A multi-preference based optimization approach for planning the multiple water resources and multiple water-receiving cities management under uncertainty

X.X. Ma[1], H.L. Wang[2], L. Yu[3*], Y.P. Li[4], Y.R. Fan[5], J.P. Zhang[6], J.L. Zhang[7]

[1] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: maxx@zzu.edu.cn

[2] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: wanghlns@163.com

[3*] (Corresponding Author) School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; Zhengzhou Key Laboratory of Water Resource and Environment, Zhengzhou, 450001, China; Henan Key Laboratory of Groundwater Pollution Prevention and Rehabilitation, Zhengzhou, 450001, China; E-mail: yulei2018@zzu.edu.cn

[4] School of Environment, Beijing Normal University, Beijing 100875, China; E-mail: yongping.li@iseis.org

[5] Department of Civil and Environmental Engineering, Brunel University London, Uxbridge, UB8 3PH, United Kingdom; E-mail: yurui.fan@gmail.com

[6] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: zhjp@zzu.edu.cn

[7] College of Environmental Science and Engineering, Qingdao University, Qingdao, Shandong 266071, China; E-mail: zjunlong0801@163.com

Abstract:

This study aims to develop a multi-preference based interval fuzzy-credibility constrained programming (MIFCP) approach for planning the regional-scale water-resources management system (RWMS) of Henan Province, China. This is the first attempt for planning RWMS through combining interval parameter programming (IPP), fuzzy-credibility constrained programming (FCP) and three diverse attitudes of decision makers with one framework. MIFCP cannot only address uncertainties expressed by interval and fuzzy information but also present multiple preferences of decision makers towards conservative, neutral and radical attitudes. Solutions of multiple water resources, multiple water-receiving cities and multiple water-using departments in association with multiple attitudes of decision makers and multiple credibility levels are examined. Results reveal that over the planning horizon the total supplying water of radically oriented decision maker can increase by 1.82×10^9 m^3 compared to the conservatively oriented decision maker. The obtained results also disclose that for the radically oriented decision maker, the water allocation for agriculture, industry, life and ecology during the entire horizon can respectively change by 0.24%, 0.37%, 0.67% and 0.44% as the α-cut level changes from 0.5 to 1. These findings cannot only gain insights on some desired supports for Henan Province but also provide theoretical suggestions for other study regions.

Keywords: fuzzy credibility-constrained programming; multi-preference; multiple water resources; planning; uncertainty

1. Introduction

Water is a unique fundamental resource for agriculture, industry, life and ecology (Yang et al., 2018). Increasing water demand and limited water availability aggravate the contradiction of water demand-supply owing to the population growth, industrial production and social progress (Yan et al., 2018). Simultaneously, water scarcity is a significant factor for restricting economic development and human's living standard improvement in many cities (Chen et al., 2019). Moreover, the over-exploitation and unreasonable utilization of surface water and groundwater have resulted in destruction of ecological systems and waste of water resources (Ye et al., 2018). Currently, numbers of organizations have made huge efforts to enhance efficiency for water resources management and seek methods to provide reliable water supplies to each department (Uche et al., 2015). However, for a regional-scale water-resources management system (RWMS), there are multiple water resources, multiple water-receiving cities and multiple water-using departments. Moreover, these water-receiving cities and water-using departments may have diverse water resources demands in association with various factors from hydrogeological, sociometric and environmental aspects and they can compete for water supplies at every period (Ren et al., 2017). Therefore, it is desired for formulating high-efficiency management methods that could not only improve the water efficiency but also coordinate the sustainable development among of various departments (Li et al., 2016).

Previously, a number of research works were conducted for supporting water resources management such as linear programming (LP), non-linear programming (NLP), dynamic programming (DP) and genetic algorithm (GA) (Singh, 2012). For example, Martinsen et al. (2019) presented a LP model for planning the Haihe River Basin's water allocation issues, in which the spatial variation of water quality and quantity were considered. Garga and Dadhichb (2014) conducted the NLP model for optimizing the deficit irrigation in the Lower Indus Basin. Abdulbaki et al. (2017) proposed an integer LP model for optimizing the treatment and allocation of water resources, where the cost of water treatment, transportation and waste water discharge were considered as integer variables. Li and Majozi (2018) advanced a DP approach for optimizing water networks, in which water-using units were sorted according to the concentration of the entrance and every concentration were suited at a distinct gradation. Bi et al. (2015) introduced the prescreened heuristic sampling method by improving the ability of GAs to find optimal or near-optimal decision-making alternatives for the realistic-sized water allocation optimization problem, in which hydraulic simulations were performed using EPANET 2.0. Although the above studies could effectively handle problems in RWMS when their components or parameters were deterministic (Wang et al., 2019). However, some ambiguous information in RWMS could not be accurately expressed as deterministic values such as available water resources, water demand, costs and benefits of water supply (Milan et al., 2018). In addition, these studies also have difficulties in reflecting the uncertainties caused by the changes of socio-economic, eco-environment and subjective judgements from various decision makers (Fu et al., 2018). Therefore, effective optimization methods for planning RWMS and dealing with kinds of complexities and uncertainties are desired (Kacimov et al., 2019).

