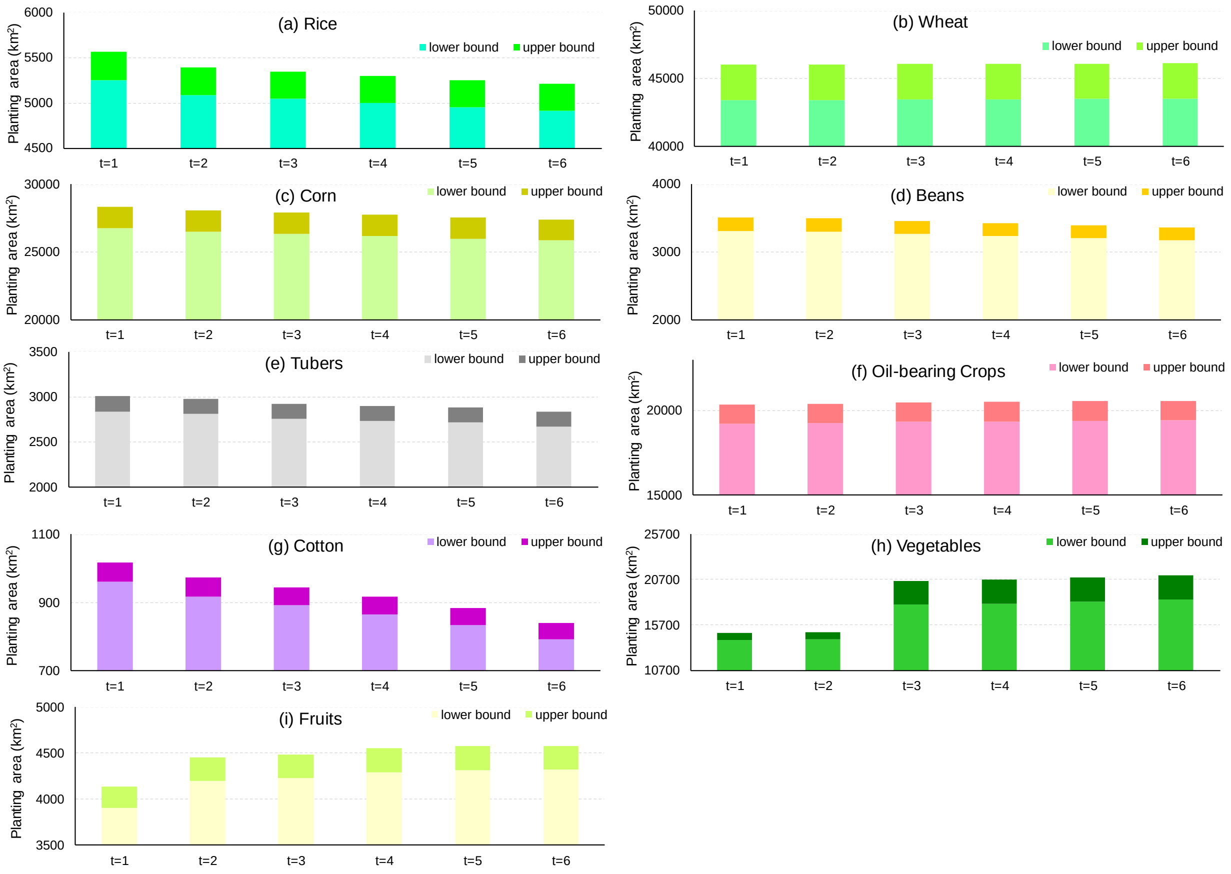


Figure 3. Planting area of different crops (km^2)

