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A factorial inexact copula stochastic programming (FICSP) approach for water-energy- food nexus system management

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ABSTRACT

In this study, a factorial inexact copula stochastic programming (FICSP) method is developed for planning the regional-scale water-energy-food nexus (WEFN) system. The FICSP cannot only deal with uncertainties expressed as interval and random parameters, but also handle the interdependence among correlated random variables. Moreover, the multilevel factorial analysis embedded in FICSP is able to reflect the main and interactive effects among uncertain parameters. The IFCCP approach was then applied to planning the WEFN system for the City of Jinan, Shandong Province, China. A FICSP-WEFN model has been established under consideration of various restrictions related to water and land availability, food and vegetable demands and other environmental constraints. The obtained results indicated that the surface water and groundwater availabilities would be highly correlated with their marginals fitted through the Gaussian distribution and their dependence described by the Gaussian copula. Under limited water resources, the corn cultivation would be prioritized but the increase of water resources tends to increase the wheat cultivation and reduce corn planting. Under the advantageous conditions where sufficient water resources are available, the additional water resources tend to be allocated to wheat and vegetables whilst corn cultivation would not be changed. Moreover, the surface and recycled water would be first utilized for crop production, with the remaining water requirements satisfied by groundwater. The results from factorial analysis indicated that the system benefits would be increased under the demanding conditions through increasing the joint risk level and also the violation risk for surface water availability or decreasing the violation risk of groundwater availability. Nevertheless, the increase in the violation risks under the advantageous conditions would not necessarily lead to increased system benefit, implying that the crop cultivation patterns may be influenced by other restrictions rather than the water availability. In general, the developed FICSP method cannot only generate desired management strategies for WEFN system under consideration of joint risks, but also help track the factors that make dominant impacts on the WEFN management practices.

1. Introduction

There are increasing demands for water, energy and food to support socio-economic development, prosperous population and also decent living standards. This is particularly true for some developing countries such as China, which leads to an urgent request for efficient management for water, energy and food systems. However, water, energy and food systems are highly correlated among each other. For instance, the irrigation is required for agricultural planting which needs both water resources and energies (e.g., diesel or electricity). At the same time, the effluents from farming will lead to pollution issues for the water systems. Consequently, management of water-energy-food nexus

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(WEFN) system is becoming attractive for administrators, academic researchers and other relevant stakeholder (Liu et al., 2015; Keskinen et al., 2016; Shang et al., 2018; Owen et al., 2018). Nevertheless, there are a number of challenges to develop efficient management strategies for water-energy-food nexus, with various uncertainties being one of the major issues to be addressed. There are generally extensive uncertainties in the water-energy-food nexus system, which are embedded in different system components and also present different formats such as fuzzy, interval and random variables (Yu et al., 2020a; Ji et al., 2020a; b; Yan et al., 2021). These uncertainties would interact among each other, intensifying the complexities in managing the WEFN system. Therefore, it is desired to develop effective planning and management policies for water-energy-food nexus under consideration of various uncertainties.

Recently, there are amounts of studies to explore efficient management of water-food nexus or water-energy-food nexus. For instance, Salmoral and Yan (2018) used the theory of virtual water and embedded energy to explore water and energy allocations in the economic system. Zhang and Vesselinov (2017) developed an integrated model, called WEFO, to address the trade-off and support decisions for the nexus management of water, energy and food resources. Moreover, there are also some studies to develop inexact optimization approaches to reflect uncertainties in the water and food systems. For instance, Sun et al. (2019) developed a possibilistic-flexible chance-constrained programming approach to explore the impacts of irrigation efficiency on agricultural water-land nexus system management in Amu Darya River basin, Central Asia. Li et al. (2019) developed an AWEFSM (Agricultural Water-Energy-Food Sustainable Management) model for the sustainable management of limited water-energy-food resource in an agricultural system. Ji et al. (2020b) proposed a multi-stage stochastic fuzzy random programming (MSFRP) model for WEFN management under uncertainties.

For the various uncertainties in the WEFN system, many parameters are random in nature and some of them are highly correlated such as surface water and groundwater resources. The chance-constraint programming (CCP) approaches have been proposed to deal with random parameters in the WEFN system. For instance, Ma et al. (2020) ever employed the chance constraint to reflect the randomness in water resources for managing the water-food-ecology nexus system. Chen et al. (2020) used the CCP method to reflect the random electricity demand in planning the energy-water-environmental nexus through an integrated method. However, some parameter/variables in the WEFN system may be correlated among each other such as availabilities of different water resources, supplies of water resources and energies, and so on. These correlated variables can hardly be well reflected through traditional CCP or joint CCP techniques especially when different variables are quantified by different probabilistic distributions. The copula-based stochastic programming approaches have recently been advanced to deal with the above challenge in which the copula method was adopted to reflect complex dependence structures among correlated variables/parameters. For instance, Yu et al. (2020a) coupled the two-level programming and copula for optimizing energy-water nexus system management at the Henan province in which the correlation between water availability and electricity demand was quantified by the copula method. Zhang et al. (2022) developed a generalized copula-based chance-constrained programming (GCBCP) approach to assess the composite risk of the water-energy-food nexus system among water, energy and food shortage. Even though the copula-based approaches are effective to tackle correlated random variables, some issues still needs to be addressed: (i) the copula-based chance constraints are usually converted into linear constraints before solving the optimization model but such a conversion process has not been well elaborated; (ii) in the copula-based stochastic programming approaches, there would be different risks including the risk for a single variable and the joint/overall risk under consideration of parameter/variable correlation, but the individual and interactive effects of single and joint risks on the WEFN system management have not been addressed.

Consequently, this study aims to develop a factorial inexact copula stochastic programming (FICSP) approach to support management of the water-energy-food nexus system under compound uncertainties. The FICSP approach will be proposed through integrating the interval linear programming (ILP) method, copula-based stochastic programming (FCCP) method and factorial analysis into a framework to (i) deal with uncertainties presented in interval and random formats, (ii) tackle complex dependence among random variables/parameters and (iii) investigate the individual and interactive effects of different risks. The FICSP method will then be applied for developing management strategies for the water-energy-food nexus at the City of Jinan, China to demonstrate the applicability of the proposed method.

2. Methodology

2.1. Formulation of the FICSP-WEFN model

Management of the water-energy-food nexus (WEFN) system is complicated in which multiple uncertainties embedded in multiple components need to be well reflected. Moreover, different requirements such as water and energy availabilities, food demand and cultivation areas for different crops should be under consideration. This implies that the decision maker would not only consider the overall profit of the water-energy-food nexus system but also balances the contradiction between agricultural production and water and energy availabilities. Consequently, a water-energy-food nexus (WEFN) model aims to provide support for efficient agricultural activities to achieve maximum system benefits under consideration of various constraints such as water and energy consumptions, fertilizer and pesticide utilization. In detail, the agriculture profits include revenue of crops, and the costs for the consumption of various resources (e.g., water, energy, fertilizer, and pesticides). In addition, the labor cost has not been taken into account. Therefore, the objective of the WEFN model can be formulated as:

$$\text{Max}\, f^{\pm} = f_1 - f_2 - f_3 - f_4 - f_5 - f_6 - f_7 \tag{1a}$$

(1) Revenues of agricultural products

$$f_1 = \sum_{t=1}^{T}\sum_{v=1}^{V} PA_{t,v}^{\pm} \times UW_{t,v}^{\pm} \times UP_{t,v}^{\pm} \tag{1b}$$

(2) Cost for water supply

$$f_2 = \sum_{t=1}^{T}\sum_{i=1}^{I} WSR_{t,i}^{\pm} \times WS_{t,i}^{\pm} \tag{1c}$$

(3) Cost for water treatment

$$f_3 = \sum_{t=1}^{T}\sum_{i=1}^{I} WSC_{t,i}^{\pm} \times WS_{t,i}^{\pm} \tag{1d}$$

(4) Cost for fertilizer utilization

$$f_4 = \sum_{t=1}^{T}\sum_{v=1}^{V} FC_{t}^{\pm} \times FU_{t,v}^{\pm} \times PA_{t,v}^{\pm} \tag{1e}$$

(5) Cost for pesticide utilization

$$f_5 = \sum_{t=1}^{T}\sum_{v=1}^{V} PC_{t}^{\pm} \times PU_{t,v}^{\pm} \times PA_{t,v}^{\pm} \tag{1 f}$$

(6) Cost for energy consumption

$$f_6 = \sum_{t=1}^{T}\sum_{v=1}^{V} \left(UDC_{t,v}^{\pm} \times UDP_{t}^{\pm} + UEC_{t,v}^{\pm} \times UEP_{t}^{\pm} \right) \times PA_{t,v}^{\pm} \tag{1 g}$$

(7) Cost for seeds

$$f_7 = \sum_{t=1}^{T}\sum_{v=1}^{V} SEDP_{t,v}^{\pm} \times PA_{t,v}^{\pm} \tag{1 h}$$

Based on the current situation and future development strategy, the WEFN model would consider multifaceted and comprehensive constraints (e.g., limited farming areas for different crops, water resources and energy availabilities). The constraints can help plan the agricultural development, alleviate the contradictions among the development of socio-economic, environmental protection and other aspects, which will ultimately realize the sustainable development.

(1) Arable land constraint: The planting areas for different crops should be limited due to competitive land utilization among different sectors (e.g., industrial, commercial and residential) and also requirements of environmental protection, which can lead to constraints of cultivation restriction as follows:

$$PA_{t,v}^{min\pm} \le PA_{t,v}^{\pm} \le PA_{t,v}^{max\pm} \tag{2a}$$

$$\sum_{v=1}^{V} PA_{t,v}^{\pm} \le TPA_t^{\pm} \tag{2b}$$

The minimum and maximum planting areas of crops are bounded in Constraint (2a) to prevent from remarkable price fluctuations for agricultural products. In addition, the total planting area cannot exceed the available arable land (i.e. $TPA_t^{\pm}$) in planning periods as expressed in Constraint (2b).

(2) Food demand constraint: The crop yield should satisfy local basic food requirements to guarantee food security. Firstly, the constraint for the cereal demand is formulated as:

$$\left(1-\gamma_v^{\pm}\right) \times \sum_{v=1}^{2} PA_{t,v}^{\pm} \times UW_{t,v}^{\pm} \ge \lambda \times FD_t^{\pm} \times P_t^{\pm} \tag{3a}$$

where$FD_t^{\pm}$is cereal demand standard per person (kg/person) at period t; $P_t^{\pm}$denotes population size at time period *t*; $\gamma_v^{\pm}$represents the food loss rate in production, transportation and other processes for crop v; λdenotes the food self-sufficiency rate for the study area. Since the wheat and corn are the two major cereal crops, only these two crops (i.e. $v = 1$ and 2) will be considered in Eq. (3a). In addition, the constraint for the vegetable demand can be similarly formulated as:

$$\left(1-\eta^{\pm}\right) \times PA_{t,3}^{\pm} \times UW_{t,3}^{\pm} \ge \lambda \times VD_t^{\pm} \times P_t^{\pm} \tag{3b}$$

where$\eta^{\pm}$is the loss rate for vegetables production and$VD_t^{\pm}$denotes the vegetable demand per person (kg/person) at period *t*.