Over the past decades, many effective methods were proposed to tackle complexities and uncertainties in RWMS such as interval parameter programming (IPP), fuzzy programming (FP) (Zhang and Guo, 2017). For instance, Maqsood et al. (2005) adopted the IPP method to plan water resources of an unregulated reservoir in a dry season, where water demand for agriculture and industry were regarded as interval numbers. Ren et al. (2017) formulated a FP approach to optimize the Wuwei City's irrigation water and land resources issues, in which the amount of surface water and groundwater were considered as the fuzzy sets. Zhang et al. (2018) applied a fuzzy-credibility constrained programming (FCP) method to optimize water resources allocation in Yingke Irrigation District, in which monthly rainfall and inflow were presented as the fuzzy sets. Singh (2015) developed a chance-constrained programming (CCP) model for the seasonal optimal allocation of available land and water resources, in which the net irrigation demand was solved as a random variable. Li et al. (2019a) proposed a fuzzy gradient chance-constrained programming (FGCCP) to address different uncertainties in evacuation management and planning, where decision makers' subjective judgements were interpreted as fuzzy information. In general, the IPP can deal with uncertain parameters in the format of interval numbers, but cannot reflect the reliability of satisfying system constraints in an imprecise context (Li et al., 2015). CCP and FCP are efficacious for reflecting the risk violation caused by uncertainty in the system (Charnes and Cooper, 1959; Liu and Liu, 2002; Sun et al., 2019; Zhang et al., 2019a). However, in the practical application, obtaining probability distribution couples with many complexities and uncertainties in association with information quality, while fuzzy sets may be relatively feasible when its membership function is determined (Zhang and Huang, 2010; Zhang and Huang, 2011b; Dai et al., 2016). Besides, the traditional FCP methods are over-simplified and they cannot fully present the decision makers' subjective judments (Liu et al., 2017). The FGCCP can reflect decision makers' eclectic attitudes through introducing a linear combination of possibility and necessity (Xu et al., 2017). However, in real-world water resources management issues, it is difficult to exactly reflect preferences of different stakeholders towards various perspectives in decision-making processes of water resources allocation (Zomorodian et al., 2018). For instance, water managers with a radically oriented attitude may prefer the smallest credibility level with extremely high system benefits. While, the conservatively oriented water manager prefers the largest value of credibility level and water resources demand constraints satisfied thoroughly. Neutral oriented water manager usually secures the medium value of credibility level, and the reasonable probability that the projected goals will be reached (Ji et al., 2018).

Thus, this study aims at proposing a multi-preference based interval fuzzy-credibility constrained programming (MIFCP) approach for multi-uncertainty reflection through combining IPP, FCP and three diverse attitudes (i.e. conservative, neutral and radical attitudes) of decision makers. MIFCP cannot only address uncertainties expressed by interval and fuzzy information but also reflect multiple preferences of decision makers. Then, a MIFCP-RWMS model is developed for water resources management of Henan Province, China. In the MIFCP-RWMS model, three preferences towards three attitudes of decision makers and three satisfaction degrees of the water demand in multiple departments (i.e. agriculture, industry, life and ecology) will be considered. Summarily, the MIFCP-RWMS could help decision makers: (a) handle uncertainties presented as interval values and fuzzy sets; (b) develop comprehensive water allocation schemes under different attitudes of decision makers; (c) balance the contradiction among economic benefits, water demand-supply, waste water discharge, chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) emissions.

2. Methodology

The water managers are charged with allocating multiple water resources to meet the water requirements for multiple water-using departments (Milan et al., 2018). However, in practical water resources management problems, the water resources demand can vary from different departments in each city at every period (Wang and Huang, 2012). FCP is effective for reflecting the satisfaction degrees of the constraints using fuzzy sets (Li et al., 2013). A general FCP model can be described as:

$$\text{Min } E = \sum_{j=1}^{n} c_j x_j \tag{1a}$$

subject to:

$$Cr\left\{\sum_{j=1}^{n} a_{ij} x_j \le \tilde{b}_i\right\} \ge \lambda_i,\ i = 1, 2, \ldots, m \tag{1b}$$

$$x_j \ge 0,\ j = 1, 2, \ldots, n \tag{1c}$$

where E is the objective function; x_j are decision variables; and a_{ij}, $\tilde{b}_i$ and c_j are coefficients. Fuzzy credibility was firstly proposed by Liu and Liu (2002) and was a measure of confidence level in fuzzy environment to tackle uncertainties expressed as fuzzy sets (Zhang and Huang, 2011a; Zhang et al., 2012). The credibility level (λ_i) represent the satisfaction degree of the associated constraint (Huang, 2006; Rong and Lahdelma, 2008).

The triangular fuzzy membership function is one of the most popular possibility distributions, and it is adopted in this study due to its computational efficiency (Chang and Wang, 1997; Sasikumar and Mujumdar,2000; Zhang and Huang, 2010). Let ξ be fuzzy variables with membership function μ and $\tilde{t}$ be a fuzzy set (Huang, 2006). Thus, we have:

$$\mu(r)=\begin{cases}\dfrac{r-\underline{t}}{t-\underline{t}} & \text{if } \underline{t}\le r\le t\\ \dfrac{r-\overline{t}}{t-\overline{t}} & \text{if } t\le r\le \overline{t}\\ 0 & otherwise\end{cases} \tag{2}$$

where $\underline{t}$, $\overline{t}$, and t are the minimum, maximum, and most-likely values of $\tilde{\xi}$, respectively, r is real number (Li et al, 2013; Zhang et al., 2018).

According to the definition of credibility, the credibility of $r \le \xi$ can be depicted as (Zhang and Huang, 2011b):

$$Cr(r\le\xi)=\begin{cases}1 & \text{if } r\le\underline{t}\\ \dfrac{2t-\underline{t}-r}{2(t-\underline{t})} & \text{if } \underline{t}\le r\le t\\ \dfrac{r-\overline{t}}{2(t-\overline{t})} & \text{if } t\le r\le\overline{t}\\ 0 & \text{if } r\ge\overline{t}\end{cases} \tag{3}$$

Let $\sum_{j=1}^{n} a_{ij}x_j = s_i$. Thus Equation (1b) can be transformed into:

$$Cr\left\{s_i \le \tilde{b}_i\right\} \ge \lambda_i,\ i=1,2,\dots,m \tag{4}$$

Generally, the λ_i varies from 0 to 1 (Zhang and Huang, 2010; Xu et al., 2017). However, in real-world management issues, decision makers prefer that the constraint should be satisfied under a high necessity degree which is greater than 0.5 (Yu et al., 2016; Zhang and Guo, 2017; Zhang et al., 2018). Thus, we have the following for each $1 \geq \mu_{\tilde{b}_i} \geq \lambda_i \geq 0.5$:

$$\frac{2b_i - \underline{b}_i - s}{2(b_i - \underline{b}_i)} \geq \lambda_i \tag{5}$$

By introducing λ into the intricate system, decision makers can gain many feasible plans through repeatedly modifying the tradeoffs among satisfaction constraints by shifting credibility levels (Tu et al., 2015). Therefore, how to choose the credibility level (λ) would have significant impact on the optimal strategies in water resources management. Nevertheless, it is difficult to present the multiple preferences of decision makers in the actual processes of water resources allocation. The multi-preference based programming (MP) approach is useful for handling fuzzy credibility levels of different decision makers (Ji et al., 2018). Generally, the conservatively oriented decision makers prefer to select the larger credibility level with high water demand satisfaction, the neutrally oriented decision makers usually take the middle credibility level to reach the projected goal, and the radically oriented decision makers are willing to choose the smaller credibility level with extremely high system benefits.

