Journal of Environmental Informatics Letters 9(1) 49-59 (2023)

Journal of Environmental Informatics Letters

www.iseis.org/jeil

Interval Multi-Random Factorial Programming for Coupled Farmland and Water Resources Management -- A Case Study of Songhua River Watershed, China

N. Wang[1], C. Z. Huang[2 *], M. Y. Zhai[3], G. H. Cheng[4], F. Wang[5], L. J. Lin[6], and B. Luo[7]

[1] *College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, 712100, China*
[2] *Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta T6G2R3, Canada*
[3] *Institute of Circular Economy, Beijing University of Technology, Beijing 100124, China*
[4] *Guangdong Provincial Key Laboratory of Water Quality Improvement and Ecological Restoration for Watersheds, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, 510006, China*
[5] *State Key Joint Laboratory of Environmental Simulation and Pollution Control, China-Canada Center for Energy, Environment and Ecology Research, UR-BNU, School of Environment, Beijing Normal University, Beijing 100875, China*
[6] *School of Chemical Engineering, Fuzhou University, Fuzhou, 350108, China*
[7] *Institute for Energy, Environment and Sustainability Research, UR-NCEPU, North China Electric Power University, Beijing 102206, China*

Received 15 January 2023; revised 25 February 2023; accepted 14 March 2023; published online 28 March 2023

ABSTRACT. The Songhua River Watershed (SHRW) in China has been challenged by water shortages, water pollution, water leakage, and soil erosion in recent years. In the next few decades, these problems will continue to exist and even worsen, threatening the quality of the regional ecological environment and socio-economic development. These issues must be alleviated through coupled farmland and water resources management (CFWRM) but are challenged by multiple system complexities. To fill this gap, this study developed an Interval Multi-Random Factorial Programming (IMRFP) to eliminate potential problems in SHRW and improve the reliability of the decision support process. A series of systematic CFWRM measures were applied to promote the harmonious SHRW ecological environment and social economy. For example, due to the significant contribution of agriculture to the regional economy, planting should always be a priority. As a major commercial crop, rice cultivation should be allocated the most irrigation water, followed by corn, potatoes, and soybeans. Therefore, after fully balancing the trade-off between the environment and the economy, policymakers should adopt the most reasonable proposals. Various support policies are needed to fully implement these measures in SHRW. For example, it is suggested to improve and update the construction of the water supply network in the SHRW area and appropriately change taxes and prices to follow the overall crop planting plan. The modeling solution shows that the IMRFP method can systematically optimize the allocation of water resources and farming patterns so that water shortage, water pollution, water leakage, and soil erosion in the SHRW can be alleviated.

Keywords: water resources management, Songhua River Watershed, factorial design

1. Introduction

The imbalance between the supply and the demand of global water resources is becoming increasingly severe with the rapid growth of population and social development. For instance, the primary water user in sub-Saharan Africa is agriculture, and the region's fast-expanding population is driving up food demand and water scarcity. Indeed, water resources management has already become a critical constraint for sustainable development in many areas. Songhua River Watershed (SHRW) is a significant open system in China, which consists of many components (e.g., resource availability, allocation, and policy), processes (e.g., technology utilization, hydrological processes, and pollutant transport) and external factors (e.g., social, economic, and natural conditions). Over the past decades, some pollutants from human activities and soil erosion have been discharged into the Songhua River due to unreasonable industrial structure. Generally, it is a massive challenge for local governments and stakeholders to determine reasonable allocation schemes of farmland and water resources. Such a program has led to limited water resources and land use, further aggravating pollution, leakage in the water supply system, and soil erosion. It is critically necessary to implement a trustworthy and effective management strategy to coordinate the interests of different stakeholders and mitigate potential issues, which can promote social and economic development without impairing the quality of the ecological environment under the complexity of numerous systems. These issues, related factors, and parameters involve multiple forms of uncertainty, leading to various complications in the relevant decision-making process.

Previously, a few researches about the optimal scheme were undertaken to support coupled farmland and water resources management (CFWRM) (Liu et al., 2007; Li et al., 2008; Zhang et al., 2012; Yang et al., 2015; Yu et al., 2016,

* Corresponding author. Tel.: 1-778-858-0870.
E-mail address: charleyhuang33@gmail.com (C. Z. Huang).

ISSN: 2663-6859 print/2663-6867 online
 doi:10.3808/jeil.202300099

Figure 1. Location of the Songhua River Watershed.

Dong et al., 2018). For instance, Zhang et al. (2012) recommended allocating water resources for hydropower projects using a multi-objective planning approach. An integrated interval-fuzzy optimization model was put up by Dong et al. (2018) to support the water allocation plan and policy recommendations in SHRW. Yu et al. (2016) created a deterministic linear programming model to optimize total water pollutant emissions distributions. Liu et al. (2007) and Li et al. (2008) suggested potential solutions for mitigating organic pollution based on qualitative evaluations from the perspective of managing water quality. The CFWRM is hampered by the coexistence of dual uncertainties in water-related activities in the global water resources system, challenging the viability and efficacy of existing alternative water resources management techniques (e.g., Richter et al., 2003; Hajkowicz and Collins, 2007; Singh, 2014; Albert et al., 2016; Dyckman, 2016; Turner et al., 2016; Serrao-Neumann et al., 2017; Dong et al., 2018; Luo et al., 2020). The absence of systemic analysis, administration, and coordination of the CFWRM system, as well as the CFWRM measurements themselves, is the fundamental problem with CFWRM.

However, no study was conducted to guide the integrated management considering water quantity, water quality, water price change, leakage in the water supply system, soil erosion, and farmland use in the CFWRM system from a comprehensive perspective. Besides, these impact factors may generate a variety of interactive effects, and such effects can hardly be directly reflected by conventional optimization models. There fore, the development of a more robust approach to reflect such complexities is desired.

As an extension of the previous research, the objective of this study is to present an Interval Multi-Random Factorial Programming (IMRFP) model for optimization of the CFWRM scheme and applied to SHRW. A chance-constrained programming, interval linear programming, and factorial design are integrated into IMRFP to deal with the random and interval uncertainties in the CFWRM system, respectively. IMRFP can provide scientific support for CFWRM with water allocation, water contamination, water price change, farmland use, leakage in the water supply network, and soil erosion from a comprehensive perspective. It is also expected to provide a robust CFWRM optimization framework for regions with similar irrigation and unreasonable industrial patterns to SHRW. In detail, the objective entails: (i) identifying the impact factors, structure, components, and their interactions within the SHRW-CFWRM system; (ii) parameterizing multiple uncertainties in the SHRW-CFWRM system; (iii) constructing an IMRFP model based on the real-world issues in SHRW; (iv) offering decision support, particularly with regard to allocation plans for the use of farmland and water resources.