(3) Water resources availability: Water irrigation is of great importance in the agricultural sector. Nevertheless, the water availability for agricultural irrigation is generally limited for most areas due to increasing water consumption from other sectors. Consequently, the constraint describing water irrigation can be formulated as follows:

$$\theta^{\pm} \times \sum_{v=1}^{V} PA_{t,v}^{\pm} \times IQ_{t,v}^{\pm} \le \sum_{i=1}^{I} WS_{t,i}^{\pm} \tag{4a}$$

where $\theta^{\pm}$is the reliability of irrigation which indicates the probability that the irrigation quota can be satisfied;$IQ_{t,v}^{\pm}$ denotes the irrigation quota for different crops in different planning periods. In addition to the irrigation constraints for different crops, the water resource supply should not exceed the maximum available amounts from different water sources:

$$\Pr\left\{WS_{t,1}^{\pm} \le AVW_{t,1}^{p_1}\right\} \tag{4b}$$

$$\Pr\left\{WS_{t,2}^{\pm} \le AVW_{t,2}^{p_2}\right\} \tag{4c}$$

$$C(1-p_1, 1-p_2) = 1-p \tag{4d}$$

$$WS_{t,3}^{\pm} \le AVW_{t,3}^{\pm} \tag{4e}$$

(4) Energy availability: The energy used in food production mainly include the electricity consumption for irrigation and the fossil consumption for machinery operation, which can be formulated as follows:

$$\sum_{v=1}^{V} PA_{t,v}^{\pm} \times UEC_{t,v}^{\pm} \le TAE_t^{\pm} \tag{5a}$$

$$\sum_{v=1}^{V} PA_{t,v}^{\pm} \times UDC_{t,v}^{\pm} \le TAD_t^{\pm} \tag{5b}$$

where $UEC_{t,v}^{\pm}$and $UFC_{t,v}^{\pm}$ respectively represents the unit electricity consumption (kWh/ha) and unit fossil consumption (kg/ha), whilst $TAE_t^{\pm}$ and $TAD_t^{\pm}$indicate the total availabilities for electricity and fossils allocated to agricultural production.

(5) Restrictions for fertilizers and pesticides: Due to requirements on pollution control and greenhouse gas emission, the utilization of fertilizers and pesticides would also be restricted in the proposed FICSP-WEFN model, which can be formulated as follows:

$$\sum_{v=1}^{V} PA_{t,v}^{\pm} \times FA_{t,v}^{\pm} \le TAF_t^{\pm} \tag{6a}$$

$$\sum_{v=1}^{V} PA_{t,v}^{\pm} \times PA_{t,v}^{\pm} \le TAP_t^{\pm} \tag{6b}$$

where$TAF_t^{\pm}$and$TAP_t^{\pm}$ respectively denotes the total availabilities for fertilizer and pesticide for agricultural production at time period *t*.

The proposed FICSP-WEFN model (i.e., Equations (1) – (6)) are formulated through referring relevant studies (e.g., Li et al., 2019; Tang et al., 2019; Yu et al., 2020a). The system benefit is to be maximized, taking into account for revenues of crop productions as well as costs for water, energy, and agricultural production conditions (Singh and Panda, 2012; Miao et al., 2014; Simić et al., 2017). Consequently, the crop cultivation patterns as well as the corresponding system benefit would be influenced and limited by the synthetic action of productive resources (e.g., water, energy, food and land) (Zuo et al., 2021). Thus, the integrated consideration for restrictions on energy demand-supply, water resources supply, and arable area availability, flood guarantee, and other production conditions can form an internal self-regulating mechanism and optimize the WEF Nexus to some extent (Zhang and Vesselinov, 2017; Zuo et al., 2021). Specifically, even though the agricultural energy demand-supply (i.e., Eqs. (5a) and (5b)) is only considered in the FICSP-WEFN model, these constraints can reflect the impact of energy supply on the crop structure, which can further imply whether the current energy consumption pattern such as the ratio of agricultural energy consumption needs to be adjusted.

The definitions for the variables and parameters used in the proposed WEFN model are listed in Table 1. In this study, all parameters except the availabilities for surface and ground water are presented as intervals, which would reflect uncertainties in future conditions such as crop price. The interval parameters in the proposed WEFN model are mainly used since it is easier to specify the boundaries of an interval parameter based on limited data availabilities. Moreover, the groundwater and surface water availabilities are considered as random variables because: i) they are generally random in nature due to the main effect from local weather conditions, and ii) sufficient samples can be obtained through the local statistical yearbooks to quantify the probabilistic features for these two parameters. It is straightforward that these two parameters are highly correlated, which can be quantified by the copula method. In addition, to further explore the impact of parameter uncertainties on the resulting management strategies for the WEFN system, the factorial analysis method will be introduced into the proposed WEFN model to reveal both individual and interactive effects from parameter uncertainties. Therefore, a factorial inexact copula stochastic programming (FICSP) approach will be proposed for solving the above WEFN

Table 1
Definitions of symbols used in the WEFN model.

	Definition
Indices	
t	index of time period
v	index of crop (1 for wheat, 2 for corn, 3 for vegetables)
i	index of water resources (1 for surface water, 2 for groundwater, 3 for recycled water)
Decision variables	
$PA_{t,v}^{\pm}$	decision variables for planting areas of crop v in period t (ha)
$WS_{t,i}^{\pm}$	decision variables for water supplies of water source i in period t (m^3)
Objective functions	
$f^{\pm}$	The objective function for the total of WEFN system
Parameters	
$UW_{t,v}^{\pm}$	The unit production of crop v in period t (kg/ha)
$UV_{t,v}^{\pm}$	The unit price of crop v in period t (RMB ¥/ha)
$WSR_{t,i}^{\pm}$	The cost for water supply from different water resources ((RMB/m^3)
$WSC_{t,i}^{\pm}$	The water treatment cost (RMB/m^3)
$FC_{t}^{\pm}$	The unit cost of fertilizer (RMB ¥/ha)
$FU_{t,v}^{\pm}$	The fertilizer utilization per unit area for crop v at time period t (kg/ha)
$PC_{t}^{\pm}$	The unit cost of pesticide (RMB ¥/ha)
$PU_{t,v}^{\pm}$	The pesticide utilization per unit area for crop v at time period t (kg/ha)
$UDC_{t,v}^{\pm}$	The unit fossil (i.e., diesel) consumption per unit area for crop v at time period t (kg/ha)
$UDP_{t}^{\pm}$	The unit fossil price in time period t (RMB ¥/kg)
$TAD_{t,v}^{\pm}$	The total availability of fossil for agricultural production in time period t (kg)
$UEC_{t,v}^{\pm}$	The unit electricity consumption (kWh/ha) for crop v in period t
$UEP_{t}^{\pm}$	The unit electricity price in time period t (RMB ¥/kWh)
$TAE_{t}^{\pm}$	The total availability of electricity for agricultural production in time period t (kWh)
$SEDP_{t,v}^{\pm}$	The unit cost for seeds for crop v in period t (RMB ¥/ha)
$PA_{t,v}^{\min\pm}$	The lower bounds of planting areas for crop v in time period t (ha)
$PA_{t,v}^{\max\pm}$	The upper bounds of planting areas for crop v in time period t (ha)
$TPA_{t}^{\pm}$	The total the available arable land in time period t (ha)
$\gamma_{v}^{\pm}$	The loss rate in production, transportation and other processes for cereals ($v = 1, 2$)
$P_{t}^{\pm}$	The total population in time period t
$FD_{t}^{\pm}$	The unit food demand per person (kg/person) in period t
λ	food self-sufficiency rate
$\eta^{\pm}$	The loss rate in production, transportation and other processes for vegetables
$VD_{t}^{\pm}$	the vegetable demand per person (kg/person) at period t
$IQ_{t,v}^{\pm}$	The irrigation quota for crop v in period t (m^3/ha)
$\theta^{\pm}$	The reliability of irrigation
$AVW_{t,i}^{p_i}$	The availability of water source i ($i = 1, 2$) period t (m^3) under a violation risk of p_i
p_i	The violation risk for availability constraint of water source i ($i = 1$ for surface water, $i = 2$ for groundwater)
p	The overall violation risk for the water availability constraints
$AVW_{t,i}^{\pm}$	The availability of water source i at time period t ($i = 3$ for recycled water)
$TAF_{t}^{\pm}$	The total fertilizer availability for agricultural production (kg)
$TAP_{t}^{\pm}$	The total pesticide availability for agricultural production (kg)

Note: ± in superscript indicate interval parameters/variables

model.

2.2. Solution process of the FICSP method

The proposed FICSP integrates the interval mathematical programming (IMP), joint chance constraint programming (JCCP), and factorial analysis into a framework. In detail, the interval copula stochastic programming (ICSP) approach would be first formulated based on IMP, JCCP and copula functions to deal with interval and also correlated random parameters, which is expressed as:

$$Maxf^{\pm} = \sum_{j=1}^{n} c_j^{\pm} x_j^{\pm} \tag{7a}$$

Subject to

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm}, \ i = 1, 2, ., s \tag{7b}$$

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{p_i}(\omega), \ i = s+1, ., m \tag{7c}$$

$$C(1 - p_{s+1}, 1 - p_{s+2}, ., 1 - p_m) = 1 - p \tag{7d}$$

$$x_j^{\pm} \ge 0 \tag{7e}$$

In Model (7), constraints (7b) and (7c) are generated through introduce the copula function C(.) into the joint chance constraint $\Pr\{\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i(\omega), \ i = s+1, ., m\} \ge 1 - p$to describe the dependence among random parameters $b_i(\omega)$. $b_i^{p_i}(\omega) = F_i^{-1}(p_i)$ and $F_i^{-1}(p_i)$ is the inverse of the cumulative probability function (CDF) for the random variable$b_i(\omega)$under a CDF value of p_i. $a_{ij}^{\pm} (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$, $b_i^{\pm} (i = 1, 2, ., s)$and $c_j^{\pm}$ are interval parameters presented in a general form as $\{t^{\pm} | t^{-} \le t \le t^{+}$, any $t \in R\}$. $x_j^{\pm}$ are the decision variables to be generated in Model (7) which can also be expressed as intervals.

In the ICSP method, the copula function is adopted to quantify the dependence among correlated random parameters and further convert the joint chance constraint into equivalent linear constraints. The copula function C(.) is able to join or couple one-dimensional marginal distribution functions to a multivariate distribution function for the correlated random variables. Take two correlated random variables X_1 and X_2 as an example, the joint probability distribution can be formulated through the copula function and their marginals as follows (Nelsen, 2006):

$$F(x_1, x_2) = C(u_1, u_2) \tag{8}$$

where C is the copula function, $u_1, u_2 \in [0, 1]$, $u_1 = F_1(x_1)$, and $u_2 = F_2(x_2)$. $F_1(x_1)$ and$F_2(x_2)$are the marginal distributions for the random variables X_1 and X_2. There are a number of copula functions applied in water and environmental studies (Favre et al., 2004; Bárdossy and Hörning, 2016; Huang and Fan, 2021; Fan et al., 2020a; b), which are mainly classified into four categories: Archimedean, extreme value, elliptical and other miscellaneous families (Wong et al., 2010; Kong et al., 2018; Zhang et al., 2022).