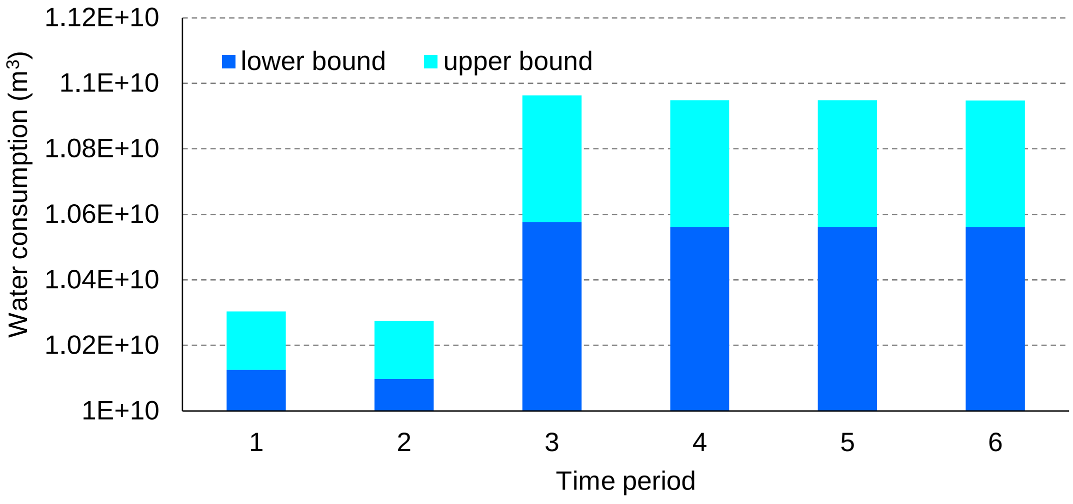
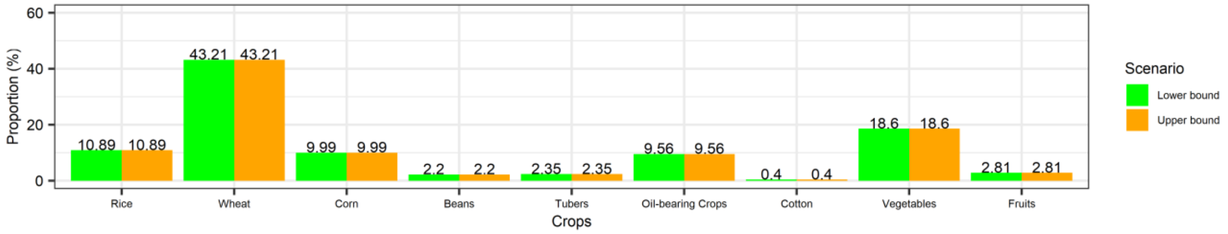
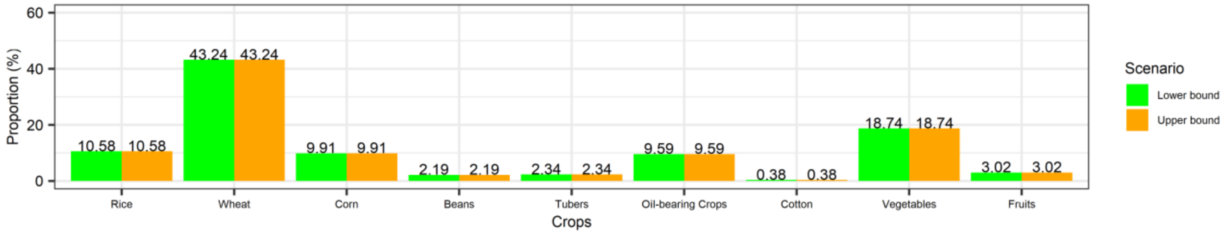