2. Complexities of Agricultural Water Resources System in the Songhua River Watershed

2.1. Songhua River Watershed

SHRW is the largest basin in Northeast China (Figure 1). It mainly passes through Inner Mongolia, Jilin, and Heilongjiang Provinces, accounting for 28, 24, and 48% of the total basin area. SHRW has a well-developed river system with numerous tributaries. There are 86 rivers with an area larger than 1000 km^2 and 16 with a size larger than 10000 km^2. The administrative region covers 24 cities and 84 counties in Northeast China. The Nen River and the Second Songhua River, which come from the Changbai Mountains, combine to form the Songhua River. SHRW follows the Yangtze River and the

Yellow River for a distance of 2308 km, spanning a sizable area of 55.7104 km^2 (Lei et al., 2008). The Songhua River has an average annual water availability of 88.0 billion m^3, of which 11.7 billion m^3 is groundwater and 73.5 billion m^3 is surface water. A wide range of pertinent observation data sets, government reports, scholarly works, and statistics yearbooks were gathered to compile this study. SHRW system boundaries and their composition, structure, complexity, and potential issues are thoroughly identified based on these data.

2.2. Problems of the SHRW-CFWRM

The pressure on SHRW's water resources, which has been increasing in recent years, is mainly caused by inappropriate industrial structure, rapid economic growth, and ineffective related technologies (Li et al., 2009). SHRW is also more vulnerable to outside perturbations because it contains one of the largest concentrations of the wetland due to infrequent precipitation and low evaporation. Moreover, agricultural non- point pollutants such as total nitrogen and phosphorus, toxins from home, and industrial wastes have severely damaged the water body and wetland (Zhang et al., 2012; Xu et al., 2014). In SHRW, subsequent excessive reclamation causes significant soil erosion over time to meet rising food demand. The depth and nutrients of the soil have been further diminished by soil erosion, and some agricultural areas have been lost. In 2013, there was 71.47 billion m^2 of soil erosion (Miao et al., 2011). Many wastewater treatment facilities were built in the previous decades as part of ongoing attempts to improve water quality. However, existing facilities cannot meet the present needs due to rising wastewater production from home and industrial uses some of which may be immediately released into rivers. The contaminated body of water intensifies the water deficit problem while risking human and ecological health.

The disparity between the availability and demand for water resources is getting more apparent. The distribution of water resources in SHRW is more in the East and less in the West, more in the North and less in the South, and more on edge and less in the hinterland, which is inconsistent with the distribution of productivity. Without considering the water quality shortage, the average water shortage for many years is close to 5 billion m^3, mainly manifested in inadequate water supply for agricultural irrigation, low water supply guarantee degree in the basin, and lack of water storage projects. The water supply capacity of current water storage projects only accounts for 21% of the surface water supply capacity. At the same time, people's water saving consciousness is not that strong, and water utilization efficiency is low.

The water resources in the Songhua River Basin have become a critical problem that needs to be solved urgently. Therefore, the decision-makers should vigorously reform the production structure and mode, try to improve the utilization rate of water, and develop water-saving users. The comprehensive development and utilization of water resources should consider economic, social, and environmental benefits. In planning water resource allocation, priority should be given to people's livelihood, urban and industrial water use, and the need for agricultural production and comprehensive utilization in all aspects should also be fully considered.

2.3. Interval Multi-Random Factorial Programming

To quantify the coupled farmland and water resources management (CFWRM) in SHRW, an Interval Multi-Random Factorial Programming (IMRFP) model is created using an efficient parameterization technique according to the system mentioned above identification. The parameterization approach can be represented as a group of connected operations. IMRFP will parameterize and optimize the decision variables for the various CFWRM activities, such as irrigation patterns and alternative water distribution. The objective function of the IMRFP model is to translate the decision-desire makers into the CFWRM system in SHRW. Constraints of the IMRFP are expressed as a range of resource/technical restrictions or mass-balancing relationships that may conflict with one another.

In modeling research, it is standard procedure to compare modeling results to actual observations to assess the validity of a model that has been built. This study uses an IMRFP model with coarse temporal and geographical resolutions and a medium planning period duration to simulate the CFWRM system in SHRW. Regarding influencing factors like water availability and demand, which may nevertheless gradually change even at coarse temporal or geographical resolutions, it is reasonable to determine their status in each planning period through trend analysis.

The IMRFP is built based on the system parameterization results. Crop cultivation areas, water allocation amounts to end-users, and distribution of groundwater and surface water resources to the three provinces of Inner Mongolia, Jilin, and Heilongjiang, make up the decision variables in this model that correspond to the alternative CFWRM measures. Nearly all CFWRM challenges conclude that these measurements are connected to complex tradeoffs between CFWRM system components in temporal and spatial dimensions.

In the presence of these tradeoffs, the IMRFP's objective function is to maximize the net economic gain, which is represented as the linear sum of the difference between each CFWRM activity's benefit and cost. The limits are reflected in the other possible objectives, such as controlling soil erosion and water quality. This is because municipal governments have passed laws governing soil erosion and pollutant emissions. Only the most significant net economic gain is anticipated by the CFWRM system's governors in SHRW, who also ensure these rules are followed. Over SHRW, it is expected that there will be an equal distribution of agriculture and water resources. This model incorporates capacities for wastewater treatment. Appropriate soil erosion and pollution control (such as nitrogen and phosphorus discharge) are carried out by environmental standards for the water bodies. The 15-year planning period of the IMRFP model is further broken into three parts (2020 to 2024, 2025 to 2029, and 2030 to 2034). The following section and Supporting Information (SI) show the detailed IMRFP model, parameter definition, solution algorithm, and some relevant inputs.

3. Development of the Interval Multi-Random Factorial Programming

This section describes the investigated IMRFP model. The general procedure is schematized in Figure 2, and details are provided in the following subsections.

3.1. Chance-Constrained Programming

The following is a general formulation of a stochastic linear programming (SLP) problem (Cheng et al., 2009):

$$Min C(\omega) X \tag{1}$$

subject to:

$$A(\omega) \le B(\omega) \tag{2}$$

$$x_j \ge 0, x_j \in X, j = 1,\ 2,\ ...,\ n \tag{3}$$

where X is a vector of decision variables, and $A(x)$, $B(x)$, and $C(x)$ are sets with random elements. An "equivalent" deterministic version of this model can be defined and solved. The chance-constrained programming (CCP) strategy, which sets a specific level of probability ($p_i \in [0, 1]$) for each constraint and assumes a condition that the i_{th} constraint is satisfied with at least a probability of $1 - p_i$, can be used to achieve this. The following limitations can be placed on the set of possible solutions (Charnes et al., 1959):

$$\Pr\left[A_i(\omega) \le b_i(\omega)\right] \ge 1 - p_i,\ A_i(\omega) \in A(\omega)\ i = 1,\ 2,\ ...,\ m \tag{4}$$

The set of viable constraints may get more difficult if A and B are both random variables. Particularly, if a_{ij} and b_i are normally distributed with known means and variances:

$$a_{ij}(\omega) \sim N\left(a_{ij},\ \sigma^2_{a_{ij}(\omega)}\right) \tag{5}$$

$$b_i(\omega) \sim N\left(b_i,\ \sigma^2_{b_i(\omega)}\right) \tag{6}$$

$$\sigma a_{ij}(\omega),\ \sigma b_i(\omega) \in \{t \mid t \in R,\ t \ge 0\} \tag{7}$$

where $a_{i1}(\omega)$, $a_{i2}(\omega)$, …, $a_{ij}(\omega)$, $b_i(\omega)$ are independent upon each other. The following deterministic nonlinear inequality might therefore be created from constraint:

$$\sum_{j=1}^{n} a_{ij} x_{ij} - \Phi^{-1}(p_i)\sqrt{\sigma^2_{b_i(\omega)} + \sum_{j=1}^{n} x_{ij}^2 \sigma^2_{a_{ij}(\omega)} \le b_i}, \forall i \tag{8}$$

where $\phi^{-1}(t)$ is the cumulative distribution function of the typical normally distributed random variables' inverse function. $\sigma_{aij}(\omega)$ is the standard deviation of $a_{ij}(\omega)$, $\sigma_{bi}(\omega)$ is the standard deviation of $b_i(\omega)$. $P_i \in [0, 1]$ means an admissible risk of violating an uncertain constraint i. An uncertain constraint i must be satisfied with a probability level of at least $1 - p_i$. An increased probability level (p_i) translates into a relaxed constraint and, consequently, a higher risk of violating the system constraint. If the p_i level is set too high, there is a greater chance that the system will fail.