The proposed ICSP approach can be solved through an interactive solution algorithm, in which two submodels with deterministic coefficients are formulated respectively corresponding the lower and upper bounds of the objective function (Huang, 1998; Fan et al., 2009, 2012; Li et al., 2015; Yu et al., 2018). In detail, the submodel for the upper bound of the objective corresponds to the optimistic/advantageous conditions, which is formulated as follows:

$$\text{Max} \quad f^{+} = \sum_{j=1}^{k} c_j^{+} x_j^{+} + \sum_{j=k+1}^{n} c_j^{+} x_j^{-} \tag{9a}$$

Subject to

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^{-} Sign\left(a_{ij}^{\pm}\right) x_j^{+} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^{+} Sign\left(a_{ij}^{\pm}\right) x_j^{-} \le b_i^{+}, \ i = 1, 2, \ldots, s \tag{9b}$$

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^{-} Sign\left(a_{ij}^{\pm}\right) x_j^{+} + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^{+} Sign\left(a_{ij}^{\pm}\right) x_j^{-} \le b_i^{p_i}, i = s+1, \ldots, m \tag{9c}$$

$$C(1 - p_{s+1}, 1 - p_{s+2}, ., 1 - p_m) = 1 - p \tag{9d}$$

$$x_j^{\pm} \geq 0 \tag{9e}$$

where $c_j^{\pm} \geq 0$, for $j = 1, 2, \ldots, k$, and $c_j^{\pm} \leq 0$, for $j = k + 1, \ldots, n$. $p \in [0, 1]$is the overall risk for constraint violation whilst$p_i \in [0, 1]$is the violation risk for constraint *i*. Similar to the optimistic model, the pessimistic submodel can be formulated as:

$$\text{Max} \quad f^- = \sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^- x_j^+ \tag{10a}$$

Subject to

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^+ Sign\left(a_{ij}^{\pm}\right)x_j^- + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^- Sign\left(a_{ij}^{\pm}\right)x_j^+ \leq b_i^-, i = 1, 2, \ldots, s \tag{10b}$$

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^+ Sign\left(a_{ij}^{\pm}\right)x_j^- + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^- Sign\left(a_{ij}^{\pm}\right)x_j^+ \leq b_i^{p_i}, i = s + 1, \ldots, m \tag{10c}$$

$$C(1 - p_{s+1}, 1 - p_{s+2}, ., 1 - p_m) = 1 - p \tag{10d}$$

$$0 \leq x_j^- \leq x_{jopt}^+, j = 1, 2, \ldots, k. \tag{10e}$$

$$x_j^+ \geq x_{jopt}^-, j = k + 1, k + 2, \ldots, n. \tag{10 f}$$

where x_{jopt}^+($j = 1, 2, \ldots, k$) and x_{jopt}^-($j = k + 1, \ldots, n$) are the solutions obtained from the optimistic submodel (i.e. Model (9)). Based on Submodels (9) and (10), the interval solutions for Model (7) can be obtained as

$$f_{opt}^{\pm} = \left[f_{opt}^-, f_{opt}^+\right] \tag{11a}$$

$$x_{jopt}^{\pm} = \left[x_{jopt}^-, x_{jopt}^+\right] \tag{11b}$$

Since parameters in Model (7) are presented either in intervals or probabilistic distributions, it is desired to explore how both the individual and interactive effects of parameter uncertainties on the resulting solutions. Consequently, a factorial inexact copula stochastic programming (FICSP) will be developed to integrate the ICSP method into the factorial analysis framework to address the above issue. Factorial analysis is widely used to quantify the effect of uncertain parameters to reveal the hidden interrelationships and thereby provide decision makers with a comprehensive understanding regarding the effect of the variation of uncertain parameters on the responses of the model (Zhao et al., 2022). In factorial analysis, an experimental design is employed to account for all combinations of the levels of factors to help visualize the single effects of factors with discrete values (or levels) and their interactive effects on a response variable (Fan et al., 2020b). Consider a system which has two factors (A and B), with each factor respectively having *I* and *J* levels. The statistical effect from those two factors can be expressed as

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \begin{cases} i = 1, 2, ., I \\ j = 1, 2, ., J \\ k = 1, 2, ., K \end{cases} \tag{12}$$

where μ denotes the overall mean effect; α_i,$\beta_j$respectively indicate the main effect for factor A at the *i*th level and factor B at the *j*th level; $(\alpha\beta)_{ij}$indicates the interaction between factors A and B; ε_{ijk} means the random error component. The variability in *Y* can be decomposed into its component parts as follows:

$$SS_T = SS_A + SS_B + SS_{AB} + SS_e \tag{13a}$$

and

$$SS_T = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} Y_{ijk}^2 - \frac{Y_{.}^2}{IJK} \tag{13b}$$

$$SS_A = \frac{1}{JK} \sum_{i=1}^{I} Y_{i.}^2 - \frac{Y_{.}^2}{IJK} \tag{13c}$$

$$SS_B = \frac{1}{IK} \sum_{j=1}^{J} Y_{.j.}^2 - \frac{Y_{.}^2}{IJK} \tag{13d}$$

$$SS_{AB} = \frac{1}{K} \sum_{i=1}^{I} \sum_{j=1}^{J} Y_{ij.}^2 - \frac{R_{.}^2}{IJK} - SS_A - SS_B \tag{13e}$$

where$Y_{ij.} = \sum_{k=1}^{K} Y_{ijk}$, $Y_{i.} = \sum_{j=1}^{J}\sum_{k=1}^{K} Y_{ijk}, Y_{.j.} = \sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ijk}, Y_{.} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{ijk}$. SS_A, SS_B and SS_{AB} respectively denote the sums of squares of single factor A, B and their interaction; SS_T and SS_E mean the total of squares and the error component. The factors' contribution is calculated as the ratio of the summation of their squares to the total summation of squares.

Through integrating the ICSP model into the factorial analysis framework, the proposed FICSP model can be solved through the following steps:

Step 1: Formulate the ICSP model presented in Model (7).

Step 2: For the factors to be analyzed, build their factorial design matrix with specified levels for each factor.

Step 3: for each row in the factorial design matrix, formulate the lower and upper bound submodels for Model (7). Here the factors to be addressed in factorial analysis would be considered as deterministic parameters and choose their specified values in the factorial design matrix.

Step 4: Specify the violation risk of p, as well as (m – s - 1) values of p_i, generate the last p_i through solving Eqs. (9d) and (10d).

Step 5: Solve the two submodels to get the corresponding solutions of $f_{opt}^{\pm} = [f_{opt}^-, f_{opt}^+]$ and $x_{jopt}^{\pm} = [x_{jopt}^-, x_{jopt}^+]$.

Step 6: Repeat Steps 3–5 for all the rows in the factorial design matrix and generate corresponding solutions.

Step 7: Calculate the total sum of squares and its components through Equations (13) based on the lower and upper bounds of objective functions obtained through Steps 3 – 6.

Step 8: Calculate the main effects and their interactions of the addressed factors respectively on the lower and upper bounds of the model objective.

3. Case study

3.1. Overview of the studied area

The proposed FICSP approach will be applied for system management practices for the water-energy-food nexus at the City of Jinan, Shandong Province. As the capital of Shandong Province, the City of Jinan is located in the central part of the province. After merging the City of Laiwu in 2019, the City of Jinan is now covering an area of 10244 km^2 and having a population of 8.90 million. The gross domestic product (GDP) more than one thousand billion RMB with the growth rate of 7.4% in 2020, which is the second largest city of Shandong. Jinan is experiencing prosperous growth for both population and economy, leading to increasing demand for water and food. There are several crops planted in the City of Jinan such as wheat, rice, corn, beans, cottons, vegetable and so on. However, wheat, corn and vegetables are the three major crops planted in Jinan. For instance, the sown areas for wheat, corn and vegetables were 2.16×10^6, 2.11×10^6, and 0.89×10^6 ha, respectively, making a respective contribution of 38%, 37% and 15% to the total sown area. The total water demand is about 1.96×10^9 m^3 in 2019, in which water demands for agricultural, industrial, municipal and environmental sectors are respectively 8.24×10^8, 2.95×10^8, 3.59×10^8, and 2.51×10^8 m^3 (Shandong Water Department, 2019). The water supply for Jinan mainly come from surface water, groundwater and recycled water. In 2019, these three water sources contributed about 11.64×10^8, 6.44×10^8 and 1.52×10^8 m^3 to the total water supply (Shandong Water Department, 2019). Nevertheless, the total water availability is limited, especially for agriculture in the City of Jinan due to uneven precipitation, competitive water demands from other sectors such as environmental protection, whilst there is an increasing demand for food supply as the enhancement of life standard. Moreover, the increasing energy consumption especially after 2019, also implied remarkable deficits and serious competition for energy consumption between agricultural production and other sectors (Nie et al., 2021; Xu et al., 2022). Consequently, it is desirable to develop effective management strategies for the water-energy-food nexus system at the City of Jinan.

3.2. Data collection

The whole planning horizon covers the next three years (2022–2026), which also assumed to have five planning periods. Many parameters are required in development the management strategies for the water-energy-food nexus system at the City of Jinan, such as demands for food and vegetables, limits for sown areas of different plants, water availability from different sources. These data are collected from both provincial (http://tjj.shandong.gov.cn/col/col6279/index.html) and local (http://jntj.jinan.gov.cn/col/col27523/index.html) statistic yearbooks and also some relevant literatures (Ji et al., 2020b; Ma et al., 2020; Xiao et al., 2021; Mei et al., 2021; Xu et al., 2022). Table 2 presents the agriculture-related parameters including the unit products for different crops in different planning periods and the sown area limits for different crops obtained from the Jinan Statistical Yearbook (http://jntj.jinan.gov.cn/col/col27523/index.html). The prices of agricultural products, fertilizers and pesticides, as well as the unit utilization of fertilizer and pesticide for different crops are obtained from the cost-benefit analysis of agricultural products (National Development and Reform Commission, 2018, 2019). The irrigation quotas as well as the corresponding reliabilities of irrigation for different crops are obtained from the local irrigation policy (No. DB37/T 3772–2019) released by the Shandong Water Resources Department.

The costs for water supply and water treatment, as presented in Table 3, are adopted from relevant studies (e.g., Ji et al., 2020b). The water availability for different sources is dealt with different approaches. The availabilities of surface water and groundwater are

Table 3
Water-related parameters.

	t = 1	t = 2	t = 3	t = 4	t = 5
The cost for water supply from different water resources (RMB/m^3)					
Groundwater	[0.116, 0.129]	[0.129, 0.143]	[0.144, 0.159]	[0.160, 0.176]	[0.177, 0.196]
Surface water	[0.087, 0.096]	[0.094, 0.104]	[0.102, 0.113]	[0.110, 0.122]	[0.119, 0.132]
Recycle water	[0.089, 0.098]	[0.083, 0.092]	[0.078, 0.086]	[0.073, 0.081]	[0.068, 0.076]
The water treatment costs (RMB/m^3)					
Groundwater	[0.034, 0.037]	[0.038, 0.042]	[0.043, 0.047]	[0.047, 0.052]	[0.052, 0.058]
Surface water	[0.027, 0.030]	[0.031, 0.034]	[0.035, 0.039]	[0.040, 0.044]	[0.046, 0.051]
Recycle water	[0.018, 0.020]	[0.020, 0.022]	[0.022, 0.024]	[0.024, 0.027]	[0.026, 0.029]
Water availability from recycled water (10^8 m^3)					
Recycle water	[1.213, 1.265]	[1.387, 1.447]	[1.583, 1.650]	[1.804, 1.881]	[2.047, 2.134]

Table 2
Agricultural parameters.