Figure 4. The total water requirements in different planning periods

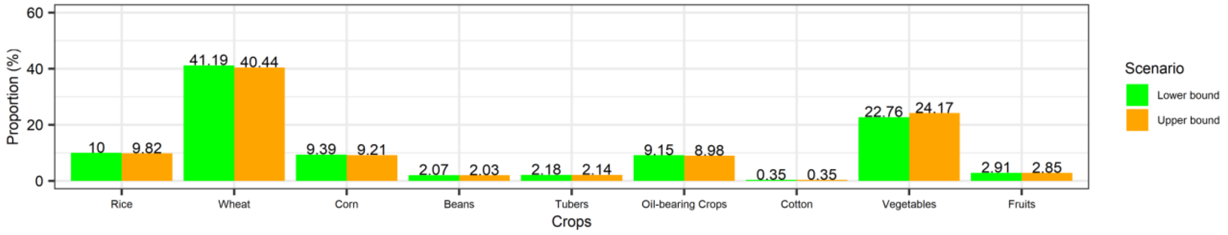
(a) t = 1



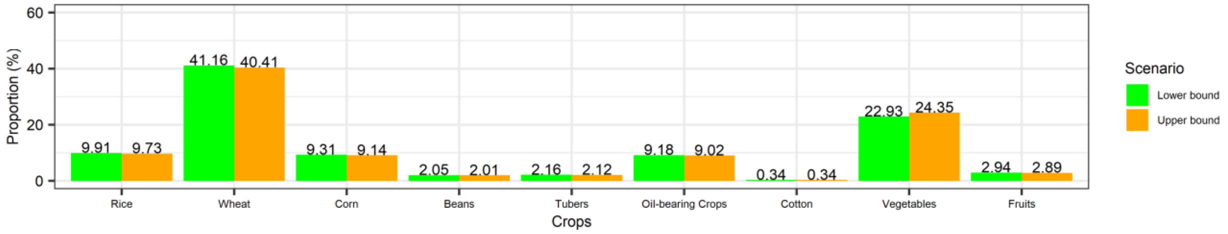
(b) t = 2



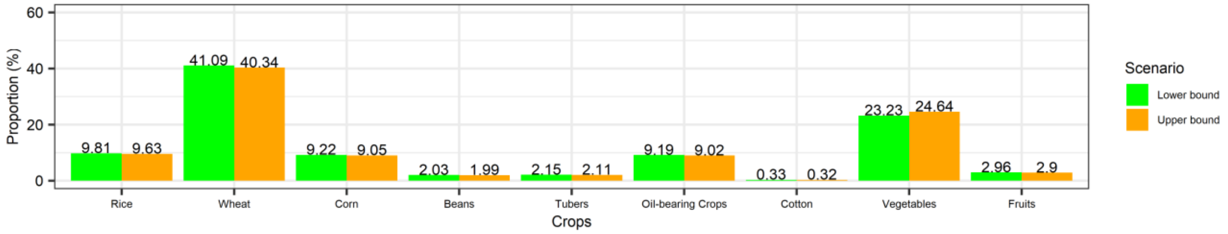
(c) t = 3



(d) t = 4



(e) t = 5



(f) t = 6

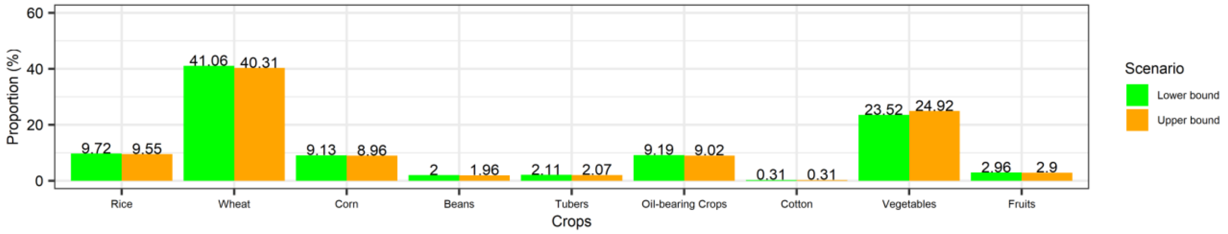


Figure 5. Allocation proportion of water resources to different crops