A simple mathematical inequality is as follows:

$$\sqrt{\sum_{i=1}^{r}\left(a_i^2\right)} \le \sum_{i=1}^{r} a_i,\ a_i \in \{a \mid a \in R,\ a \ge 0\} \tag{9}$$

Then, according to Ağpak and Gökçen (2007), constraint could be converted into a linear format as follows:

$$\sum_{j=1}^{n}\left[a_{ij} - \Phi^{-1}(p_i)\sigma_{a_{ij}(\omega)}\right] x_{ij} \le b_i + \Phi^{-1}(p_i)\sigma_{b_i(\omega)}, \forall i \tag{10}$$

Based on the aforementioned justifications, the model restrictions could be converted into a "equivalent" deterministic linear format that can be handled by the current programming methodology (simplex method). In this study, two p_i values were determined, $p_i = 0.01$ and $p_i = 0.1$ respectively. An alternate way for undertaking risk analysis in water management is the CCP method. Policy makers may find the information on the trade-offs between the value of the objective function, the tolerance values of the constraint, and the required level of probability useful.

3.2. Interval Linear Programming

The properties of interval uncertainties can be expressed as interval sets (Huang et al., 1992) that are defined as closed and bounded sets of real numbers. One representative characteristic is that the distributional information is unknown for any real number in interval sets. Reflection of these properties in other forms, e.g., real numbers, random variables, fuzzy sets or their combinations would decrease the robustness of the constructed programming model (Dong et al., 2014). Simplification of interval sets into constants may lead to loss of valuable information. Coefficients in both the objective function and constraints of interval linear programming (ILP) models can be interval sets. It is of low reliability that a deterministic solution is provided under interval uncertainties. The solution can hardly reflect the trade-off between system optimality and constraint-violation risks. A solution which is a set of interval sets is desired for ILP problems. Accordingly, a generalized ILP model is an LP model where both coefficients and decision variables are interval sets. The first generalized ILP model is proposed by Huang et al. (1992) based on the interval analysis. An ILP model can be formulated as:

$$Max f^{\pm} = C^{\pm} X^{\pm} \tag{11}$$

where $X^{\pm} = \{x_j^{\pm}\}^{n \times 1}$, $C = \{c_j\}^{1 \times n}$, $A = \{a_{ij}\}^{m \times n}$, $b = \{b_i\}^{m \times 1}$; n and m are numbers of decision variables $\{x_j\}$ and constraints, respectively; for any $i \in \{1, 2, \ldots, m\}$ and $j \in \{1, 2, \ldots, n\}$, coefficients c_j, a_{ij} and b_i are interval sets of which values range from a real-valued lower bound to a real-valued upper bound without

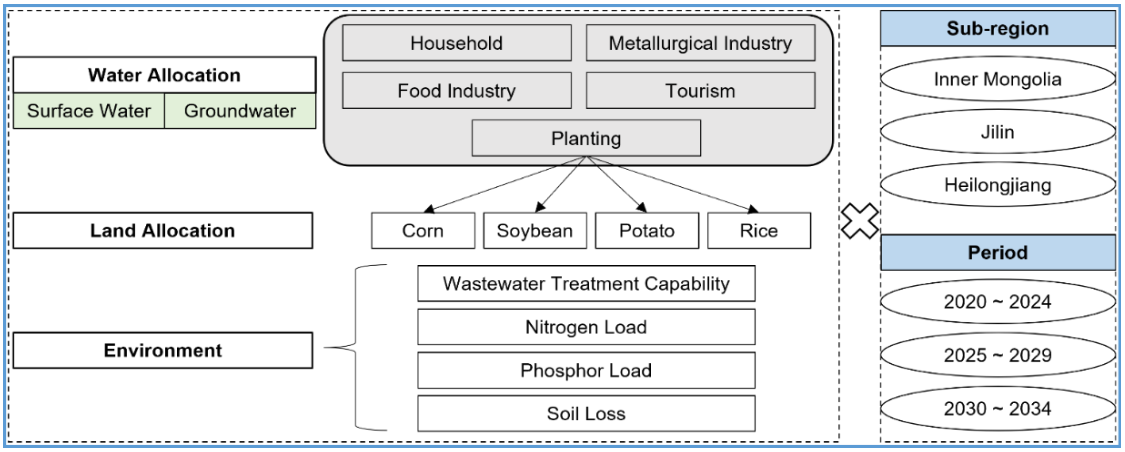

Figure 2. The framework of Interval Multi-Random Factorial Programming (IMRFP).

distribution information (Huang et al., 1992); the lower and upper bounds of interval sets are denoted as symbols "$^-$"and "$^+$", respectively; decision variables $\{x_j^\pm \mid j = 1, 2, \ldots, n\}$ as well as the objective function value ($F^\pm$) are also interval sets due to interval uncertainties of coefficients.

In order to further reduce the impact of uncertainties in the model, an Interval Multi-Random Factorial Programming (IMRFP) was constructed to deal with the random and interval uncertainties in SHRW-CFWRM system.

3.3. Factorial Analysis

The model's multiple uncertainties make it challenging to design the best water allocation techniques for SHRW. The numerous economic and environmental factors that contribute to these uncertainties can have a big impact on how the system reacts. Therefore, it is crucial to highlight any potential links between a range of uncertain characteristics and their effects on system performance (Box et al., 1978).

Generally, the 2^n factorial design, which calls for all combinations of two levels of each n variable, is the simplest form of factorial analysis. If a variable is continuous, its high and low values are represented by its two levels; if a variable is qualitative, its presence and absence are represented by its two levels. A complete 2^n design would include $2n$ - 1 effects, which are made up of n main effects, two-factor interactions, three-factor interactions, and one n factor interaction. n represents the main effects, $n(n\text{-}1)/2$ represents two-factor interaction effects, $n(n\text{-}1)(n\text{-}2)/(2\cdot 3)$ represents three-factor interaction effects, and $n(n\text{-}1)(n\text{-}2)\ldots, n(n\text{-}m\text{-}1)/m!$ represents m factors' interactive effects (Qu and Wu 2005).

In this study, a two level, five factors factorial design was constructed to reveal the interaction among water price change, leakage of water supply networks, surface water utilization, groundwater utilization and p_i value. Based on the collected data in the past few years in SHRW, 32 scenarios were designed by five factors and two levels (2^5) respectively, the specific design level is presented in Table 1.