Time Period	t = 1	t = 2	t = 3	t = 4	t = 5
unit weight of different crops (kg/ha)					
Wheat	[5696,6182]	[5696,6182]	[5696,6182]	[5696,6182]	[5696,6182]
Corn	[5748,6452]	[5748,6452]	[5748,6452]	[5748,6452]	[5748,6452]
Vegetables	[65475,66918]	[65475,66918]	[65475,66918]	[65475,66918]	[65475,66918]
Unit price of different crop products (RMB/kg)					
Wheat	[2.52, 2.57]	[2.57, 2.62]	[2.62, 2.67]	[2.67, 2.73]	[2.73, 2.78]
Corn	[1.73, 1.89]	[1.76, 1.93]	[1.80, 1.97]	[1.83, 2.01]	[1.87, 2.05]
Vegetables	[1.75, 1.80]	[1.78, 1.84]	[1.82, 1.87]	[1.85, 1.91]	[1.89, 1.95]
The amount of fertilizer utilization per unit area for crop (kg/ha)					
Wheat	[425,470]	[404,447]	[384,424]	[365,403]	[346,383]
Corn	[375,415]	[356,394]	[339,374]	[322,356]	[306,338]
Vegetables	[640,687]	[608,652]	[577,620]	[548,589]	[521,559]
The unit price of fertilizer (RMB/kg)					
	[5.34, 5.79]	[5.45, 5.90]	[5.56, 6.02]	[5.67, 6.14]	[5.78, 6.26]
The amount of pesticide utilization per unit area for different crops (kg/ha)					
Wheat	[9, 10.05]	[8.55, 9.55]	[8.12, 9.07]	[7.72, 8.62]	[7.33, 8.19]
Corn	[10.83, 11.37]	[10.29, 10.80]	[9.77, 10.26]	[9.28, 9.75]	[8.82, 9.26]
Vegetables	[37.84, 39.73]	[35.95, 37.75]	[34.15, 35.86]	[32.44, 34.07]	[30.82, 32.36]
The unit price of the pesticide (RMB/kg)					
	[30.47, 31.99]	[31.08, 32.63]	[31.70, 33.28]	[32.33, 33.95]	[32.98, 34.63]
Irrigation Quota for different crops (m^3/ha)					
Wheat	[3300,3675]	[3300,3675]	[3300,3675]	[3300,3675]	[3300,3675]
Corn	[1155,1545]	[1155,1545]	[1155,1545]	[1155,1545]	[1155,1545]
Vegetables	[2400,3075]	[2400,3075]	[2400,3075]	[2400,3075]	[2400,3075]
Minimum sown areas for different crops (10^5 ha)					
Wheat	[1.68, 1.89]	[1.68, 1.89]	[1.68, 1.89]	[1.68, 1.89]	[1.68, 1.89]
Corn	[1.51, 1.69]	[1.51, 1.69]	[1.51, 1.69]	[1.51, 1.69]	[1.51, 1.69]
Vegetables	[0.64, 0.72]	[0.64, 0.72]	[0.64, 0.72]	[0.64, 0.72]	[0.64, 0.72]
Maximum sown areas for different crops (10^5 ha)					
Wheat	[2.20, 2.64]	[2.20, 2.64]	[2.20, 2.64]	[2.20, 2.64]	[2.20, 2.64]
Corn	[2.32, 2.78]	[2.32, 2.78]	[2.32, 2.78]	[2.32, 2.78]	[2.32, 2.78]
Vegetables	[1.0, 1.2]	[1.0, 1.2]	[1.0, 1.2]	[1.0, 1.2]	[1.0, 1.2]
The total available arable land (10^5 ha)					
	[5.356, 5.540]	[5.356, 5.540]	[5.356, 5.540]	[5.356, 5.540]	[5.356, 5.540]

mainly affected by the weather conditions, which are random in nature. Moreover, the groundwater and surface water availabilities are highly correlated. Consequently, the copula model would be adopted to reflect the probabilistic features of surface and ground water availabilities and their interdependence. In comparison, the recycled water would be generally controlled by technical and regulation factors and thus its availability is projected though regression methods based on historical water supplies from recycled water from 2011 to 2018 (Shandong Water Resources Department, 2019). The future demands for wheat and corn, as well as the vegetables are presented in Table 4. These parameters are adopted from the projections from China Agricultural Outlook (2020–2029) (MARA, 2020). In Table 4, the demands for wheat and corns consists of those directly applied for food production and also those indirectly used such as wheat or corns used for fodder for livestock.

4. Result analysis

4.1. Dependence between groundwater and surface water availabilities

Since the availabilities of surface water and groundwater are generally random in nature, their probabilistic features are quantified through some parametric distributions based on the historical data from 2000 to 2019. In this study, the Gamma, Pearson Type III (i.e., P3), normal and lognormal distributions are employed to quantify the randomness for the surface water and groundwater availabilities. Fig. 2 shows the comparison between the empirical cumulative probabilities and theoretical values obtained through the fitted distributions. The results indicate that all the fitted distributions are agree well with the empirical probabilities, which indicates that all the four distributions are applicable to characterize the probabilistic features for the surface water and groundwater availabilities. To further evaluate the performances of the four distributions, goodness-of-fit tests are performed through the Anderson-Darling (AD) test, root mean square error (RMSE) and the Akaike information criterion (AIC). The detailed procedures for those three goodness-of-fit tests can be found in some literatures (e.g., Gabriel and Fan, 2022). Table 5 presents the results for the goodness-of-fit tests. The results suggest that all the distributions can pass the AD test, which indicates their applicability for modelling the distributions of surface water and groundwater availabilities. Nevertheless, based on the results of RMSE and AIC, the normal distribution would perform best in describing the probabilistic features for both surface water and groundwater availabilities. Consequently, the normal distribution would be adopted in this study to quantify the randomness for the two water availabilities.

The availabilities of surface water and groundwater are generally correlated among each other. Based on the historical data from 2000 to 2019, these two water resources have a Pearson correlation of 0.78 and Kendall's τ of 0.64, implying the high dependence between these two water availabilities. Consequently, it is required to consider both the single and joint probabilistic features in developing the management strategies of water-energy-food nexus at the City of Jinan.

The normal distribution has been demonstrated to best quantify the randomness for both water resources, whilst the dependence between these two variables would be quantified through the copula method. In this study, the Gaussian, Student t, Gumbel, Frank and Joe copulas are adopted to quantify the dependence between surface water and groundwater availabilities with their detailed expressions and properties being referred to previous studies (Nelsen, 2006). Also, the performances of different copulas are evaluated through the Cramér–von Mises (CvM) test (e.g., Genest et al., 2009), RMSE and AIC (Gabriel and Fan, 2022). Table 6 shows the results of goodness-of-fit through different evaluation methods. The results indicate that all the selected copulas are statistically applicable to model the dependence between surface water and groundwater availabilities with the p-value of CvM test higher than 0.05. However, the lowest RMSE and AIC values from the Gaussian copula suggest the kind of copula function would be the best one to modeling the joint probabilistic features for these two water resource variables. Also, the joint CDF function of surface water and groundwater availabilities, based on the Gaussian copula, are presented Fig. 3, indicating the dependent probabilistic features between these two variables.

Table 4
Demands for cereals and vegetables in the planning periods (MARA, 2020).

Time period	Food (wheat and corn) (kg/person)	Vegetables
t = 1	[285,315]	[372,411]
t = 2	[291,322]	[379,419]
t = 3	[294,325]	[385,426]
t = 4	[298,330]	[391,432]
t = 5	[301,332]	[396,438]

4.2. Solutions under a joint violation risk level of 0.1

Through the developed FICSP-WEFN model, the cultivation structures and water supply patterns can be generated under different single and joint risk levels. In detail, the risk level p in Eq. (4d) represents the overall violation risk that the irrigation water needs cannot be satisfied by either the surface water or groundwater resources. The risk level p_1 in Eq. (4b) indicates, with a predefined overall violation risk (i.e., p in Eq. (4d)), the probability that the surface water supply for agricultural irrigation cannot be satisfied, whilst p_2 in Eq. (4c) represents the probability that the groundwater supply is not satisfied. The overall risk level p can be predefined by the decision maker. In this study, $p = 0.1$ is primarily specified through referring relevant studies (Yu et al., 2020b; Zhang et al., 2021; Zhang et al., 2022). This means that the decision maker wants to ensure the surface and ground water supplies to irrigation can be satisfied with a probability of 90%. Such a risk level also implies that, even for some drought conditions with relatively less water availabilities, the obtained cultivation pattern would still be feasible.

When the joint violation risk level is set to be 0.1 (i.e., $p = 0.1$), there would be different options to specify the associated violation risk levels for surface water (i.e., p_1) and groundwater (i.e., p_2) availabilities: (i) specify the risk level of groundwater availability and solve Eq. (4d) to generate the risk level for surface water availability; (ii) predefine the risk level for surface water and solve Eq. (4d) to obtain the risk level for groundwater. In this study, both of these two options would be considered with the overall risk of 0.1 and the predefined risk of either groundwater or surface water being 0.09, 0.07, 0.05. Table 7 presents the scenarios of risk levels of surface water and groundwater under an overall risk of 0.1. It can be concluded that for a specified joint risk level, there would be different risk levels for individual constraints. Also, due to the different risk levels for groundwater and surface water constraints, there would be different availabilities for these two water resources and also the total water resources, as presented in Table 8. With different joint and single risk levels, the proposed FICSP-WEFN model is to be converted to two submodels corresponding to the upper and lower bounds of the objective function based on the process described through Submodels (9) and (10). Each submodel is a linear programming model which is solved by Lingo in this study with a computation time about 3 s

Table 9 presents the cultivation pattern and also water allocations under an overall risk level of 0.1. The results indicate that, for the specified overall risk level, there would be distinguishable crop planting structures and water allocation schemes under different combinations of single risk levels. Also, under each risk combination, the planting areas for different crops would vary in different planning periods due to the socioeconomic and environmental restrictions as well as the water resource availabilities.

Under the risk scenario of $p = 0.1$ (overall risk), $p_1 = 0.035$ (surface water), $p_2 = 0.09$ (groundwater), the planting area for corn would be 1.784×10^5 ha in period 1 and 2.318×10^5 ha in period 5 with an increasing rate of 30% under the demanding conditions. In comparison,

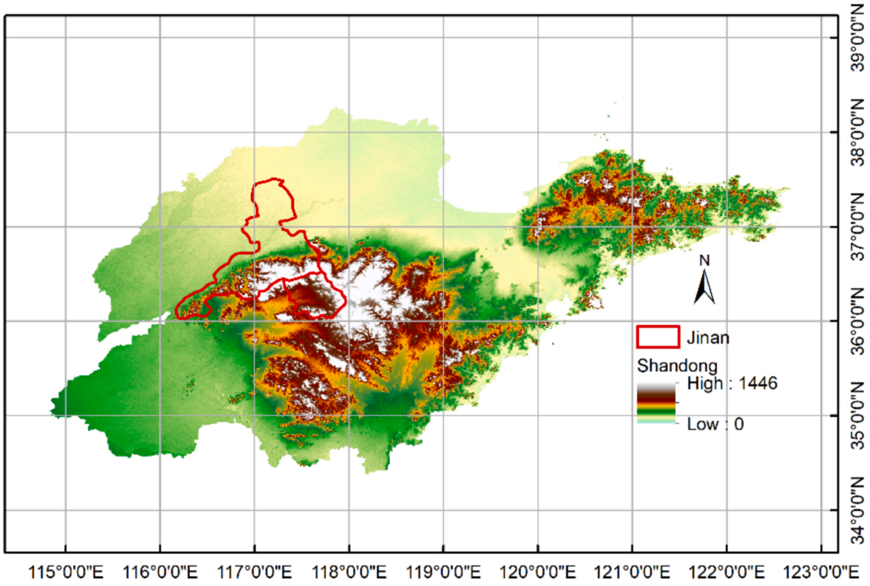

Fig. 1. The location of the study area.