An α-cut is defined as the set of elements that belong to a fuzzy set $\tilde{\lambda}_i$ at least to the degree of α (Zhang and Huang, 2010; Ji et al., 2018). Based on the α-cut level, the value range of corresponding credibility level under three different attitudes of decision makers can be obtained. In fact, some system parameters can hardly be expressed as fuzzy sets when the information quality is failed to create membership functions. However, these parameters can be presented as intervals by knowing their lower and upper bounds (Li et al., 2008; Zhang and Huang, 2011b).

Hence, through coordinating MP and IPP into FCP, a general MIFCP can be described as:

$$\text{Min } E^{\pm} = \sum_{j=1}^{n} c_j^{\pm} x_j^{\pm} \tag{6a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i + (1-2\tilde{\lambda}_i)(b_i - \underline{b}_i),\ i = 1, 2, \ldots, m \tag{6b}$$

$$x_j^{\pm} \ge 0,\ j = 1, 2, \ldots, n \tag{6c}$$

where $a_{ij}^{\pm} \in \left\{R^{\pm}\right\}^{m\times n}$, $c_j^{\pm} \in \left\{R^{\pm}\right\}^{1\times n}$, $x_j^{\pm} \in \left\{R^{\pm}\right\}^{n\times 1}$; $R^{\pm}$ mean interval numbers ('-' is the lower bound and '+' is the upper bound); $\tilde{\lambda}_i$ present ambiguous credibility levels with multi-preference (Ji et al., 2018). $x_j^{\pm}$ present decision variables that are divided into two sorts: continuous and binary variables. Since the follow-up developed MIFCP-RWMS model includes more than 3,900 parameters and 600 decision variables, and there is no constraint violation existing in the interval linear programming (ILP) solution space (i.e. the symbols of $a_j^{\pm}$ and $c_j^{\pm}$ in MIFCP-RWMS model are simultaneously positive or negative) (Fan and Huang, 2012; Yu et al., 2018). Therefore, the two-step method (TSM) that can effectively solve the ILP issues by its high computational efficiency will be used for obtaining the lower and upper bounds of the desired objective function values (Huang et al., 1992). Based on the simplex algorithm, the resulting linear programming model (RWMS-MIFCP model) will be solved through *Lingo* version 10.0 (Dantzig, 1955; Cottle and Dantzig, 1970; Dantzig, 1982; Huang and Loucks, 2000; Singh and Yadav, 2015; Rani et al., 2016).

The first sub-model of MIFCP corresponding to f^+ is:

$$\text{Max } f^+ = \sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1}^{n} c_j^+ x_j^- \tag{7a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^- Sign\left(a_{ij}^{\pm}\right) x_j^+ + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^+ Sign\left(a_{ij}^{\pm}\right) x_j^- \leq b_i + \left(1 - 2\tilde{\lambda}_i\right)\left(b_i - \underline{b}_i\right), i = 1, 2, \ldots, m. \tag{7b}$$

$$x_j^+ \geq 0,\ j = 1, 2, \ldots, k \tag{7c}$$

$$x_j^- \geq 0,\ j = k+1, \mathrm{k}+2, \ldots, n \tag{7d}$$

Solutions of $x_{jopt}^+ \left(j = 1, 2, \ldots, k\right)$ and $x_{jopt}^- \left(j = k+1, k+2, \ldots, n\right)$ can be obtained through solving sub-model (7). Based on the solutions of model (7), the sub-model corresponding to f^- can be formulated as follows (assume that $b_i^{\pm} > 0$ and $f^{\pm} > 0$):

$$\text{Max } f^- = \sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^- x_j^+ \tag{8a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^+ Sign\left(a_{ij}^{\pm}\right) x_j^- + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^- Sign\left(a_{ij}^{\pm}\right) x_j^+ \leq b_i + \left(1 - 2\tilde{\lambda}_i\right)\left(b_i - \underline{b}_i\right), i = 1, 2, \ldots, m. \tag{8b}$$

$$0 \leq x_j^- \leq x_{jopt}^+,\ j = 1, 2, \ldots, k \tag{8c}$$

$$x_j^+ \geq x_{jopt}^-,\ j = k+1, k+2, \ldots, n \tag{8d}$$

From model (8), solutions of $x_{jopt}^- \left(j = 1, 2, \ldots, k\right)$ and $x_{jopt}^+ \left(j = k+1, k+2, \ldots, n\right)$ can be obtained (Huang and Loucks, 2000). Thus, the final solutions of $f_{opt}^{\pm} = \left[f_{opt}^-, f_{opt}^+\right]$ and

$x_{jopt}^{\pm} = \left[x_{jopt}^{-}, x_{jopt}^{+} \right]$ can be obtained for model (6).

3. Application

3.1 Statement of problems

Henan Province is located in the central part of China, which covers an area of around 167 × 10^3 km^2 and has a population of 107.88 × 10^6, as shown in Figure 1. With the rapid development of socio-economy, the per capita gross domestic production (GDP) of Henan reached 42.58 × 10^3 (¥), while the per capita water resources of Henan was merely 442.6 m^3 (less than 1/5 the national average) (HSY, 2017; ND, 2017). Unbalanced spatial and temporal distributions of water resources aggravated the contradiction between regional economic development and water resources demand, particularly in the area of dense population and developed industry. Confronting with these situations, the Middle Route of South to North Water Diversion Project (MRSNWDP) would be of indispensability in alleviating tremendous pressure on water resources and promoting sustainable development of Henan Province. Furthermore, the excessive exploitation of groundwater caused the degradation of water-quality and the exhaustion of rivers and lakes. These mentioned problems would not only restrict the sustainable development of local socio-economic activities but also affect the protection of eco-environment. Therefore, it is essential for local government to make decisions in a sustainable pathway for allocation of multiple water resources for multiple water-using departments in order to alleviate the contradictions among economic development, water demand-supply balance and environmental pollution mitigation.