As a result, numerous pertinent official papers, scholarly works, statistics yearbooks, and other information are exhaustively gathered to help set the factors and levels. In this study, 13 kinds of responses are selected, these are: optimal system benefits; profits of water usage; cost of water usage; pollutant from users; wastewater amount from user; wastewater treatment cost; pollutant emission; cost of water irrigation; profits of crops cultivation; pollutant from cultivation; soil loss from irrigation; coefficients of water allocation for four users and coefficients of water allocation for irrigation.

Table 1. Scenario Design of Factorial Design

Factor	Level	Coefficient
Water Price Change	1	120%
	2	150%
Leakage of Water Supply Networks	1	20%
	2	15%
Surface Water Utilization	1	68%
	2	72%
Groundwater Utilization	1	75%
	2	80%
p_i	1	0.01
	2	0.1

4. Results Analysis

This section presents the optimal CFWRM scheme's ranges in SHRW. These ranges assist in producing various decision possibilities for decision-makers under the diversity and uncertainty of system components. The upper/lower bounds of net system benefits correspond to two extreme CFWRM schemes in terms of the trade-off between economic growth and environmental development. The multidimensional comparisons of the best methods reveal a number of consequences.

4.1. Cultivation Schemes of SHRW

Table 2 shows the areas used for four crops grown in three regions throughout periods 1 and 3. The most significant area for crop production is in Heilongjiang, followed by Inner Mongolia and Jilin. The most widely grown commercial crop is rice

Table 2. Cultivated Area (km^2) and Water Allocated to Irrigations (million m^3) in Three Provinces

	Province	Crop	Period t = 1	t = 2	t = 3
Cultivated Area	Inner Mongolia	Corn	[18175.60, 19283.85]	[18095.80, 18942.80]	[10283.10, 10283.10]
		Soybean	[10566.45, 10566.45]	[10431.45, 10431.45]	[10283.10, 10283.10]
		Potato	[10566.45, 10566.45]	[10431.45, 10431.45]	[17595.00, 18809.95]
		Rice	[32161.50, 33068.25]	[31875.30, 32568.30]	[31222.80, 32216.85]
	Jilin	Corn	[14346.30, 15434.75]	[13613.40, 14862.45]	[7646.25, 7646.25]
		Soybean	[8048.10, 8048.10]	[7898.10, 7898.10]	[7646.25, 7646.25]
		Potato	[8048.10, 8048.10]	[7898.10, 7898.10]	[13216.20, 13993.35]
		Rice	[24907.50, 25798.05]	[24062.40, 25084.35]	[23325.30, 23961.15]
	Heilongjiang	Corn	[35168.80, 39867.45]	[13449.75, 13449.75]	[11964.75, 11964.75]
		Soybean	[14948.10, 14948.10]	[13449.75, 13449.75]	[11964.75, 11964.75]
		Potato	[14948.10, 14948.10]	[30506.20, 35660.25]	[27315.65, 33751.75]
		Rice	[53235.00, 57079.35]	[46968.30, 51185.25]	[41927.85, 47193.75]
Water Allocated to Irrigation	Inner Mongolia	Corn	[2726.34, 3856.77]	[2714.37, 3788.56]	[1542.47, 2056.62]
		Soybean	[1479.30 ,2324.62]	[1460.40, 2294.92]	[1439.63, 2262.28]
		Potato	[2113.29, 2641.61]	[2086.29, 2607.86]	[3519.00, 4702.49]
		Rice	[11578.14, 16534.13]	[11475.11, 16284.15]	[11240.21, 15249.31]
	Jilin	Corn	[2151.95, 3086.95]	[2042.01, 2972.49]	[1146.94 ,1529.25]
		Soybean	[1126.73, 1770.58]	[1105.73, 1737.58]	[1070.48, 1682.18]
		Potato	[1609.62, 2012.03]	[1579.62, 1974.53]	[2643.24, 3498.34]
		Rice	[8966.70, 12899.03]	[8662.46, 12542.18]	[8397.11, 11729.49]
	Heilongjiang	Corn	[5275.32, 7973.49]	[2017.46, 2689.95]	[1794.71, 2392.95]
		Soybean	[2092.73, 3288.58]	[1882.97, 2958.95]	[1675.07, 2632.25]
		Potato	[2989.62, 3737.03]	[6101.24, 8915.06]	[5463.13, 8437.94]
		Rice	[19164.60, 28539.68]	[16908.59, 25592.63]	[15094.03, 23596.88]

(45.00% of the total farmed area), which is followed by corn (31.43%), potato (11.78%), and soybean (11.78%). In addition, production of rice, soybeans, and corn declines gradually in periods 2 and 3. This is because water and fertilizer usage limit their reduced planting areas. In contrast, period 2 is expected to see a rise in potato yield to support grain productivity. The growing regions of crops should shift from rice, corn, and potato to soybean in Heilongjiang province, as is the case in Inner Mongolia and Jilin province. It is inferred that the differences in water needs, fertiliser usage, and other associated characteristics among crops have a considerable impact on farming water resource management techniques in SHRW when compared to the spatial and temporal dissimilarity of schemes among the three provinces.

4.2. Irrigation Schemes of SHRW

According to Table 2, surface water is primarily responsible for the water allotted for irrigation in Inner Mongolia. Throughout the course of three periods, there has been a constant decline, which is partially due to a reduction in the need for corn irrigation in period 3. For soybean planting, [1479.30, 2324.62], [1460.40, 2294.92], and [1439.63, 2262.28] million m^3 of surface water is provided to ensure steady economic benefits in periods 1 to 3, respectively.

Potatoes require [2113.29, 2641.61], [2086.29, 2607.86], and [3519.00, 4702.49] million m^3 of surface water in periods 1 to 3, respectively, due to their huge cultivation areas and low unit water demands. The water demand in period 3 is almost two times as much as it was in periods one and two. In general, rice farming uses up the most surface water resources; if irrigation technologies become more effective in the future, the surface water allocation will be slightly less in period three.

The province of Jilin has the lowest water demand of any place. In particular, being the second-largest crop, corn receives [2151.95, 3086.95], [2042.01, 2972.49], and [1146.94, 1529.25] million m^3 of surface water in periods 1 to 3, with a huge reduction in period 3. Because to their modest cultivation areas, soybeans require the least quantity of water. In periods 1, 2, and 3, potatoes, which increased by about 138% in period 3, consume [1609.62, 2012.03], [1579.62, 1974.53], and [2643.24, 3498.34] million m^3 of surface water each. The main consumer of water is still rice, with variations comparable to those in Inner Mongolia. Since Heilongjiang produces the most crops, there is a great demand for water resources for irrigation. As shown in Table 1, the decrease in surface water allotted for maize planting in period 2 is mostly due to a decline in demand and production. Soybeans, a drought-resistant plant, only need a small amount of surface water. In comparison, the amount of surface water available for rice cultivation in Inner Mongolia and Jilin uses nearly 1.5 times as much water. These results of the water supply have shown how the distribution of different types of crop irrigation varies throughout three provinces (or autonomous regions) and the changing trend over three time periods.