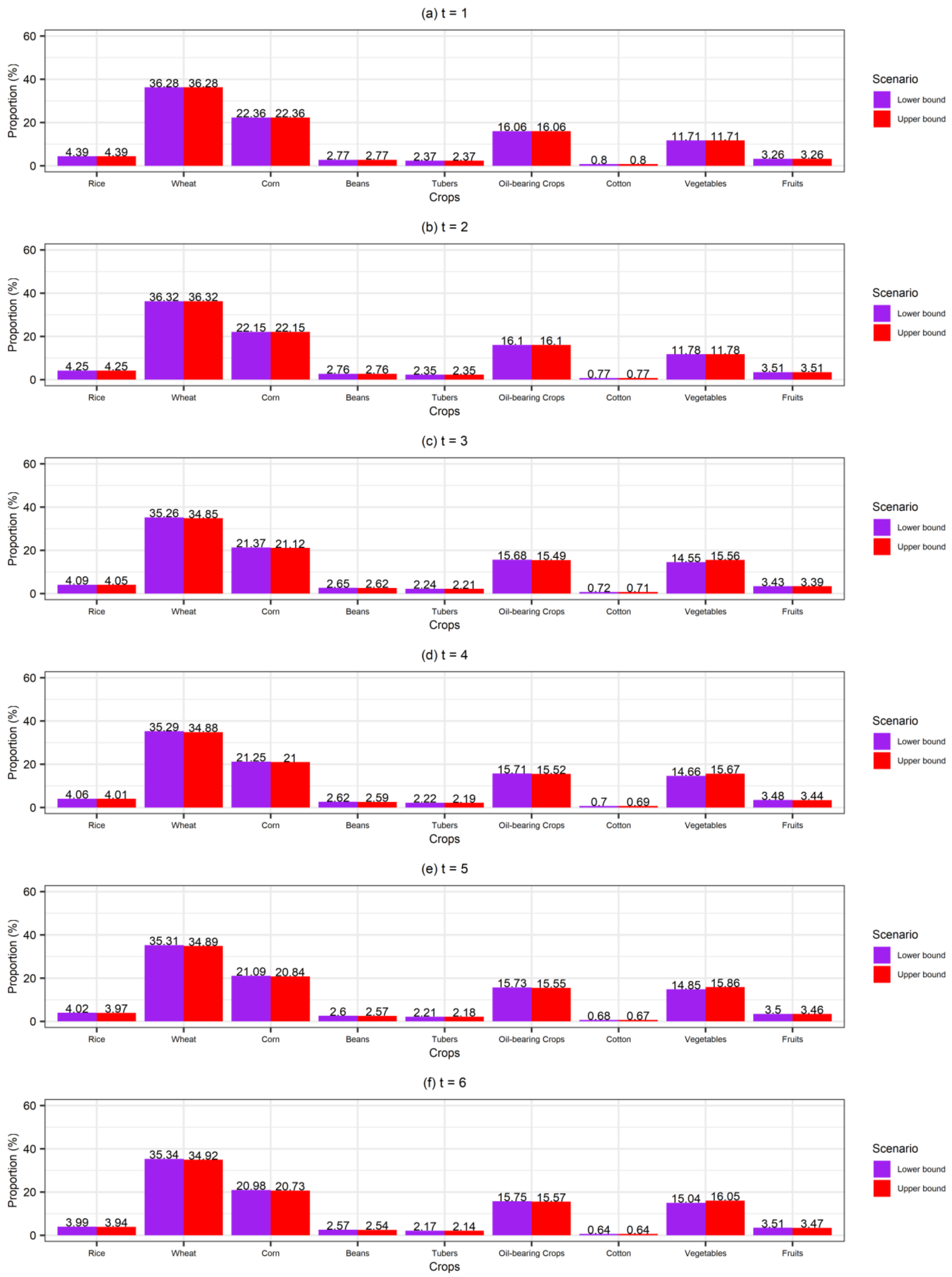


Figure 6. Allocation proportion of energy to different crops

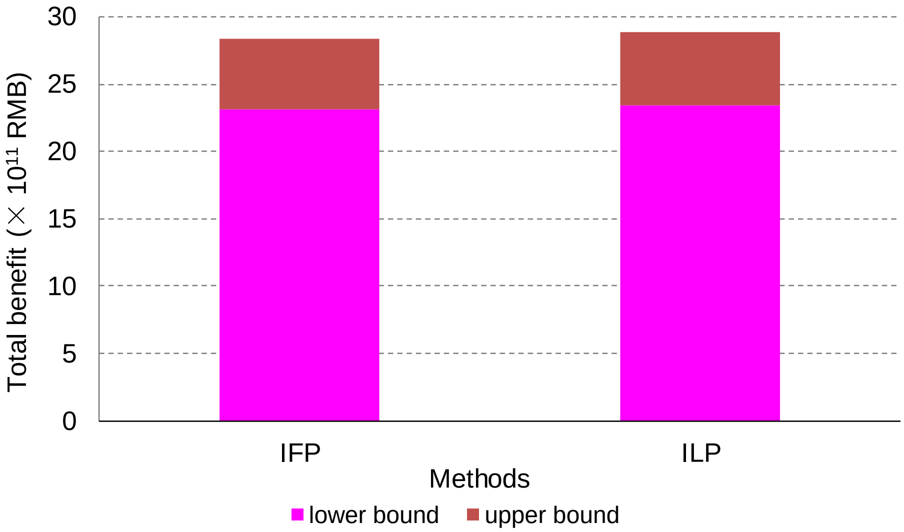


Figure 7 The total benefits obtained from the IFP-WEFN model and ILP-WEFN model

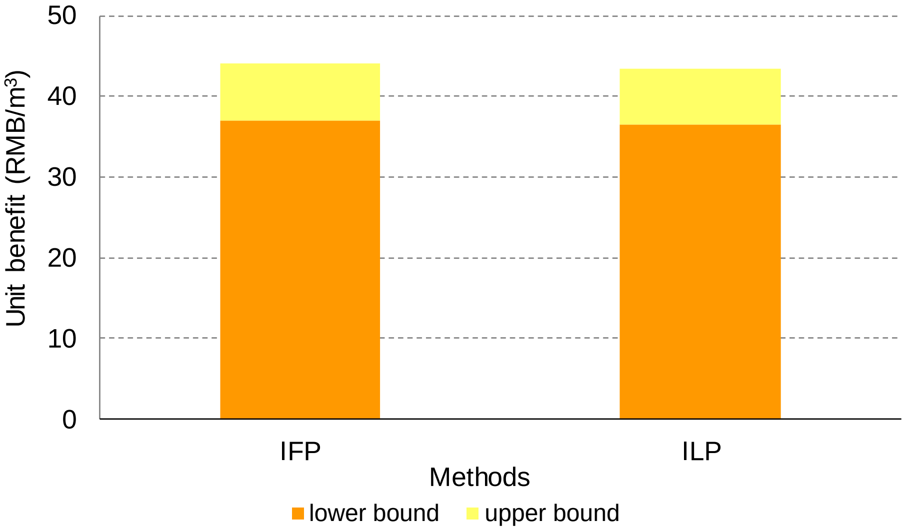


Figure 8 The unit benefits with respect to water consumption obtained from the IFP-WEFN model and ILP-WEFN model