Place Figure 1 here

3.2 MIFCP-RWMS modeling formulation

The detailed framework of the formulated MIFCP-RWMS model is shown in Figure 2. The first part is the identification of complexity and uncertainty, including multiple water resources (i.e. surface water, groundwater and other water), multiple water-using departments (i.e. agriculture, industry, life and ecology), multiple water-receiving cities (i.e. Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Xuchang, Luohe, Sanmenxia, Nanyang, Shangqiu, Xinyang, Zhoukou, Zhumadian and Jiyuan), and multiple planning periods (i.e. years of 2020, 2025 and 2030). In the second part, the MIFCP method was developed based on the IPP, FCP and MP methods, which could not only resolve uncertainties presented as interval values and fuzzy sets but also reflect multiple preferences of decision makers towards the conservative, neutral and radical attitudes. The last part was the formulation of MIFCP-RWMS model and its application to Henan Province, including the objective, constraints and solutions.

Place Figure 2 here

In this study, the objective of MIFCP-RWMS model is to maximize the total system benefits over the planning horizon, including the benefits from four water resources demand departments and the cost of three supplying water resources (Fu et al., 2018). The objective function can be formulated as follows:

$$\text{Max } f^{\pm} = (1)+(2)+(3)+(4) \tag{9a}$$

(1) *Benefits for agriculture:*

$$\sum_{s=1}^{3}\sum_{c=1}^{18}\sum_{t=1}^{3} AW_{s,c,t}^{\pm} \times \left(AB_{s,c,t}^{\pm} - AC_{s,c,t}^{\pm} \right) \tag{9b}$$

(2) *Benefits for industry:*

$$\sum_{s=1}^{3}\sum_{c=1}^{18}\sum_{t=1}^{3} IW_{s,c,t}^{\pm} \times \left(IB_{s,c,t}^{\pm} - IC_{s,c,t}^{\pm} \right) \tag{9c}$$

(3) *Benefits for life:*

$$\sum_{s=1}^{3}\sum_{c=1}^{18}\sum_{t=1}^{3} LW_{s,c,t}^{\pm} \times \left(LB_{s,c,t}^{\pm} - LC_{s,c,t}^{\pm} \right) \tag{9d}$$

(4) *Benefits for ecology:*

$$\sum_{s=1}^{3}\sum_{c=1}^{18}\sum_{t=1}^{3} EW_{s,c,t}^{\pm} \times \left(EB_{s,c,t}^{\pm} - EC_{s,c,t}^{\pm} \right) \tag{9e}$$

where $f^{\pm}$ is the objective function reflecting system benefits in planning periods (¥); s denotes water resource, with (s = 1, 2, 3); c denotes city, (c = 1, …, 18); t denotes planning period, (t = 1, 2, 3); $AW_{s,c,t}^{\pm}$, $IW_{s,c,t}^{\pm}$, $LW_{s,c,t}^{\pm}$ and $EW_{s,c,t}^{\pm}$ is the amount of water allocated to agriculture, industry, life and ecology in planning period (m^3); $AB_{s,c,t}^{\pm}$, $IB_{s,c,t}^{\pm}$ $LB_{s,c,t}^{\pm}$ and $EB_{s,c,t}^{\pm}$ are the benefits coefficient of agriculture, industry, life and ecology (¥/m^3); $AC_{s,c,t}^{\pm}$, $IC_{s,c,t}^{\pm}$, $LC_{s,c,t}^{\pm}$ and $EC_{s,c,t}^{\pm}$ are the cost coefficient of agriculture, industry, life and ecology

(¥/m^3);

Constraints mainly consist of water resources demand-supply, pollutions discharge, water resources for limitation constraint, policy constraint as well as nonnegative constraints. These constraints can be depicted as follows:

(1) *The total amount of water supply constraint:*

$$\sum_{c=1}^{18}\left(AW^{\pm}_{s,c,t}+IW^{\pm}_{s,c,t}+LW^{\pm}_{s,c,t}+EW^{\pm}_{s,c,t}\right)\leq\sum_{c=1}^{18}WS^{\pm}_{s,c,t} \tag{10}$$

where constraint (10) is the supplying of water availability constraints. $WS^{\pm}_{s,c,t}$ is the supplying of available water (m^3).

(2) *The total amount of water demand constraints:*

$$\begin{gathered}Cr\left\{\sum_{s=1}^{3}AW^{\pm}_{s,c,t}\geq\widetilde{AWD}_{c,t}\right\}\geq\tilde{\lambda}_i\\ \sum_{s=1}^{3}AW^{\pm}_{s,c,t}\geq AWD_{c,t}+\left(1-2\times\tilde{\lambda}_i\right)\left(AWD_{c,t}-\underline{AWD}_{c,t}\right)\end{gathered} \tag{11a}$$

$$\begin{gathered}Cr\left\{\sum_{s=1}^{3}IW^{\pm}_{s,c,t}\geq\widetilde{IWD}_{c,t}\right\}\geq\tilde{\lambda}_i\\ \sum_{s=1}^{3}IW^{\pm}_{s,c,t}\geq IWD_{c,t}+\left(1-2\times\tilde{\lambda}_i\right)\left(IWD_{c,t}-\underline{IWD}_{c,t}\right)\end{gathered} \tag{11b}$$

$$\begin{gathered}Cr\left\{\sum_{s=1}^{3}LW^{\pm}_{s,c,t}\geq\widetilde{LWD}_{c,t}\right\}\geq\tilde{\lambda}_i\\ \sum_{s=1}^{3}LW^{\pm}_{s,c,t}\geq LWD_{c,t}+\left(1-2\times\tilde{\lambda}_i\right)\left(LWD_{c,t}-\underline{LWD}_{c,t}\right)\end{gathered} \tag{11c}$$

$$\begin{aligned} & Cr\left\{\sum_{s=1}^{3} EW_{s,c,t}^{\pm} \geq EW\tilde{D}_{c,t}\right\} \geq \tilde{\lambda}_i \\ & \sum_{s=1}^{3} EW_{s,c,t}^{\pm} \geq EWD_{c,t} + \left(1-2\times\tilde{\lambda}_i\right)\left(EWD_{c,t} - EW\underline{D}_{c,t}\right) \end{aligned} \qquad (11d)$$

where constraints (11a) - (11d) are the total amount of water resources demand constraints; $AWD_{c,t}^{\pm}$, $IWD_{c,t}^{\pm}$, $LWD_{c,t}^{\pm}$ and $EWD_{c,t}^{\pm}$ are the amount of water resources demand for agriculture, industry, life and ecology (m^3).