The best agricultural irrigation plans depend on cultivation schemes, which has key implications for the ideal irrigation schemes over SHRW. Another is that surface water is allocated

Table 3. Water Allocated to End-Users in Three Provinces

Province	End-User	Period $t = 1$		$t = 2$		$t = 3$	
		Surface Water	Groundwater	Surface Water	Groundwater	Surface Water	Groundwater
Inner Mongolia	Planting	[17146.61, 24233.64]	0	[16989.20, 23868.07]	0	[17300.27, 24258.94]	0
	Metallurgy	[1794.45, 1825.48]	[221.79, 225.62]	[1844.92, 1871.12]	[228.02, 231.26]	[1906.93, 1947.84]	[235.69, 240.74]
	Food Industry	[2638.90, 2684.53]	[326.16, 331.80]	[2713.12, 2751.65]	[335.33, 340.09]	[2804.31, 2864.46]	[346.60, 354.03]
	Tourism	[916.98, 916.98]	[2613.32, 2804.26]	[1839.27, 2065.65]	[1631.05, 1831.80]	[1816.11, 2127.57]	[1610.51, 1886.72]
	Household	[2883.25, 2915.32]	[2556.85, 2585.28]	[2094.85, 3742.54]	[3458.24, 3554.27]	[3023.46, 3050.92]	[2681.18, 2705.53]
Jilin	Planting	[13278.51, 18896.07]	0	[12832.60, 18374.17]	0	[12913.92, 18039.28]	0
	Metallurgy	[2017.75, 2048.48]	[249.38, 253.18]	[2117.33, 2136.56]	[261.69, 264.07]	[2168.00, 2192.11]	[267.95, 270.94]
	Food Industry	[2967.28, 3012.47]	[366.74, 372.33]	[3113.72, 3142.00]	[384.84, 388.34]	[3188.23, 3223.69]	[394.05, 398.43]
	Tourism	[569.28, 569.28]	[1374.11, 1480.71]	[731.34, 731.34]	[1156.28, 1370.56]	[1002.76, 1137.02]	[889.24, 1008.30]
	Household	[3308.06, 3344.85]	[2933.56, 2966.19]	[3370.46, 4277.23]	[2988.90, 3034.41]	[3420.27, 3493.64]	[3033.07, 3098.13]
Heilongjiang	Planting	[28318.97, 41614.42]	0	[26429.07, 38796.22]	0	[23591.46, 35811.36]	0
	Metallurgy	[2624.24, 2680.53]	[324.34, 331.30]	[2705.86, 2758.27]	[334.43, 340.91]	[2779.04, 2829.98]	[343.48, 349.77]
	Food Industry	[3859.18, 3941.96]	[476.98, 487.21]	[3979.21, 4056.28]	[491.81, 501.34]	[4086.83, 4161.74]	[505.11, 514.37]
	Tourism	[8575.23, 9425.28]	[7604.45, 8358.26]	[8402.96, 9602.78]	[7451.68, 8515.67]	[8329.82, 9780.03]	[7386.82, 8672.86]
	Household	[4574.68, 4634.94]	[4056.80, 4110.23]	[4698.55, 4750.81]	[4166.64, 4212.98]	[4797.51, 4841.08]	[4254.39, 4293.03]

more water than groundwater in SHRW because to its affordability, availability, and ease of access.

4.3. Water Allocation Schemes of SHRW

Table 3 provides the water allocations for various end users in the Provinces of Inner Mongolia, Jilin, and Heilongjiang over the course of the three time periods. For instance, the main user of surface water is agriculture. No groundwater is used for irrigation due to financial and environmental limitations. From [1794.45, 1825.48] and [1844.92, 1871.12] to [1906.93, 1947.84] million m^3 of surface water are allocated to metallurgy in period 1 to 3, with groundwater quantity being [221.79, 225.62], [228.02, 231.26], and [235.69, 240.74] million m^3 accounting for a small portion. Similar to this, surface water serves as the primary water source for the food sector. Tourism and domestic customers receive the majority of groundwater deliveries. According to their consumption of surface water, which in period 1 accounted for 74.39%, 8.95%, 8.24%, 5.60%, and 2.81% of the total amount. In Inner Mongolia, distribution is greater than half what is needed for irrigation.

In periods 1 to 3, planting in the province of Jilin uses [13278.51, 18896.07], [12832.60, 18374.17], and [12913.92, 18039.28] million m^3 of surface water, correspondingly, with no groundwater supplies. Meanwhile, [2017.75, 2048.48], [2117. 33, 2136.56], and [2168.00, 2192.11] million m^3 of surface water are allocated to metallurgy in three periods, while the food industry utilizes [2967.28, 3012.47], [3113.72, 3142.00], and [3188.23, 3223.69] million m^3 of surface water. Besides, only [249.38, 253.18] and [366.74, 372.33] million m^3 of groundwater are supplied for metallurgy and the food industry in period 1.

In contrast to Inner Mongolia and Heilongjiang provinces, there are fewer water resources available for the tourism industry. The dominant user of groundwater has traditionally been the household. Similar to Inner Mongolia, the top three users of surface water are the agriculture, household, and food industries, with metallurgy and tourist consuming the next two spots. Based on its ecological and economic qualities, the top two users of groundwater are households and the tourism. As a huge agricultural and industrial province, Heilongjiang uses more water than the other two provinces. In particular, the, surface water allocated for irrigation in periods 1 to 3 is [28318.97 41614.42], [26429.07, 38796.22], and [23591.46, 35811.36] million m^3, or nearly double what the province of Jilin uses.

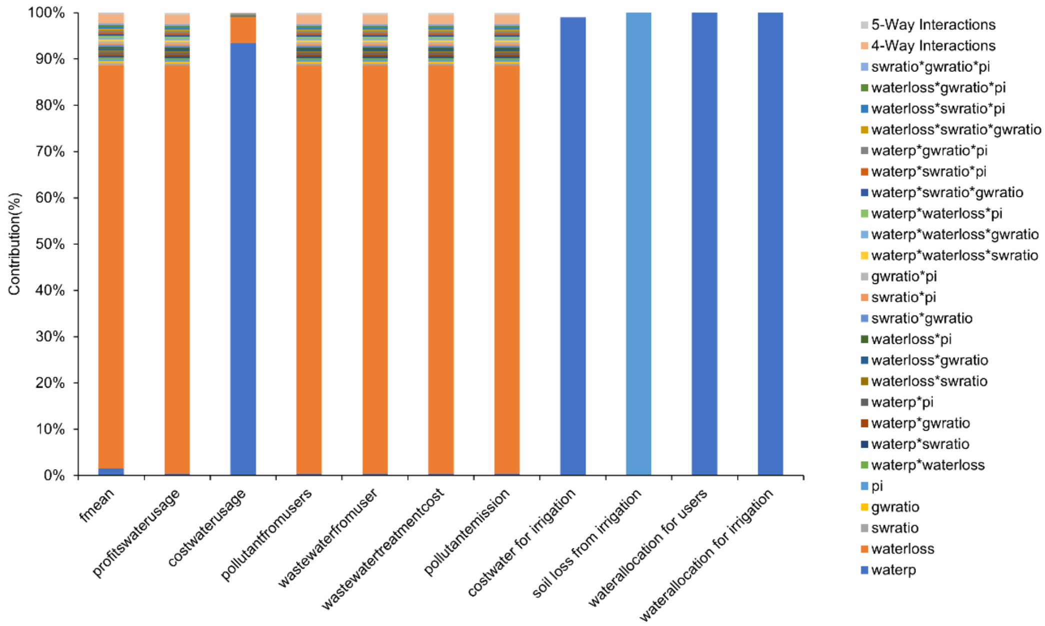

Figure 3. The contribution rate among 32 scenarios.