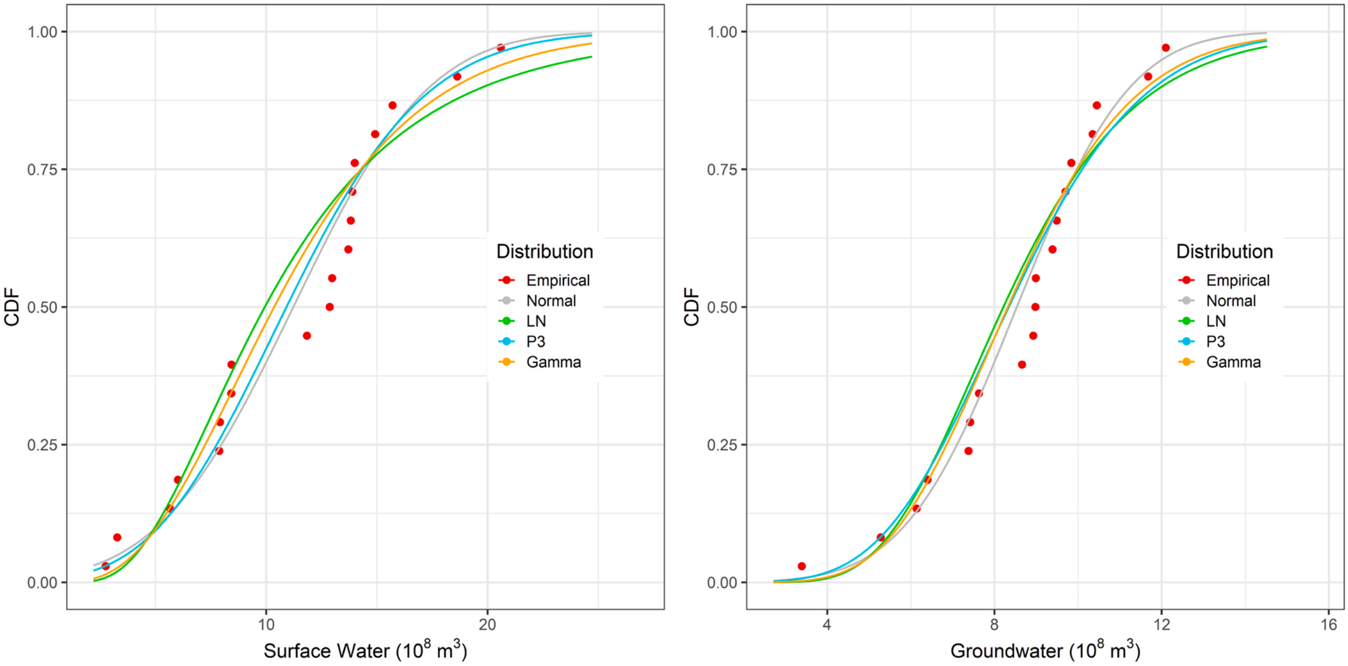

Fig. 2. The comparison between empirical and theoretic CDFs for groundwater and surface water availabilities through different distributions.

Table 5

Performances of different marginal distributions for surface and groundwater availabilities.

		AD-statistic	P-Value	RMSE	AIC
Surface Water	Gamma	0.615	0.632	0.075	-92.402
	P3	0.460	0.786	0.067	-96.519
	Lognormal	0.822	0.464	0.084	-88.141
	Normal	0.408	0.839	0.063	-99.129
Groundwater	Gamma	0.572	0.673	0.070	-95.084
	P3	0.547	0.697	0.070	-95.309
	Lognormal	0.751	0.516	0.080	-90.183
	Normal	0.313	0.927	0.052	-106.206

Table 6

Performances of different copulas for surface and groundwater availabilities.

	Statistic CvM	P-value	RMSE	AIC
Gaussian	0.084	0.580	0.055	-108.473
Student t	0.086	0.490	0.055	-108.458
Gumbel	0.111	0.270	0.057	-106.570
Frank	0.089	0.360	0.058	-106.332
Joe	0.082	0.920	0.063	-102.910

cultivation area for wheat would be 1.89×10^5ha for all the planning periods, which is the upper bound of the minimum planting limit. The results imply that, with strict restrictions (e.g., water resource availabilities), the corn seems to be prioritized between corn and wheat in the planting structure to satisfy the cereal demand from local population.

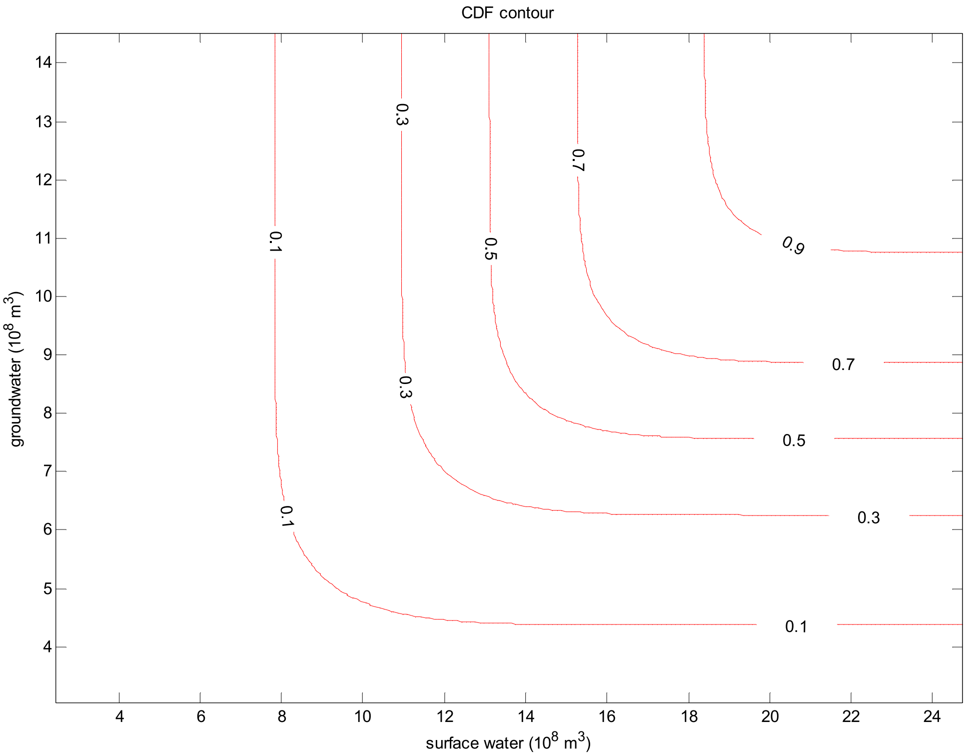

Fig. 3. The joint CDF of groundwater and surface water availabilities through Gaussian copula.

Table 7
Scenarios for joint risk levels and the associated risk for groundwater and surface water.

	Fixed groundwater risk		Fixed surface water risk	
Joint Risk (p)	Risk of surface water (p_1)	Risk of groundwater (p_2)	Risk of surface water (p_1)	Risk of groundwater (p_2)
0.1	0.035	0.09	0.09	0.035
	0.064	0.07	0.07	0.064
	0.081	0.05	0.05	0.081

Table 8
Water availabilities under different risk levels for surface and ground water.

Scenario	Risk level for surface water	Risk level for groundwater	Surface water availability (× 10^8 m^3)	Groundwater availability (× 10^8 m^3)	Sum of SW and GW (× 10^8 m^3)
a	0.035	0.090	2.495	5.691	8.186
b	0.064	0.070	3.874	5.404	9.278
c	0.081	0.050	4.486	5.046	9.531
d	0.090	0.035	4.762	4.693	9.455
e	0.070	0.064	4.111	5.300	9.411
f	0.050	0.081	3.296	5.569	8.865

More specifically, as the cereal demand increases, these demands would also be satisfied by corn, and thus lead to an increasing trend for corn cultivation over the planning horizon. In addition, the cultivation area for vegetables would slightly increase from [0.921, 1.204] × 10^5 ha in period 1 to [1.003, 1.204] × 10^5 ha in period 5 with an increasing rate of 8.9% for the lower bound. The increasing trend for vegetable cultivation under the demanding conditions (i.e., lower bound) may also be attributed to the increasing vegetable demand over the planning horizon. However, under the advantageous conditions where relative loose restrictions (e.g., upper bound of water availability) are adopted, these additional resources tend to be allocated to wheat and vegetables whilst the corn cultivation would not be changed. For instance, with more resources available, the upper bound of wheat and vegetable cultivation would respectively increase to 2.553 × 10^5 ha and 1.204 × 10^5 ha. This may be due to the relative high benefits generated wheat and vegetable cultivation and thus additional resources would be allocated to these two crops.

In terms of water resource allocation, the results in Table 9 indicate that the surface water and recycled water would be used for agricultural irrigation with deterministic water allocations for these two water resources under both advantageous and demanding conditions. For instance, the water allocation amount from surface water would be 2.495 × 10^8 m^3 for all the five planning periods under the risk scenarios of $p = 0.1, p_1 = 0.035$ and $p_2 = 0.09$, whilst the water allocation amount would reach the lower bound of recycled water availability at each time period. This may be due to the relative lower cost in water supply and water treatment for surface and recycled water. In addition, the remaining irrigation water requirement would be satisfied by the groundwater resource. Specifically, under the advantageous conditions (i.e., the upper bound of the objective function), all groundwater resources (i.e., 5.691 ×10^8 m^3) would be utilized for agricultural production in the studied area. This implies that, under this risk scenario ($p = 0.1, p_1 = 0.035$ and $p_2 = 0.09$), the water availabilities would be a key factor to influence the crop cultivation structures in the studied area.

As indicated in Table 7, there would be different risk levels for groundwater and surface water availabilities that satisfy the overall risk level of 0.1. Under different single risk levels, there are varied water availabilities from surface water and groundwater resources as presented in Table 8. Table 9 and Fig. 4 present the crop cultivation structures at the studied region over the planning horizon under different single risk combinations with an overall risk level of 0.1. It is apparent that different planting schemes, especially for wheat and corn, would be generally obtained from the FICSP-WEFN model with a predefined overall risk of 0.1. This is due to the different combinations of single risk level for surface water and groundwater availabilities under

Table 9
Solutions for planting areas ($\times 10^5$ ha) of different crops and water allocations ($\times 10^8$ m^3) of different resources.