(3) *Waste water discharge requirement constraints:*

$$\sum_{s=1}^{3} AW_{s,c,t}^{\pm} \times ADS_{c,t} \leq ATS_{c,t}^{\pm} \qquad (12a)$$

$$\sum_{s=1}^{3} IW_{s,c,t}^{\pm} \times IDS_{c,t} \leq ITS_{c,t}^{\pm} \qquad (12b)$$

$$\sum_{s=1}^{3} LW_{s,c,t}^{\pm} \times LDS_{c,t} \leq LTS_{c,t}^{\pm} \qquad (12c)$$

where constraints (12a) and (12c) are the waste water discharge requirement constraints; $ADS_{c,t}$ $IDS_{c,t}$ and $LDS_{c,t}$ are the waste water discharge coefficient of agriculture, industry and life (tonne/m^3). $ATS_{c,t}^{\pm}$, $ITS_{c,t}^{\pm}$ and $LTS_{c,t}^{\pm}$ are the total volume of agricultural, industrial and living waste water discharge permission (tonne).

(4) *COD emission limitation constraints:*

$$\sum_{s=1}^{3} AW_{s,c,t}^{\pm} \times ADS_{c,t} \times ACO_{c,t} \leq ATCO_{c,t}^{\pm} \qquad (13a)$$

$$\sum_{s=1}^{3} IW_{s,c,t}^{\pm} \times IDS_{c,t} \times ICO_{c,t} \leq ITCO_{c,t}^{\pm} \tag{13b}$$

$$\sum_{s=1}^{3} LW_{s,c,t}^{\pm} \times LDS_{c,t} \times LCO_{c,t} \leq LTCO_{c,t}^{\pm} \tag{13c}$$

where constraints (13a) - (13c) are the COD emission limitation constraints; $ACO_{c,t}$, $ICO_{c,t}$ and $LCO_{c,t}$ are the concentration coefficient of COD discharge in agricultural, industrial and living waste water discharge; $ATCO_{c,t}^{\pm}$, $ITCO_{c,t}^{\pm}$ and $LTCO_{c,t}^{\pm}$ are the total volume of COD discharge of agriculture, industry and life (tonne).

(5) *NH_3-N emission limitation constraints:*

$$\sum_{s=1}^{3} AW_{s,c,t}^{\pm} \times ADS_{c,t} \times AAN_{c,t} \leq ATAN_{c,t}^{\pm} \tag{14a}$$

$$\sum_{s=1}^{3} IW_{s,c,t}^{\pm} \times IDS_{c,t} \times IAN_{c,t} \leq ITAN_{c,t}^{\pm} \tag{14b}$$

$$\sum_{s=1}^{3} LW_{s,c,t}^{\pm} \times LDS_{c,t} \times LAN_{c,t} \leq LTAN_{c,t}^{\pm} \tag{14c}$$

where constraints (14a) - (14c) are the NH_3-N emission limitation constraints; $AAN_{c,t}$, $IAN_{c,t}$ and $LAN_{c,t}$ are the concentration coefficient of NH_3-N discharge in agricultural, industrial and living waste water discharge; $ATAN_{c,t}^{\pm}$, $ITAN_{c,t}^{\pm}$ and $LTAN_{c,t}^{\pm}$ are the total volume of NH_3-N discharge of agriculture, industry and life (tonne).

(6) *Water resources for limitation constraint:*

$$\begin{aligned} AW_{s,c,t}^{\pm} &\leq AXU_{s,c,t} \times AWD_{c,t}^{\pm} \\ AW_{s,c,t}^{\pm} &\geq AXL_{s,c,t} \times AWD_{c,t}^{\pm} \end{aligned} \tag{15a}$$

$$\begin{aligned} IW_{s,c,t}^{\pm} &\leq IXU_{s,c,t} \times IWD_{c,t}^{\pm} \\ IW_{s,c,t}^{\pm} &\geq IXL_{s,c,t} \times IWD_{c,t}^{\pm} \end{aligned} \tag{15b}$$

$$\begin{aligned} LW_{s,c,t}^{\pm} &\leq LXU_{s,c,t} \times LWD_{c,t}^{\pm} \\ LW_{s,c,t}^{\pm} &\geq LXL_{s,c,t} \times LWD_{c,t}^{\pm} \end{aligned} \tag{15c}$$

$$\begin{aligned} EW_{s,c,t}^{\pm} &\leq EXU_{s,c,t} \times EWD_{c,t}^{\pm} \\ EW_{s,c,t}^{\pm} &\geq EXL_{s,c,t} \times EWD_{c,t}^{\pm} \end{aligned} \tag{15d}$$

where constraint (15a) - (15d) is the water sources limitation constraint; $AXU_{s,c,,t}$, $IXU_{s,c,,t}$, $LXU_{s,c,,t}$ and $EXU_{s,c,,t}$ are the maximum proportion of water resource allocation for agriculture, industry, life, ecology; $AXL_{s,c,,t}$, $IXL_{s,c,,t}$, $LXL_{s,c,,t}$ and $EXL_{s,c,,t}$ are the minimum proportion of water resource allocation for agriculture, industry, life, ecology.

(7) *Policy constraint:*

$$\sum_{s=1}^{3}\sum_{c=1}^{18}\left(AW_{s,c,t}^{\pm}+IW_{s,c,t}^{\pm}+LW_{s,c,t}^{\pm}+EW_{s,c,t}^{\pm}\right)\leq PTW_t \tag{16}$$

where constraint (16) is the policy constraint; PTW_t is the total amount of allowed water consumption in 2020 (m^3).