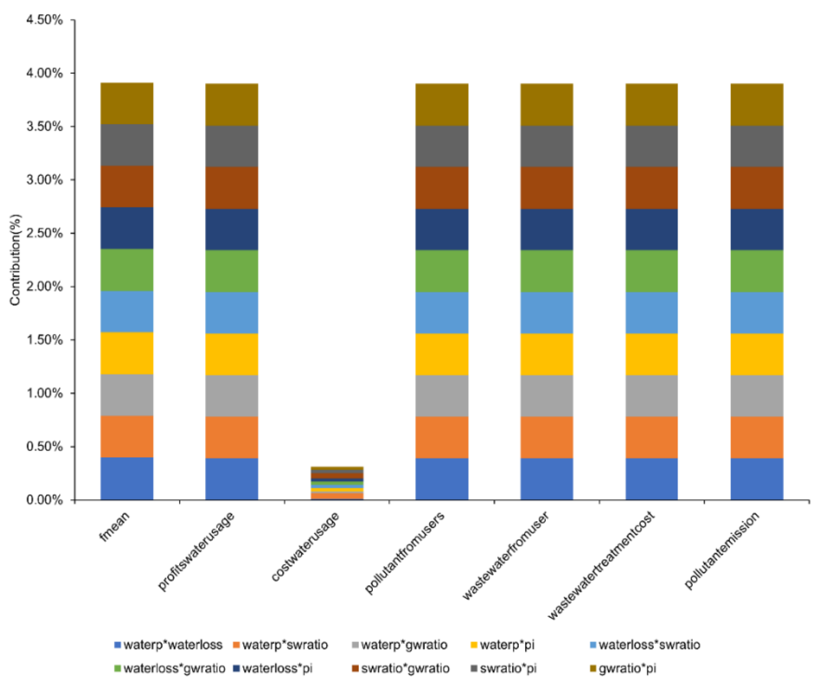

Figure 4. The contribution rate among 2 factors.

In the province of Heilongjiang, metallurgy uses relatively little water. The largest consumer of groundwater and the second largest user of water resources, respectively, is tourism. Throughout periods 2 and 3, consumption gradually decreases. Groundwater is used by households after tourism. Instead of the food industry and metallurgy, tourism and household use overtake Inner Mongolia and Jilin Provinces as the second and third consumers of surface water. In this important agricultural province, irrigation uses over half of the surface water. The two primary consumers of groundwater are tourism and household.

4.4. Factorial Design Analysis

Through the factor design analysis of the 32 scenarios, the Figure 3 is obtained. Figure 3 illustrates the multifactorial interaction among 32 scenarios. It can be seen from the figure that the amount of water leakage in the water supply pipe network largely affects the net income of the system, the profit utilization of the unit water resources, the pollutant from the users, wastewater from users, unit wastewater treatment cost and pollutant emission. One possible reason is the leakage rate of water supply networks in these two provinces has been in the top of China's provinces in the past few years. According to the statistics of urban and rural construction, the comprehensive leakage rate of China's public water supply network in 2017 was 14.57% (city and county), while the comprehensive leakage rate of water supply network in Jilin Province and Heilongjiang was 29% and 24%, respectively, the first and third places among China's 31 provinces. Since Jilin and Heilongjiang used to be important old industrial bases in Northeast China, a large number of water supply networks were built in the latter half of the last century to ensure the normal use of water at the industrial base. However, with the decline of the Northeast Industrial Zone in recent years, the aging water supply network lacks maintenance, resulting in extremely low water supply efficiency in Jilin and Heilongjiang Provinces. Figure 4 presents the contribution between the factors of the two-two interaction is basically kept at the same level. It can also be said that in this model, the contribution between the two factors is far less than the contribution of the single factor compared with single factor.

Figure 5 illustrates the 3 main effect plots (mean of net system benefits, mean of pollutants from users, and mean of water usage profits). Obviously, in the single-factor analysis, the plot of water loss shows the largest slope and plays a leading role in various responses. Moreover, the effects of the five factors on response are different. For example, when the water price changes from 1.2 to 1.5, the contribution of the water price factor is positive, and the contribution of other factors is negative. Figure 6 shows the interaction between two factors in IMRFP model. The results show the obvious interactive effects among water price, surface water ratio, groundwater ratio, and water loss. Especially, the effects between water loss and other factors are significant because of the important effects of water loss (water leakage).

5. Conclusions

The Songhua River Basin's socio-economic growth has resulted in increased water resource consumption in recent years. Meanwhile, environmental deterioration and water scarcity have gotten worse due to abuse, pollution, and unsound policies. If adequate system management cannot be implemented, these repercussions will impede future development and dam-