Risk (p, p_1, p_2)	Time period	Wheat	Corn	Vegetables	Surface Water	Groundwater	Recycled Water
(0.1, 0.035, 0.09)	t = 1	[1.889, 2.553]	[1.784, 1.784]	[0.921, 1.204]	[2.495, 2.495]	[2.979, 5.691]	[1.213, 1.213]
	t = 2	[1.889, 2.553]	[1.784, 1.784]	[0.997, 1.204]	[2.495, 2.495]	[2.805, 5.691]	[1.387, 1.387]
	t = 3	[1.889, 2.397]	[1.94, 1.94]	[1.003, 1.204]	[2.495, 2.495]	[2.442, 5.691]	[1.582, 1.582]
	t = 4	[1.889, 2.205]	[2.131, 2.131]	[1.003, 1.204]	[2.495, 2.495]	[2.016, 5.691]	[1.804, 1.804]
	t = 5	[1.899, 2.019]	[2.318, 2.318]	[1.003, 1.204]	[2.495, 2.495]	[1.573, 5.691]	[2.047, 2.047]
(0.1, 0.064, 0.07)	t = 1	[1.993, 2.019]	[2.318, 2.318]	[1.003, 1.204]	[3.874, 3.874]	[1.027, 5.404]	[1.213, 1.213]
	t = 2	[2.071, 2.071]	[2.282, 2.282]	[1.003, 1.188]	[3.874, 3.874]	[0.899, 5.404]	[1.387, 1.387]
	t = 3	[2.193, 2.193]	[2.159, 2.159]	[1.003, 1.188]	[3.874, 3.874]	[0.835, 5.404]	[1.582, 1.582]
	t = 4	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[3.874, 3.874]	[0.621, 5.194]	[1.804, 1.804]
	t = 5	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[3.874, 3.874]	[0.378, 4.951]	[2.047, 2.047]
(0.1, 0.081, 0.05)	t = 1	[2.121, 2.121]	[2.232, 2.232]	[1.003, 1.188]	[4.486, 4.486]	[0.514, 5.046]	[1.213, 1.213]
	t = 2	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.486, 4.486]	[0.425, 4.998]	[1.387, 1.387]
	t = 3	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.486, 4.486]	[0.23, 4.803]	[1.582, 1.582]
	t = 4	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.486, 4.486]	[0.009, 4.582]	[1.804, 1.804]
	t = 5	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.252, 4.486]	[0, 4.339]	[2.047, 2.047]
(0.1, 0.09, 0.035)	t = 1	[2.073, 2.073]	[2.28, 2.28]	[1.003, 1.188]	[4.762, 4.762]	[0.187, 4.693]	[1.213, 1.213]
	t = 2	[2.182, 2.182]	[2.171, 2.171]	[1.003, 1.188]	[4.762, 4.762]	[0.129, 4.693]	[1.387, 1.387]
	t = 3	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.716, 4.762]	[0, 4.527]	[1.582, 1.582]
	t = 4	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.494, 4.762]	[0, 4.305]	[1.804, 1.804]
	t = 5	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.252, 4.762]	[0, 4.063]	[2.047, 2.047]
(0.1, 0.07, 0.064)	t = 1	[2.045, 2.045]	[2.307, 2.307]	[1.003, 1.188]	[4.111, 4.111]	[0.808, 5.3]	[1.213, 1.213]
	t = 2	[2.154, 2.154]	[2.198, 2.198]	[1.003, 1.188]	[4.111, 4.111]	[0.751, 5.3]	[1.387, 1.387]
	t = 3	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.111, 4.111]	[0.605, 5.178]	[1.582, 1.582]
	t = 4	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.111, 4.111]	[0.383, 4.956]	[1.804, 1.804]
	t = 5	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[4.111, 4.111]	[0.141, 4.714]	[2.047, 2.047]
(0.1, 0.05, 0.081)	t = 1	[1.889, 2.129]	[2.208, 2.208]	[1.003, 1.204]	[3.296, 3.296]	[1.723, 5.569]	[1.213, 1.213]
	t = 2	[1.906, 2.019]	[2.318, 2.318]	[1.003, 1.204]	[3.296, 3.296]	[1.431, 5.569]	[1.387, 1.387]
	t = 3	[1.977, 2.019]	[2.318, 2.318]	[1.003, 1.204]	[3.296, 3.296]	[1.236, 5.569]	[1.582, 1.582]
	t = 4	[2.074, 2.074]	[2.279, 2.279]	[1.003, 1.188]	[3.296, 3.296]	[1.063, 5.569]	[1.804, 1.804]
	t = 5	[2.2, 2.2]	[2.153, 2.153]	[1.003, 1.188]	[3.296, 3.296]	[0.956, 5.529]	[2.047, 2.047]

such an overall risk level. For instance, Figs. 4(a) and 4(b) show the crop cultivation patterns where the violation risk for surface water increases from 0.035 to 0.064 and the risk for groundwater decreases from 0.09 to 0.07. The results indicate that the corn cultivation tends to increase under both demanding and advantageous conditions, while the planting area of wheat would keep consistency under demanding conditions but decrease under advantageous conditions over the planning horizon as shown in Fig. 4(a). In comparison, the planting area for corn would slightly decrease in the first four periods with minor increase for wheat cultivation as the same time as shown in Fig. 4(b). The main reason for the differences of cultivation pattern between these two scenarios is due to the different water availabilities in these two scenarios. Similar features presented in Fig. 4(b) can also be observed in Figs. 4(c) – 4(e) where a decreasing trend for corn cultivation would be observed in the former planning periods whilst increase in wheat cultivation may occur at the same time.

The water allocation patterns from different water resources under different risk scenarios are presented in Table 9 and Fig. 5 under advantageous and demanding conditions. The water allocation patterns from different water resources under different risk scenarios are presented in Table 9 and Fig. 5 under advantageous and demanding conditions. Deterministic water supplies are obtained for recycled and surface water resources for all six scenarios except some latter time periods in Scenarios (c) and (d). These results indicate that the surface and recycled water would be utilized for crop production firstly in both demanding and advantageous conditions. In comparison for groundwater, it can be observed that there are significant fluctuation ranges between the lower and upper bounds of groundwater allocation. A decreasing trend for would be generally observed for the lower bounds of groundwater supplies as presented in Fig. 5. Specifically for some risk scenarios (e.g., Figs. 5(c) and 5(d)), the lower bounds of groundwater supply seem to be invisible, which suggests that the water supplies from surface and recycled water can satisfy all water requirements for crop production.

Fig. 6 shows the total system benefits from the WEFN model (i.e., Equations (11) – (16)) under different risk scenarios listed in Table 8. The results indicate that, under a predefined overall system risk, the variations in the single violation levels for surface water or groundwater availabilities would also influence the system benefits from the WEFN model. In general, under the demanding conditions which corresponds to the lower bound of the objective function, the variation trend in the system benefits would be consistent with the total water availabilities from surface water and groundwater. For instance, the lower bound of the system benefit would increase from Scenario (a) (i.e., RMB 7.017 $\times 10^{10}$) to Scenario (c) (i.e., RMB 7.303 $\times 10^{10}$) and then decrease from Scenarios (c) to (f). Correspondingly, the total availability from surface water and groundwater, as presented in Table 8, also shows the same variation trend (i.e., increase from (a) to (c), and then decrease from (c) to (d)) with the trend in the lower bound of the system benefit. This means that, under the demanding conditions, the water availability may be the critical factor that influence the crop planting patterns in the studied area. However, under the advantageous conditions where more water would be available, the system benefit (i.e., upper bound) present a different variation trend from the trend in water availabilities. For instance, the highest system benefit under the advantageous conditions would be obtained at Scenario (a) (i.e., RMB 9.477 $\times 10^{10}$) whilst the availability from surface water and groundwater would be lowest (i.e., 8.186 $\times 10^{8}$ m^3) in this scenario. This implies that, in addition to water availability, the crop cultivation patterns may also be influenced by other restrictions, which can also be concluded from the results in Table 9.

4.3. *Impacts of single and joint risks*

As elaborated in Section 4.2, the variation in single violation risks in surface water and groundwater availabilities would influence the crop planting structures and also the resulting benefits from the WEFN model. However, it is unclear that whether the joint/overall risk level (i.e., p in Eq. (4d)) would also influence the crop planting patterns and how the effects of single and joint risks would pose on the benefits of the WEFN

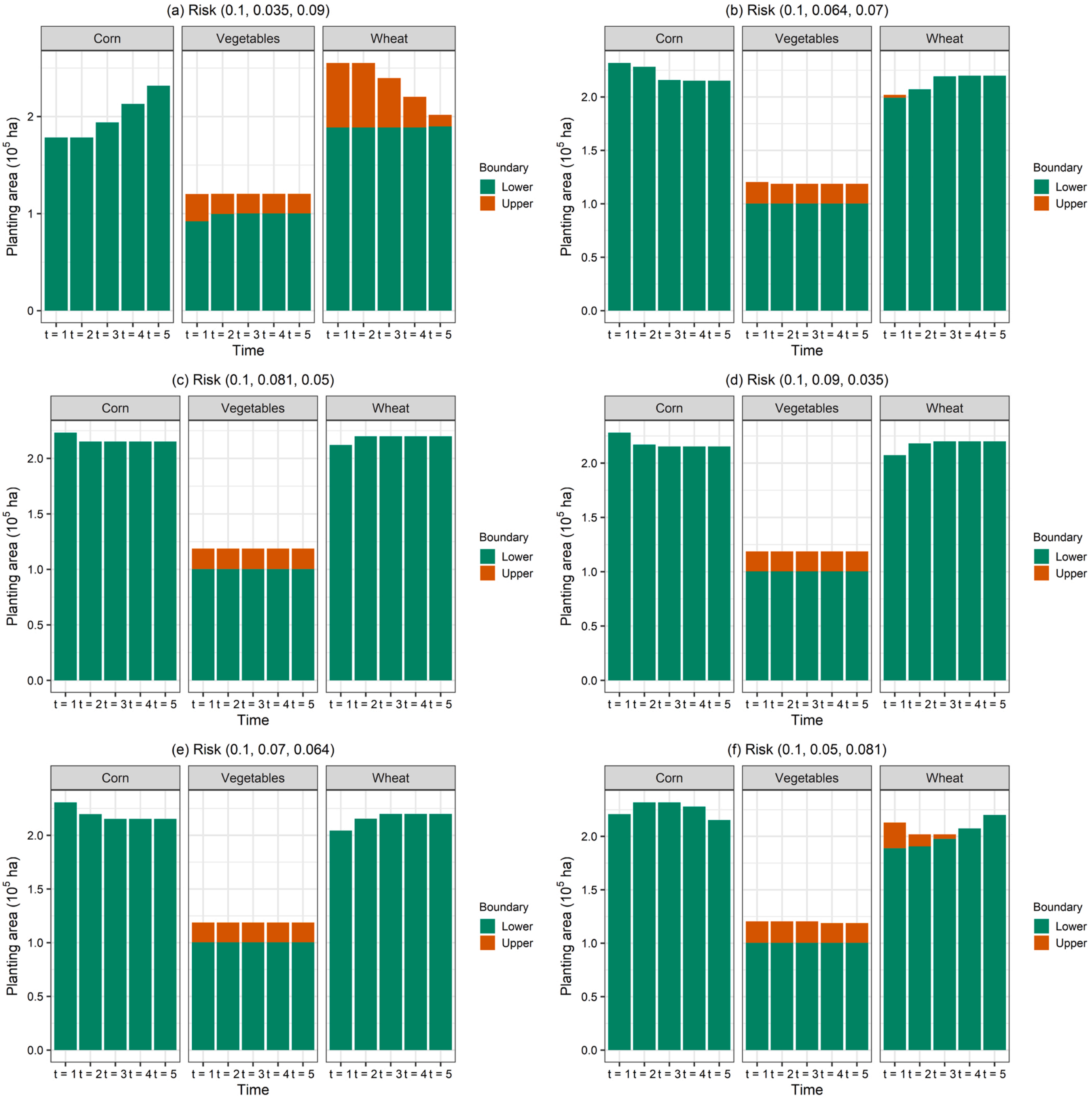

Fig. 4. The crop cultivation patterns under different scenarios for an overall risk of 0.1.

system. To address the above challenges, a factorial analysis was introduced into the FICSP-WEFN model to explore the individual and interactive effects of the single and joint risks. In detail, three levels are assigned respectively to the single and joint violation risks in which the three levels of 0.05, 0.07, 0.09 are given to the single violation risk for either surface water or groundwater availabilities and the three levels of 0.1, 0.12 and 0.14 are set the overall/joint violation risk. Moreover, for the three risk levels (i.e., p_1 for surface water availability, p_2 for groundwater availability, and p for the joint risk level) presented in Eqs. (4b) – (4d), the joint risk level p, as well as one single risk level (p_1 or p_2) can be predefined by decision makers with the other single risk level needs to be derived based on the copula function presented in Eq. (4d). Consequently, two cases would be designed to reveal the effects of single and joint risk levels on the management strategies of WEFN system at the studied region. Case 1 would consider the joint risk (i.e., p) and the risk of groundwater availability (i.e., p_2) as the studied factors whilst Case 2 would include p and p_1 as the studied factors in the factorial analysis. Table 10 present the design matrices for these two cases in the factorial analysis. Moreover, for each case, two responses will be considered, including the lower and upper bounds of the system benefit, which are presented in Table 10. Table 10 also shows the water availabilities from surface and groundwater corresponding to different joint and single risk levels.