(9) *Nonnegative constraints:*

$$AW_{s,c,t}^{\pm}, IW_{s,c,t}^{\pm}, LW_{s,c,t}^{\pm}, EW_{s,c,t}^{\pm} \geq 0 \tag{17}$$

Constraint (10) means that the amount of supplying water by three water resources in each city are limited, and the total supplying water for each department should not exceed the available water resources (Fu et al., 2018). Constraints (11a) - (11d) indicate that the water resources demand of different departments should be satisfied in order to ensure the water supply security (Tu et al., 2015). Among the water allocation schemes, the allocation for life should take the first priority owing to the harmonious development of social economy as well as the huge economic benefits when its water requirements are being met (Li et al., 2018; Chen et al., 2017). Constraints (12a) and (12c) limit the discharge of agricultural, industrial and living waste water in every city for protecting the ecological environment (Liu et al., 2018). Constraints (13a) - (13c) and constraints (14a) - (14c) are used for ensuring that the amount of COD and NH_3-N emissions should be less than the maximum emission limit (Xie et al., 2018). Constraints (15a) - (15d) are formulated to ensure that the proportion of the water resources should not exceed the requirements (Zhang and Guo, 2017). Constraint (16) is established to ensure that the annual water resources consumption should be controlled within the prescribed scope by 2020 (HWRB, 2017).

3.3 Data collection and analysis

The Appendix shows the specific abbreviation. The modeling data were mainly consist of economic, social, water resources and environmental parameters. These data were obtained from related literatures, site investigation, statistical yearbooks, and websites (Li et al., 2013; HWRB, 2017; HSY, 2017; WPN, 2017; Xie et al., 2018; Wang et al., 2019). However, the modeling coefficients could hardly be deterministic or offer enough precision due to poor information quality, observation errors and subjective experiences (Xu et al., 2017). In this study, uncertainties were depicted in various formats to present the complexities and uncertainties of the MIFCP-RWMS model. In detail, the inputs of the optimization model (i.e. benefits, cost, the supplying of surface water, groundwater and other water, the allowable emissions of waste water, COD and NH_3-H) were expressed as intervals based on the annual historical data (HWRB, 2017; HSY, 2017; WPN, 2017). In addition, the water demands for agriculture, industry, life and ecology were encoded as fuzzy sets based on expert consultations and estimations (Zhang and Huang, 2011a; Xu et al., 2017). According to the survey among the decision makers in RWMS, their preferences regarding water allocation tend to be different attitudes (i.e. conservative, neutral and radical), which indicates that the credibility level (λ) selection has great influence on the optimal solutions (Ji et al., 2018). By introducing fuzzy set theory, the ambiguous credibility level can be expressed as fuzzy number to reflect the fuzziness of decision maker's attitudes (Zhang and Huang, 2010; Ji et al., 2018). The curves of α-cut level and relative credibility level under the attitudes of three types of decision makers were depicted in Figure 3. Table 1 depicts water supply in 18 cities of Henan Province in 2017. Table 2 illustrates department water demand in 18 cities of Henan Province in 2017.

Place Tables 1,2 and Figure 3 here

----

4. Result Analysis

4.1 Solution of water supply

Figure 4 shows the allocated water for three attitudes of decision makers in Zhengzhou City during the planning horizon under $\alpha = 0.5$. Different attitudes of decision makers with diverse credibility level (λ) would have great influence on the supplying water. For example, the total supplying water during the entire planning horizon would increase by $[0.24, 0.25] \times 10^9$ m^3 (conservative attitude), $[0.22, 0.25] \times 10^9$ m^3 (neutral attitude) and $[0.23, 0.25] \times 10^9$ m^3 (radical attitude), respectively. This is because the rapid population growth, the gradually increased industrialization and urbanization would result in the growing demand for water resources; those would urge the total supplying water to increase through improving the water utilization efficiencies. Besides, different allocated water would be affected by three attitudes of decision makers. Specifically, when the attitudes of decision makers were conservative, the total amount of surface water during the planning horizon would increase by 24.42 %, the total amount of groundwater would reduce by 12.41 %, and the total amount of other water would increase by 24.66 %, respectively. This phenomenon can be attributed to the construction and operation of water conservancy projects such as the South to North Water Diversion Project. For the groundwater, local government would formulate relevant policies to restrict the exploitation of groundwater. For the other water, local government would advocate the adjustment of water-saving industries, encourage the reuse of water and speed up the development of waste water treatment technologies. Moreover, since the surface water has higher return compared to other two types of water resources, the proportion of allocated surface water would be the largest. Summarily, decision makers in different cities should select suitable water allocation schemes based on the realities of the local water resources and the requirements of various departments in order to achieve the maximum system benefits.

Place Figure 4 here

Figure 5 presents the supplying water from three water sources under different α-cut levels related to the three attitudes of decision makers. The water supply of different cities from three water sources would vary greatly from each other. For example, under radical attitude of decision makers, the supplying surface water in Xinyang city would be about 4.59 times more than that in Zhumadian City. However, the supplying groundwater in Xinyang City would be about 3.28 times less than that in Zhumadian City. In addition, the amount of other supplying water would be larger in Zhengzhou City and relatively smaller in other cities owing to the uneven distribution and various utilization policies of water resources in different cities. Three attitudes of decision makers with different α-cut levels would have great influence on the supplying water from three water sources in different cities. For example, for conservative attitude of decision makers, the lower bound of supplying water would not be affected by the change of α-cut levels, its value would always be 2.93×10^9 m^3; while the upper bound of the supplying water would lessen with the increase of α-cut levels. For neutral attitude of decision makers, the upper and lower bounds of supplying water would be influenced simultaneously. For instance, the upper value would be reduced from 2.99×10^9 m^3 ($\alpha = 0.5$) to 2.98×10^9 m^3 ($\alpha = 1$), while the lower value would be increased from 2.94×10^9 m^3 ($\alpha = 0.5$) to 2.95×10^9 m^3 ($\alpha = 1$). For radical attitude of decision makers, the upper bound of supplying water would not be affected by the alter of α-cut level, which would be kept 3.00×10^9 m^3; while the lower bound of supplying water would be increased with the augment of α-cut level. This is because different credibility level (λ) would make the water requirements of each department get different satisfaction degrees. Generally, comprehensive water resources optimal distribution management strategies (e.g., the attitude of decision makers, the advancement of irrigation modes as well as the optimization of water sources allocation patterns) need to be implemented according to the real-world conditions.