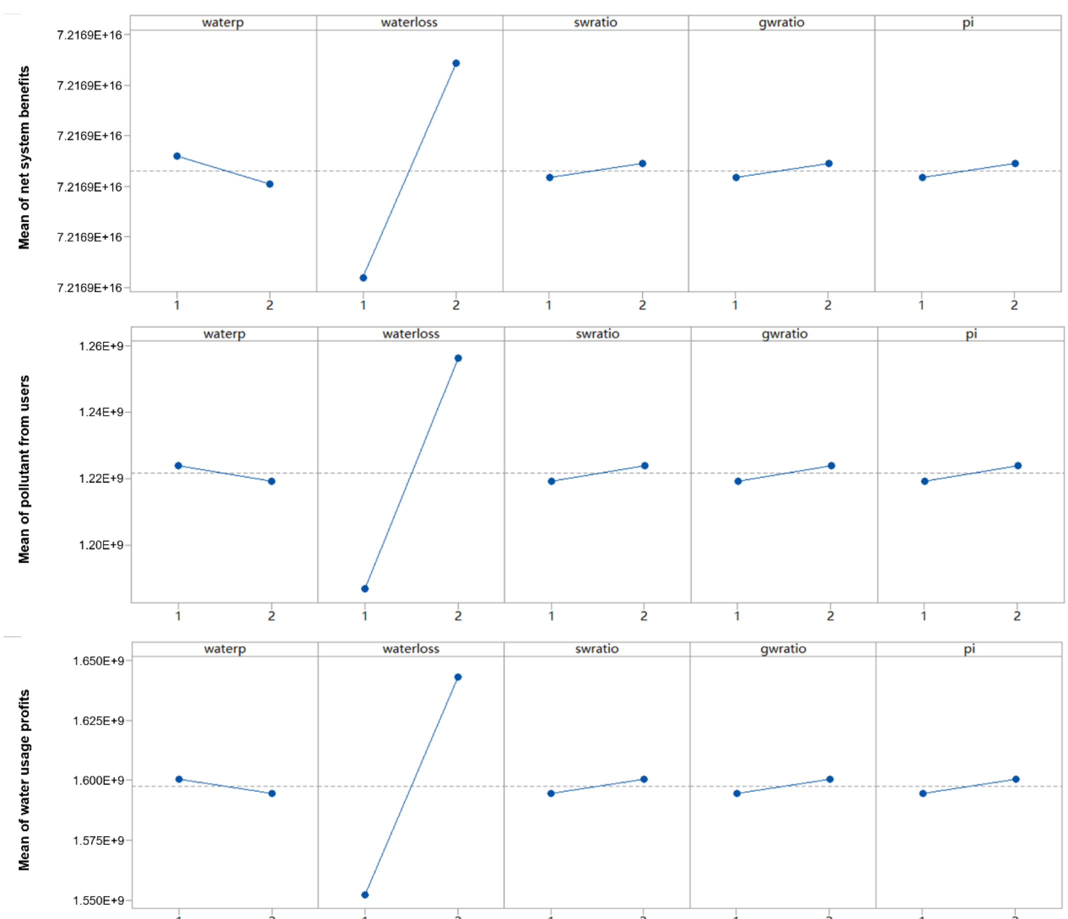

Figure 5. Main effect plots (mean of net system benefits, mean of pollutants from users, and mean of water usage profits) among water price, water loss, surface water ratio, groundwater ratio, and p_i level.

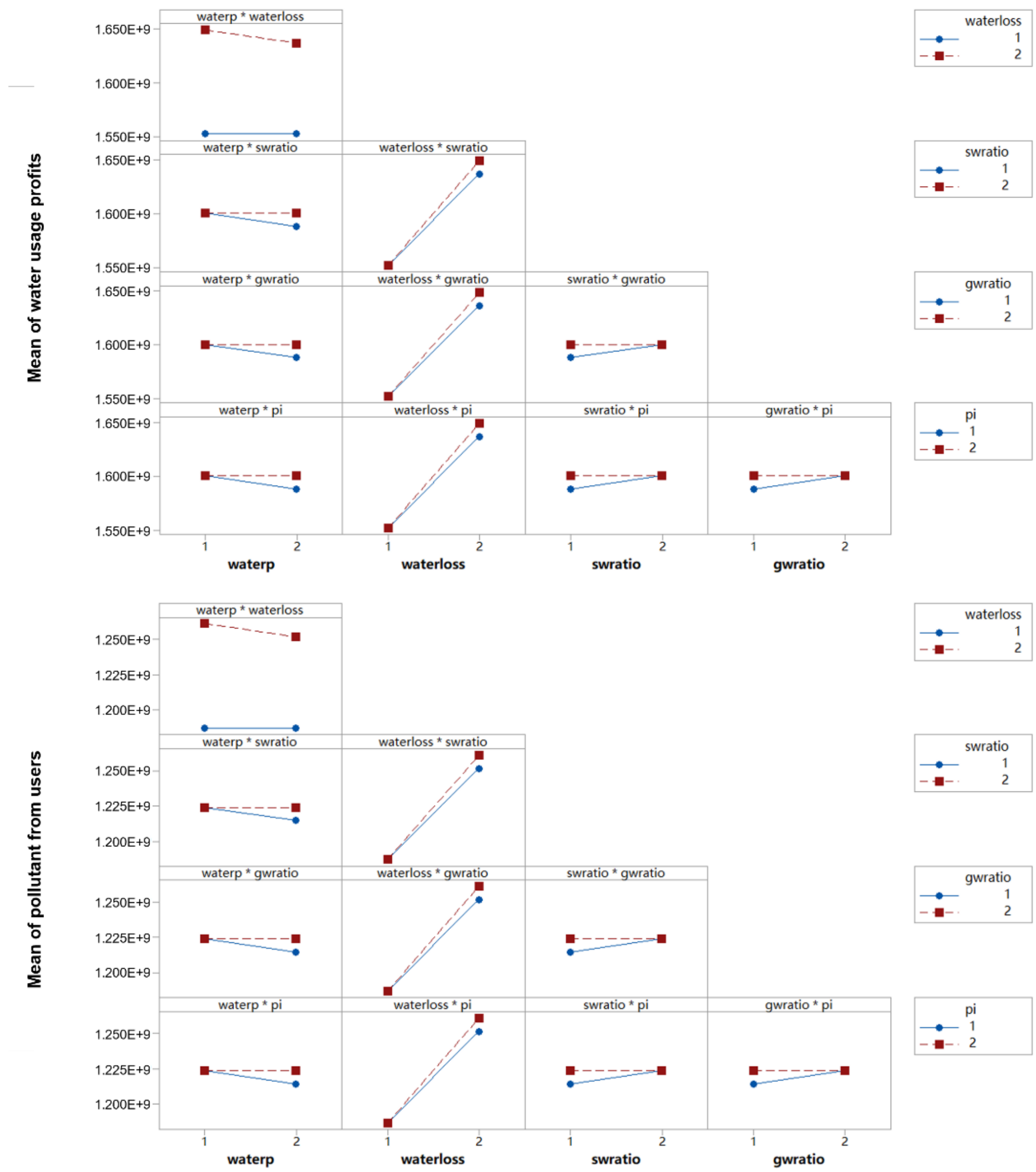

Figure 6. Interaction plot for efficiencies of profits of water usage and pollutant from users.

age the ecosystem as well as human health. In order to manage the water-related operations in SHRW, Interval Multi-Random Factorial Programming (IMRFP) was created in this study.

This study helps (1) determine the intricacies connected to SHRW's social and natural aspects; (2) tackle uncertainties expressed as intervals and probability sets, and produce interval solutions that could offer various choice possibilities for decision-makers rather than one fixed scheme; (3) identify the best allocation strategies for agricultural and water resources to conduct environmental pollution management during planning periods; (4) reveal the influence of five factors on the optimal allocation of water resources and the interaction to a certain extent through factorial design; (5) direct regulatory formulation, control water pollution, and increase economic and socio-economic benefits in SHRW.

For facilitating the balanced development of the social economic and ecological environment in SHRW, a number of recommendations were made. For instance, based on the agricultural economy's expected foundational position for the next 15 years, planting should always be the top priority. In three provinces, rice should be the main commercial crop because it requires the most irrigation water, followed by corn, potatoes, and soybeans. Benefits to the economy are inversely correlated with levels of water pollution. The modelling outcomes demonstrate that the CFWRM approach can systematically optimise water resource allocations and agricultural practises, potentially eradicating issues with water scarcity, water contamination, water supply system leaks, and soil erosion in SHRW. As an extending solution to the optimal water resources management problem, IMRFP is also expected to be a robust method in some basins with similar agricultural and environmental patterns to SHRW.