Fig. 7 presents the main effect and interaction plots for the single risk level of groundwater availability (i.e., p_2) and the joint risk level (p) on the WEFN system benefits under demanding and advantageous conditions. It is noticed that the single and joint risk levels in Case 1 pose different main and interactive effects on the WEFN system under

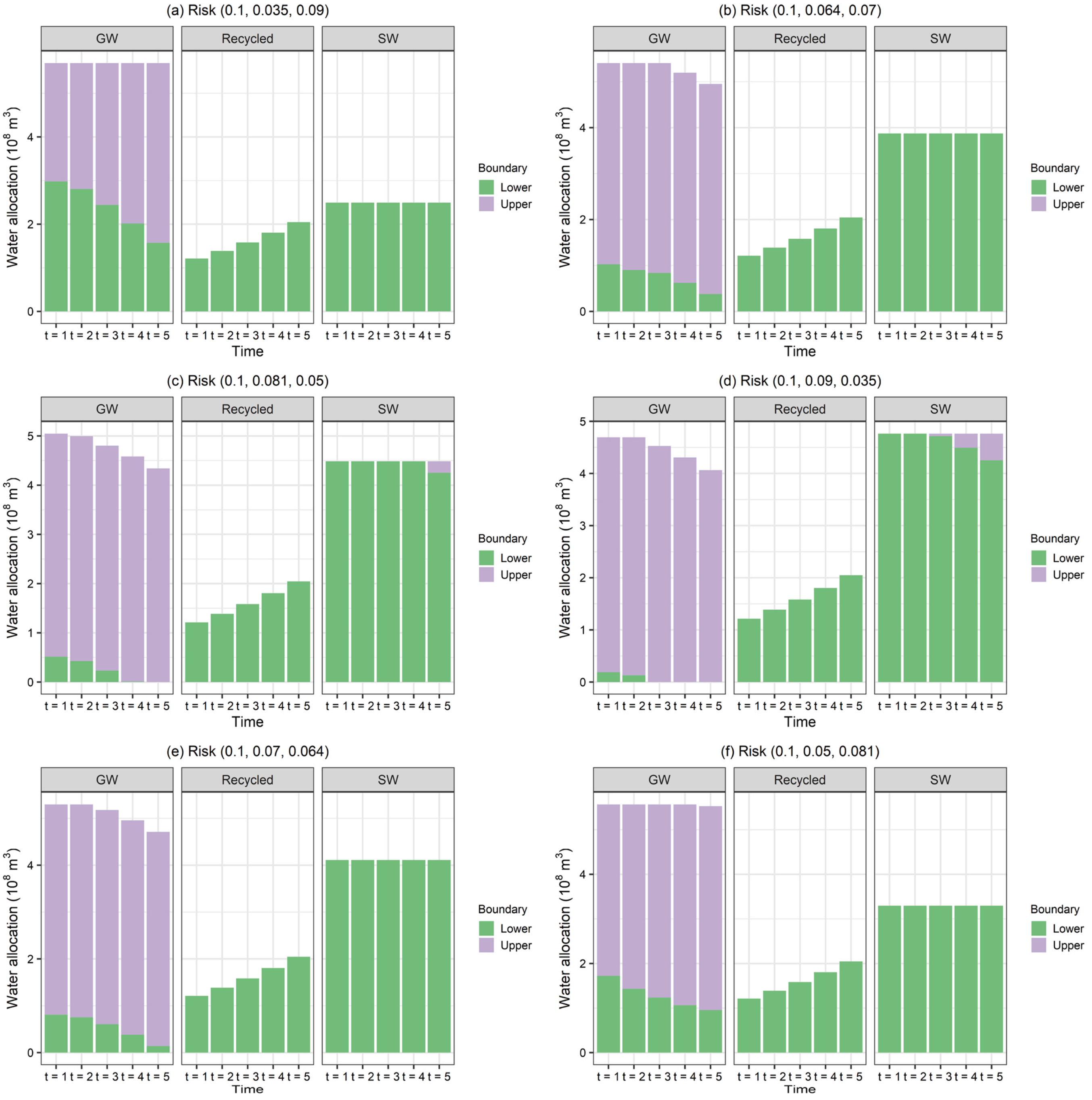

Fig. 5. The water allocation patterns under different scenarios for an overall risk of 0.1.

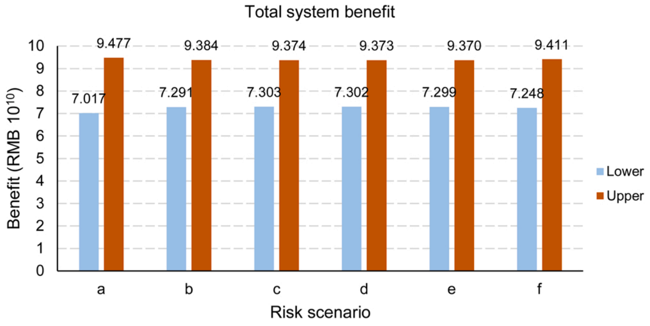

Fig. 6. The total benefit from the WEFN model under different risk scenarios.

advantageous and demanding conditions. More specifically, for the same conditions (e.g., lower bound or upper bound), the main effects from single and joint risk levels present adverse variation trends. For instance, as presented in Fig. 7(a), the system benefit would increase as the joint risk level increase from 0.10 to 0.14 whilst the benefit tends to decrease as the violation risk of groundwater availability increase from 0.05 to 0.09. This may be because that, for the specified joint risk level, the increase in p_2 would lead to decrease in the violation risk for surface water availability and also the total water availability as presented in Scenarios a to c in Table 8. This may finally lead to the decrease in the total system benefit. In comparison, system benefit under the advantageous conditions as presented in Fig. 7(b) would slightly increase with the risk increase of groundwater availability (i.e., p_2) and tend to decrease when the joint risk level increase from 0.10 to 0.12. This

Table 10
The design matrices of factorial analysis for the two cases and the corresponding water availabilities and obtained system benefits.

	Scenarios	p_1	p_2	p	Availability of SW and GW ($\times 10^8$ m^3)	f^- (RMB 10^8)	f^+ (RMB 10^8)
Case 1	1	0.035	0.090	0.100	8.186	7.017	9.477
	2	0.064	0.070	0.100	9.278	7.291	9.384
	3	0.081	0.050	0.100	9.531	7.303	9.374
	4	0.072	0.090	0.120	9.866	7.305	9.376
	5	0.091	0.070	0.120	10.210	7.307	9.377
	6	0.105	0.050	0.120	10.227	7.308	9.377
	7	0.102	0.090	0.140	10.785	7.307	9.377
	8	0.117	0.070	0.140	10.892	7.308	9.377
	9	0.128	0.050	0.140	10.793	7.309	9.377
Case 2	1	0.090	0.035	0.100	9.455	7.302	9.373
	2	0.070	0.064	0.100	9.411	7.299	9.370
	3	0.050	0.081	0.100	8.865	7.248	9.411
	4	0.090	0.072	0.120	10.195	7.306	9.377
	5	0.070	0.091	0.120	9.821	7.305	9.375
	6	0.050	0.105	0.120	9.172	7.282	9.396
	7	0.090	0.102	0.140	10.599	7.306	9.377
	8	0.070	0.117	0.140	10.122	7.305	9.375
	9	0.050	0.128	0.140	9.421	7.297	9.369

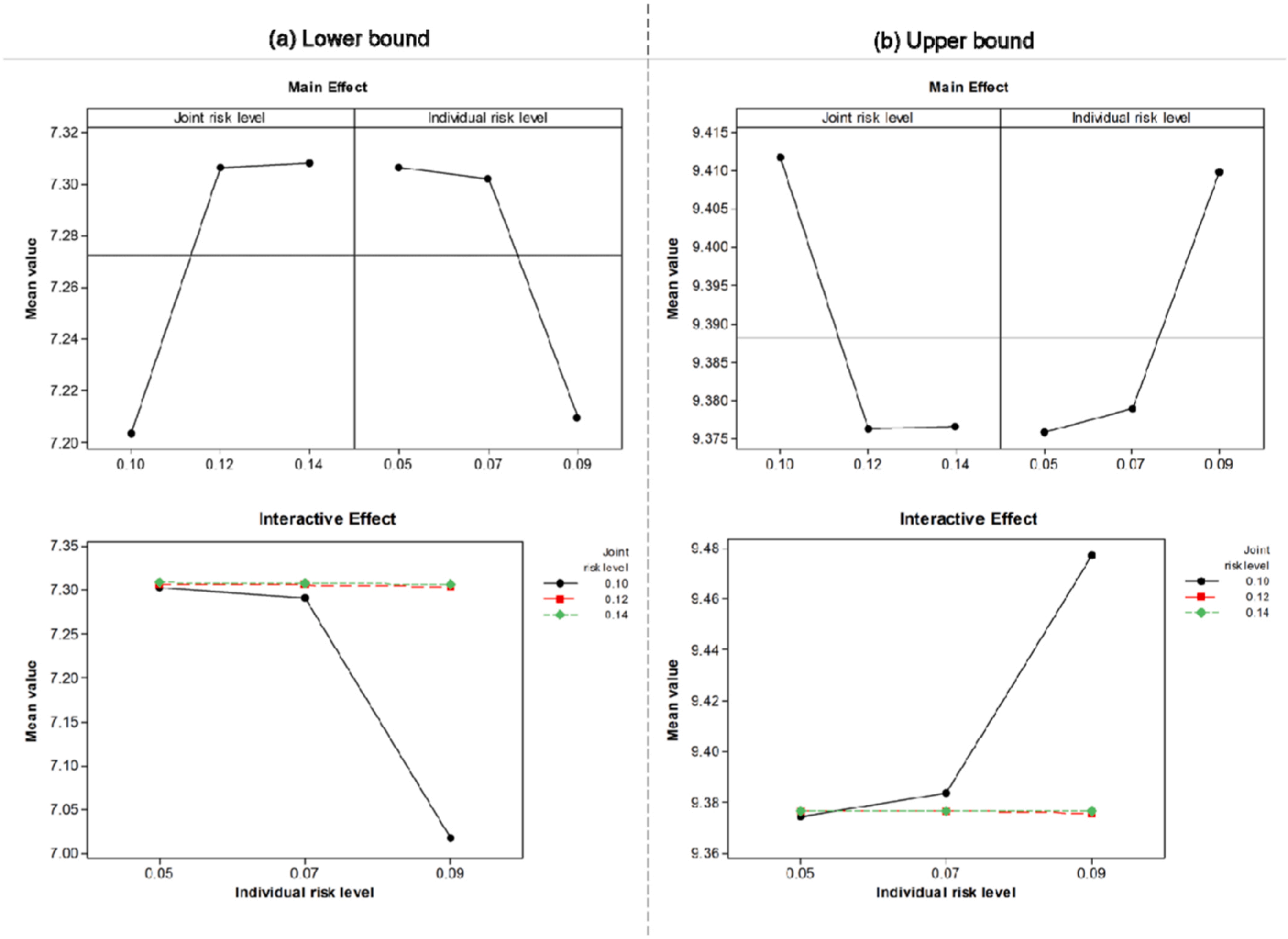

Fig. 7. The main and interactive effects of individual and joint risk levels on the WEFN system for Case 1.

implies that, under the advantageous conditions, the system benefit would not necessarily increase with the increase of the joint risk level, but such a benefit can be increased through increasing the violation risk for the groundwater availability. For the interactive effects between the joint risk level and the violation risk of groundwater availability, the results indicate that there would be significant interactions between p and p_2 when the joint risk p is set to be 0.1. If the joint risk level p increases from 0.12 to 0.14, there seem to be no interactions, as indicated by the parallel interactive curves, between the overall risk and the single risk level of groundwater availability. The main reason for the no interactive effect when $p \geq 0.12$ is that there would be sufficient water availabilities for a high joint risk level in this case. As presented in Table 10, the water availabilities from surface and groundwater would be larger than 9.86×10^8 m^3 when the joint risk level $p \geq 0.12$ while the maximum water availability under $p = 0.10$ is about 9.53×10^8 m^3. This implies that the WEFN system would be mainly influenced by other factors rather than the water availabilities for a joint risk level higher than 0.12, which is also demonstrated by the system benefits presented in Table 10.