Place Figure 5 here

4.2 Solution of water allocation

Figure 6 presents the results of water allocation in different cities under three attitudes of decision makers during the entire planning horizon. For the conservative attitude of decision makers under $\alpha = 0.5$, groundwater would account for 32.40 % of the total supplying water in Zhengzhou City, while it would be 49.26 % of the total supplying water in Xuchang City. This is because each city has unique geographical location and water resources utilization policies, the supplying water would be diverse in different cities. Additionally, there would be significant variances in the amount of water usage for different departments. For example, when the attitudes of decision maker were conservative under $\alpha = 0.5$, the surface water in Zhengzhou City for agriculture, industry, life and ecology would be 53.83 %, 38.09 %, 54.11 % and 47.08%, respectively. This is because different departments would require diverse water quantities owing to various social-economic development requirements. Furthermore, there was a significant dissimilarity in the amount of water usage in different cities which suggested that decision makers need to take both the actual availability of water resources and the related policy requirements into account and balance the contradictions of water resources for various departments. Besides, three attitudes of decision makers would give rise to markedly changes in water distribution. For instance, the allocated water for life in Zhengzhou City would be 2.09 × 10^9 m^3 (conservative attitude), 2.12 × 10^9 m^3 (neutral attitude) and 2.15 × 10^9 m^3 (radical attitude), respectively. This is because three attitudes of decision makers took different credibility levels (λ) into consideration, and the credibility levels (λ) under conservative, neutral and radical attitudes of decision makers would decrease successively. Moreover, different credibility levels (λ) would make the water requirements of each department get different satisfaction degrees, the higher credibility level would bring about smaller allocated water resources in every department. Therefore, decision makers should fully consider the characteristics associated with different requirements of water demand and supply in each city and try to adopt various attitudes of decision makers to identify effective water allocation schemes.

Place Figure 6 here

Figure 7 shows the allocated water under three attitudes of decision makers during the entire planning horizon. Generally, the allocated water would be different with time for different departments in each city toward different attitudes. For instance, when the attitudes of decision makers were neutral, the share of agricultural water in period 1 would account for 53.92% of the total water consumption, which were higher than that of other departments in Anyang City; comparably, the industry water in period 1 for Zhengzhou City and Xuchang City would take the primary roles which occupied 25.16 % and 27.76 %, respectively. This phenomenon would be caused by the water resources condition, industrial structure, living standard, and economic development. Besides, for conservative attitude of decision makers under $\alpha = 0.5$, the allocated agricultural water in Xinyang City over the planning horizon would decrease by 57.05×10^6 m^3, while the allocated water for industry, life and ecology would increase by 12.80×10^6 m^3, 65.84×10^6 m^3 and 11.42×10^6 m^3, respectively. This phenomenon would be attributed to the development of industrialization, urbanization, the steady population growth, as well as the significant improvement in human life. Since the exploitation of agricultural water-saving irrigation technology and the adjustment of planting structure played significant roles in the water consumption of agriculture, the distribution of agricultural water would decrease with time. Generally, polices and strategies should be made not only to ensure basic water demand of different departments, but also to improve water efficiency of each department, especially in agriculture and industry.

Place Figure 7 here

4.3 Solution of waste water, COD and NH_3-N emissions

Figure 8 shows the volume of industrial waste water, COD and NH_3-N emissions for three attitudes of decision makers during the whole planning horizon under $\alpha = 0.5$. There were obvious differences in the volume of discharged waste water for different cities. For example, for the radical attitude of decision makers, the volume of industrial waste water in Zhengzhou City and Xinxiang City were relatively large, which were 415.30 × 10^6 tonne and 128.19 × 10^6 tonne, respectively. On the contrary, the industrial waste water in Hebi City and Jiyuan City were relatively small, which were 36.83 × 10^6 tonne and 21.77 × 10^6 tonne, respectively. This phenomenon were the results of various industrial types, industrial development conditions and industrial water usage status in different cities. Since the capacity of industrial waste water treatment was altered from different cities, the concentration of major pollutants in waste water were also distinct. The volume of discharged COD in Nanyang City would be 15.39 × 10^3 tonne, which were 18.43 times bigger than that in Jiyuan City. Additionally, it can be clearly seen that the amounts of pollutants under radical attitude of decision makers are significantly greater than that under the conservative attitude of decision makers. This is because the radical attitude of decision makers would take smaller credibility level (λ) into consideration, the water demand of different departments would be more fully satisfied, then there would be more consumed water in the industry. In contrast, the conservative decision makers would have a relatively small amount of waste water. Results indicated that various attitudes of decision makers would lead to the change of pollutant emissions. Moreover, the pollutants mitigation levels would correspond to the city's industrial system returns. The net benefits for industry would have a decreasing tendency as the pollutant-reduction levels increasing. Results implied that effective water usage attitudes should be desired to reduce pollutant emissions, improve water utilization efficiencies and achieve the sustainable development of industry.

Place Figure 8 here

4.4 System benefits

Figure 9 shows the system benefits under conservative, neutral and radical attitudes of decision makers during the planning horizon. For conservative attitude of decision makers, the altered α-cut levels would have no impact on the lower bound of system benefits, which would be always equivalent to 19.26×10^{12} ¥; while the system benefits in upper bound would be decreased from 19.97×10^{12} ¥ ($\alpha = 0.5$) to 19.88×10^{12} ¥ ($\alpha = 1$). For neutral attitudes of decision makers, when α was 0.5, 0.8 and 1, the upper bound of system benefits would be 20.23×10^{12} ¥, 20.20×10^{12} ¥ and 20.18×10^{12} ¥, respectively. The lower bound of system benefits would be 19.43×10^{12} ¥, 19.46×10^{12} ¥ and 19.48×10^{12} ¥, respectively. For the radical attitudes of decision makers, the upper bound of system benefits would not be affected by the change of α-cut level, it would be always equivalent to 20.42×10^{12} ¥. As the increase of α-cut level, the lower bound of system benefits would be increased from 19.67×10^{12} ¥ ($\alpha = 0.5$) to 19.75×10^{12} ¥ ($\alpha = 1$). Generally, the reason was that diverse attitudes of decision makers took distinct credibility level (λ) into consideration, the credibility level (λ) under conservative, neutral and radical attitudes of decision makers would decrease successively. Different credibility levels (λ) would make the water resources demand of each department get different satisfaction degrees. Results also indicated that the conservative decision makers with the higher credibility level (λ) would lead to a less system benefits and support smaller system risk; comparably, the radical decision makers with a lower credibility level (λ) would gain a greater system benefits and bear larger system risk; the neutral decision makers would secure the medium value of credibility level (λ), and the reasonable probability that the projected goals will be reached (Ji et al., 2018).