References

Ağpak, K. and Gökçen, H. (2007). A chance-constrained approach to stochastic line balancing problem. *European Journal of Operational Research*, 180, 1098-1115. https://doi.org/10.1016/j.ejor.2006.04.042

Albert, C., Galler, C., Hermes, J., Neuendorf, F., von Haaren, C. and Lovett, A. (2016). Applying ecosystem services indicators in landscape planning and management: the ES-in-planning framework. *Ecological Indicators*, 61, 100-113. https://doi.org/10.1016/j.ecolind.2015.03.029

Bingli, L., Huang, S., Min, Q., Tianyun, L. I., & Zijian, W. A. N. G. (2008). Prediction of the environmental fate and aquatic ecological impact of nitroben-zene in the Songhua River using the modified AQUATOX model. *Journal of Environmental Sciences*, 20(7), 769-777. https://doi.org/ 10.1016/S1001-0742(08)62125-7

Box, G.E., Hunter, W.G. and Hunter, J.S. (1978). Statistics for Experimenters, Wiley, Hoboken, NJ.

Charnes, A. and Cooper, W.W. (1959). Chance-constrained programming. *Management Science*, 6, 73-79. https://doi.org/10.1287/mnsc.6.1.73

Cheng, G.H., Huang, G.H., Li, Y.P., Cao, M.F. and Fan, Y.R. (2009). Planning of municipal solid waste management systems under dual uncertainties: a hybrid interval stochastic programming approach. *Stochastic Environmental Research and Risk Assessment*, 23, 707-720. https://doi.org/10.1007/s00477-008-0251-5

Dong, C., Huang, G., Cheng, G. and Zhao, S. (2018). Water resources and farmland management in the Songhua River watershed under interval and fuzzy uncertainties. *Water Resources Management*, 32, 4177-4200. https://doi.org/10.1007/s11269-018-2035-0

Dong, C., Tan, Q., Huang, G.H. and Cai, Y.P. (2014). A dual-inexact fuzzy stochastic model for water resources management and non-point source pollution mitigation under multiple uncertainties. *Hydrology and Earth System Sciences*, 18(5), 1793-1803. https://doi.org/10.5194/hess-18-1793-2014

Dyckman, C.S. (2016). Sustaining the commons: the coercive to cooperative, resilient, and adaptive nature of state comprehensive water planning legislation. *Journal of the American Planning Association*, 82(4), 327-349. https://doi.org/10.1080/01944363.201 6.1214537

Hajkowicz, S. and Collins, K. (2007). A review of multiple criteria analysis for water resource planning and management. *Water Resources Management*, 21(9),1553-1566. https://doi.org/10.1007/s11269-006-9112-5

Huang, G.H., Baetz, B.W. and Patry, G.G. (1992) An grey linear programming approach for municipal solid waste management planning under uncertainty. *Civil Engineering Systems*, 9, 319-335. https://doi.org/10.1080/02630259208970657

Huo, A.D., Dang, J., Song, J.X., Chen, X.H. and Mao, H.R. (2016). Simulation modeling for water governance in basins based on surface water and groundwater. *Agricultural Water Management*, 174, 22-29. https://doi.org/10.1016/j.agwat.2016.02.027

Li, Y., Xu, L.Y. and Shun, L. (2009). Water quality analysis of the Song-hua River Basin using multivariate techniques. *Journal of Water Resource and Protection*. https://doi.org/10.4236/jwarp.2009.12015

Liu, J.R., Pang, Y.X., Tang, X.L., Dong, H.W., Chen, B.Q. and Sun, C.H. (2007). Genotoxic activity of organic contamination of the Songhua River in the north-eastern region of the People's Republic of China. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 634(1-2), 81-92. https://doi.org/10.1016/j.mrgentox.2007.06.002

Luo, P., Sun, Y., Wang, S., Wang, S., Lyu, J., Zhou, M., Nakagami, K., Takara, K. and Nover, D. (2020). Historical assessment and future sustainability challenges of Egyptian water resources management. *Journal of Cleaner Production*, 263, 121154. https://doi.org/10.1016/j.jclepro.2020.121154

Miao, C., Yang, L., Liu, B., Gao, Y. and Li, S. (2011). Streamflow changes and its influencing factors in the mainstream of the Songhua River basin, Northeast China over the past 50 years. *Environmental Earth Sciences*, 63, 489-499. https://doi.org/10.1007/s12665-010-0717-x

Qu, X. and Wu, C.J. (2005). One-factor-at-a-time designs of resolution V. *Journal of Statistical Planning and Inference*, 131(2), 407-416. https://doi.org/10.1016/j.jspi.2004.03.002

Richter, B.D., Mathews, R., Harrison, D.L. and Wigington, R. (2003). Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications*, 13(1), 206-224. https://doi.org/10.1890/1051-0761(2003)013[0206:ESWMMR]2.0 .CO;2

Serrao-Neumann, S., Renouf, M., Kenway, S.J. and Choy, D.L. (2017). Connecting land-use and water planning: Prospects for an urban water metabolism approach. *Cities*, 60, 13-27. https://doi.org/10.1016/j.cities.2016.07.003

Singh, A. (2014). Irrigation planning and management through optimization modelling. *Water Resources Management*, 28(1), 1-14. https://doi.org/10.1007/s11269-013-0469-y

Thenkabail, P.S., Biradar, C.M., Noojipady, P., Dheeravath, V., Li, Y., Velpuri, M., Gumma, M., Gangalakunta, O.R.P., Turral, H., Cai, X. and Vithanage, J. (2009). Global irrigated area map (GIAM), derived from remote sensing, for the end of the last millennium. *International Journal of Remote Sensing*, 30(14), 3679-3733. https://doi.org/10.1080/01431160802698919

Tong, S.T. and Chen, W. (2002). Modeling the relationship between land use and surface water quality. *Journal of Environmental Management*, 66(4), 377-393. https://doi.org/10.1006/jema.2002.0593

Turner, S.W.D., Blackwell, R.J., Smith, M.A. and Jeffrey, P.J. (2016). Risk-based water resources planning in England and Wales: challenges in execution and implementation. *Urban Water Journal*, 13 (2), 182-197. https://doi.org/10.1080/1573062X.2014.955856

Xu, S., Liu, Y. and Qiang, P. (2014). River functional evaluation and regionalization of the Songhua River in Harbin, China. *Environmental Earth Sciences*, 71, 3571-3580. https://doi.org/10.1007/s12665-013-2748-6

Yan, Z., Liu, S.X. and Chen, J.F. (2012). Water resource allocation under consideration of the national NIY plan in Harbin, China. *Journal of Resources and Ecology*, 3(2), 161-168. https://doi.org/10.5814/j.iss n.1674-764x.2012.02.00

Yang, J., Li, G., Wang, L. and Zhou, J. (2015). An integrated model for simulating water resources management at regional scale. *Water Resources Management*, 29, 1607-1622. https://doi.org/10.1007/s11269-014-0897-3

Yu, S., Jiang, H.Q. and Chang, M. (2016). Integrated prediction model for optimizing distributions of total amount of water pollutant discharge in the Songhua River watershed. *Stochastic Environmental Research and Risk Assessment*, 30, 2179-2187. https://doi.org/10.1007/s00477-015-1172-8

Zhang, L., Xu, Z.J. and Teng, Z.K. (2008). Songhua River Basin characteristics and non-point source pollution control measures. *Environmental Science and Management*, 7, 55-56+61. (in Chinese)

Zhang, X., Xu, K. and Zhang, D. (2012). Risk assessment of water resources utilization in Songliao Basin of Northeast China. *Environmental Earth Sciences*, 67, 1319-1329. https://doi.org/10.1007/s12665-012-1575-5