For Case 2 where the joint risk level (i.e., p) and the risk of surface water availability (i.e., p_1) are addressed, Fig. 8 shows the man and interactive effects of these two factors under demanding and advantageous conditions. For the demanding conditions as presented in Fig. 8 (a), the increases in both p and p_1 would lead to an increasing trend for the lower bound benefit of the WEFN system and also the interactive curves are observed to be intersected at the three levels especially for p_1 increasing from 0.05 to 0.07, implying significant interactive effects of these two risk levels on the resulting lower bound benefit. These results may be because that the demanding conditions correspond to relative strict restrictions in which the water availability is one of the major factors affecting the crop planting structures. For a specified p_1, the increases in p would lead to increasing water availabilities (see Table 10) and thus generate increased system benefits. Under the advantageous conditions where relative loose restrictions are adopted, the main and interactive effects of p and p_1 present different features from their effects on the system benefit under the demanding conditions. As presented in Fig. 8(b), the main effect of the joint risk level (i.e., p) suggest that the upper bound of the system benefit tends to decrease with the increase in p whilst the benefit of the WEFN system would decrease for p_1 increasing from 0.05 to 0.07 and then increase for p_1 increasing from 0.07 to 0.09. For the interaction between p and p_1, the interactive curves indicate that p and p_1 would have significant interactions on the upper bound of WEFN system benefit. In detail, the upper bound benefit would decrease with increasing p_1 from 0.05 to 0.07 and then slightly increase with increasing p_1 from 0.07 to 0.09 at $p = 0.10$ and 0.12. In comparison, at $p = 0.14$, the upper bound benefit shows a slightly increasing trend with the increase in the risk level of surface water availability.

In summary, the results of the multilevel factorial analysis suggest that the lower bound of the WEFN system benefit would increase with the increase of water resource availability. Moreover, the water availability can be increased through increasing the joint/overall violation risk or the violation risk of surface water availability. Also, the risk decrease in groundwater availability can also lead to increasing total water availability and thus generate increasing system benefit under the demanding conditions. In comparison, for the upper bound of the WEFN system benefit corresponding relative loose restrictions, increasing the violation risks would not necessarily lead to increased system benefit. Specifically, the increase in the joint risk level may even lead to decreased system benefit for the advantageous conditions. This may be because that there would be sufficient or even excessive water resources for irrigation requirement under the advantageous conditions and thus the WEFN system benefit may be significantly influenced by other factors.

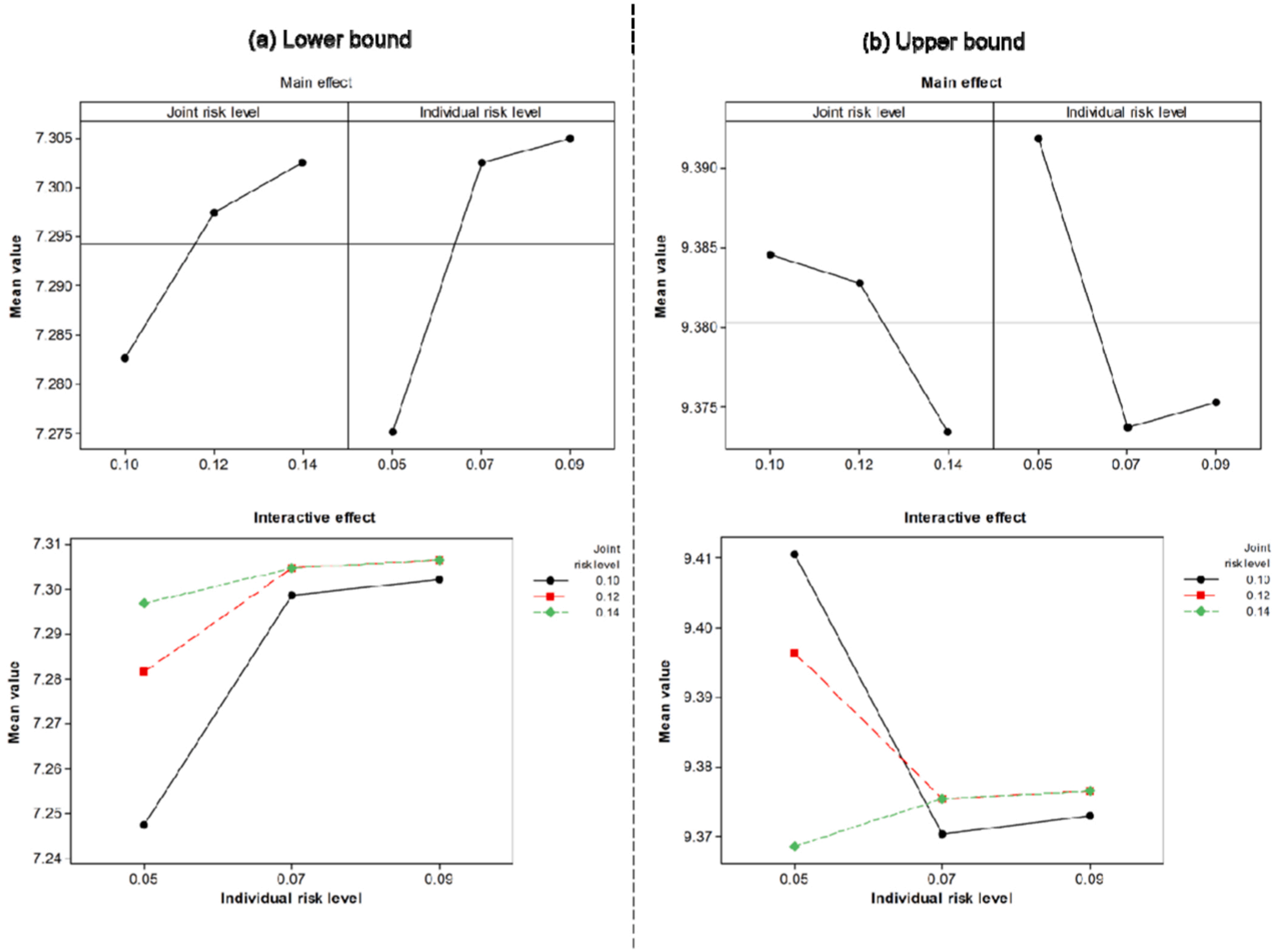

Fig. 8. The main and interactive effects of individual and joint risk levels on the WEFN system for Case 2.

5. Conclusions

In this study, a factorial inexact copula stochastic programming (FICSP) method has been developed to generate management strategies for the complex water-energy-food nexus (WEFN) system. A FICSP-WEFN model has been formulated for planning farming practices, in which the randomness of surface water and groundwater availabilities and their interdependence would be reflected through the copula method. Solutions of the planting areas for different crops within different periods can be generated through the model subject to various management requirements and different risk levels. Moreover, the factorial analysis in FICSP would be further used to investigate the main and interactive effects of the single and joint risk levels on the WEFN management strategies. The developed FICSP approach was applied for the management of water-energy-food nexus system for the City of Jinan at Shandong Province.

The obtained results indicated that the surface water and groundwater availabilities were highly correlated. Different marginal distributions and copula functions were adopted to model their probabilistic features and interdependence, in which the Gaussian distribution would perform best in reflecting the univariate randomness and the Gaussian copula performed best in describing their dependence structure. Due to the interdependence among surface water and groundwater availabilities, a joint violation risk on total water availability would lead to infinite combinations of single violation risk for surface or ground water availabilities and thus lead to different amounts of total water resources which would further lead to varied planting structures.

For the overall risk level of 0.1, six scenarios on the risk levels of surface water and groundwater availabilities were analyzed, which led to the total water resources ranging within $[8.186, 9.531] \times 10^8$ m^3. If limited water resources are available (e.g., the demanding conditions under $p = 0.1$, $p_1 = 0.035$ and $p_2 = 0.09$), the corn would be prioritized in the planting structure to satisfy the cereal demand from local population, and the increasing cereal demand over the planning horizon would also be satisfied by the increasing planting areas of corn. In comparison, when sufficient water is available under the advantageous conditions, those excessive water resources tend to be allocated to wheat and vegetables whilst the planting area of corn would not be changed. Moreover, the increase of water availability resulting from adjustment of single risk levels would increase the wheat planting whilst decrease the planting areas for corn.

For the scheme on water resource allocation, the surface and recycled water would generally be utilized for crop production first. Under the selected six scenarios for an overall risk of 0.1, all surface and recycled water would be utilized for crop irrigation under both demanding and advantageous conditions, with the remaining irrigation water needs being satisfied by the groundwater. The lower bound of the WEFN system benefit showed the same variation trend with the water availabilities under different combinations of single risk levels, implying the critical role of water availability in planning crop cultivation patterns under the demanding conditions. In comparison, under the advantageous conditions where sufficient water is available, the crop cultivation patterns would be influenced by other restrictions and thus the upper bound of WEFN system benefit showed a different variation trend with the water availabilities.

The factorial analysis included in FICSP have been further adopted to reveal the main and interactive effects of single and joint risk levels on WEFN system management under both demanding and advantageous conditions. The obtained results indicated that, under demanding conditions, the lower bound of the WEFN system benefit would tend to increase with (i) the increase in the joint/overall violation risk (especially from 0.10 to 0.12), (ii) the increase in the violation risk of surface water availability (especially from 0.05 to 0.07), or (ii) the decrease in the violation risk of groundwater availability (especially from 0.09 to 0.07). In comparison, the increase in the violation risks under the advantageous conditions would not necessarily lead to increased system benefit, and even cause decreased system benefits for the increasing joint risk level.

The FICSP approach is able to deal with various uncertainties in the WEFN system presented as random and interval variables, in which the copula method is adopted in FICSP to reflect complex interdependence among correlated random variables. The copula-based joint chance constraints have been widely adopted to deal with dependent randomness in water and environmental systems. As demonstrated in Kong et al. (2018), the inexact copula-based stochastic programming (ICSP) method can well reflect dependence including nonlinear dependence between random variables, while in comparison, traditional joint chance-constraint method can only estimate joint probability through a linear approach, weakening the interactions among random variables. In this study, the detailed procedures on converting the copula-based joint chance constraints into deterministic constraints were elaborated, making the ICSP method to be more understandable for real applications. Moreover, the factorial analysis has been introduced into FICSP to investigate the main and interactive effects from different risk levels on the WEFN system management. The developed FICSP method cannot only generate desired management strategies for WEFN system under consideration of joint risks, but also help track the factors that make dominant impacts on the WEFN management practices.

The proposed FICSP method has been used for WEFN management. However, some issues still need to be further addressed. Firstly, the energy issues in the developed WEFN model are limited in which the energy usage in agricultural production is considered. Moreover, the future surface and ground water availabilities considered in the WEFN model are random in future with their probabilistic distributions estimated by historical data. This implies that the future water availabilities are stationary when compared to historical measurements. However, such an assumption has not been demonstrated, especially under climate change. Consequently, more research works are required to develop the WEFN model to include full nexus among water, energy and food systems, and also project the surface and groundwater availabilities under climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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