Place Figure 9 here

----

5. Discussion

5.1 Comparisons among three attitudes and practical water requirements

Generally, water resource managers should rationally utilize water resources (i.e. surface water, groundwater and other water) and strengthen the unified dispatch of water resources in order to alleviate the restriction of water resources shortage and protect the security of water-supply. According to the requirement of "13th Five-Year Plan (13th FYP)" in Zhengzhou City (i.e. Water Resources Consumption Total and Intensity Dual Control Work Implementation Plan), the total annual water consumption of Zhengzhou City would be controlled within 2.25×10^9 m^3 by 2020 (ZMSM, 2017). Figure 4 shows that the amount of water allocated to Zhengzhou City in period 1 would be $[2.18, 2.22] \times 10^9$ m^3 (conservative attitude), $[2.21, 2.26] \times 10^9$ m^3 (neutral attitude) and $[2.23, 2.28] \times 10^9$ m^3 (radical attitude), respectively. This phenomenon illustrated that the results under three attitudes would be diverse, and the amount of allocated water with the conservative attitude would be smaller than that permitted in 13th FYP. As shown in Figure 10a, when $\alpha = 0.8$, the system benefits with the radical attitude (i.e. $[19.73, 20.42] \times 10^{12}$ ¥) would be higher than that with the conservative attitude (i.e. $[19.26, 19.91] \times 10^{12}$ ¥). It is mainly because the radical decision makers would prefer achieving the maximum system benefits and having more allocated water resources. Conversely, the conservative decision makers would tend to seek the system benefits within the prerequisite of minimum water resources consumption. Comparatively, the neutral decision makers would choose medium system benefits with intermediate system satisfaction (Ji et al., 2018). For example, in the actual RWMS of Henan Province, some cities (i.e. Puyang City and Jiaozuo City) would pursue the development of local economy, which would prompt the rapid increase of water demand in each department. Therefore, the local decision makers would be willing to adopt a radical attitude for allocating a larger amount of water resources and meeting economic development requirements. On the contrary, some cities (i.e. Zhengzhou City and Nanyang City) would be committed to building a water-eco-civilized city, the local decision makers would choose conservative attitude to implement strict water utilization programs, vigorously promote the construction of water-saving society, and strictly control waste water discharge. In summary, water resources managers should decide the appropriate attitude based on their own development status and economic goals (HWRB, 2017).

5.2 Comparisons among MIFCP, LP, IPP and IFCP

The study case would turn into an interval fuzzy-credibility constrained programming (IFCP) problem, when the fuzzy credibility levels under three attitudes were simplified into the assumed credibility levels (Zhang et al., 2019b; Zhang et al., 2020). The study problem could also be solved through an IPP method by transforming the fuzzy chance constraints into deterministic constraints (Liu and Hang, 2013). Then, the study problem could be further addressed through the conventional linear programming (LP) approach by simplifying the interval numbers as deterministic values (Karterakis et al., 2007). Figure 10 illustrates the compared results among LP, IPP, IFCP and MIFCP (i.e. conservative, neutral, radical) methods. As shown in Figure 10b, the amount of allocated water in Zhengzhou City during the whole planning horizon would be 7.14 × 10^9 m^3 in LP, [7.06, 7.19] × 10^9 m^3 in IPP, respectively. Results indicated that values obtained in LP would be within the water allocation range obtained by IPP with consideration of observation error, price fluctuation and subjective inference. Nevertheless, as the scope of interval values increased, the results by IPP would become more ambiguous and would not reflect the system credibility (Ji et al., 2018). IFCP could overcome the above limitations and improve the system effectiveness by conducting the tradeoffs among satisfaction of constraints and different credibility levels (Li et al., 2013). However, in practical problems, decision makers would have distinct attitudes towards their subjective preferences. MIFCP could reflect the preferred credibility level of constraints based on three attitudes of decision makers, which would produce a series of schemes for water resources allocation, system benefits and pollutant emissions. For example, the conservative decision makers would prefer to allocate less water resources for the sake of high system reliability. On the contrary, the radical decision makers would tend to allocate more water resources for maximum system benefits. As shown in Figure 10b, the upper bound of water allocation in Zhengzhou City during the planning horizon under $\alpha = 0.8$ would be 7.17 × 10^9 m^3 (IFCP), 7.06 × 10^9 m^3 (conservative), 7.15 × 10^9 m^3 (neutral), 7.25 × 10^9 m^3 (radical), respectively. Therefore, the proposed MIFCP method is superior to LP, IPP and IFCP methods. It can provide more comprehensive and reliable choices for decision managers and be applied to a wider range of problems. Summarily, the MIFCP-RWMS model could effectively describe the multiple preferences of decision makers in the process of water resource allocation among 18 cities.

Place Figure 10 here

----

6. Conclusions

In this study, a MIFCP method has been developed by integrating FCP, IPP and attitudes of decision makers into a framework. MIFCP can effectively deal with uncertainties expressed as interval and fuzzy information and reflect multiple preferences of decision makers. Then, a MIFCP-RWMS model has been established for planning the RWMS of Henan Province, China. Solutions of multiple attitudes of decision makers associated with varied credibility levels have also been obtained in the MIFCP-RWMS model.

Several findings related to water allocation, waste water discharge, COD and NH_3-N emissions as well as system benefits can be summarized as follows: over the planning horizon, a) the total supplying water from the radically oriented decision maker can increase by 1.82×10^9 m^3 compared to that from the conservatively oriented decision maker; b) for the radically oriented decision maker, the water allocation for agriculture, industry, life and ecology can respectively change by 0.24%, 0.37%, 0.67% and 0.44% as the α-cut level changes from 0.5 to 1; and c) uncertainties associated with different credibility levels and attitudes can result in varied solutions of water allocation, pollutant emissions and system benefits, and uncertainties can jointly make the system benefits change about 5.66%.

The MIFCP-RWMS model can provide useful strategies for planning the RWMS by considering uncertainties expressed as interval, fuzzy information and different attitudes of decision makers. The MIFCP-RWMS model cannot only provide some realistic supports for the study area but also supply series of theoretical suggestions for other study regions in terms of the regions' scale, complexity and uncertainty (Yu and Li, 2019; Li et al.,2019b). However, there are some potential limitations that need to be addressed in future studies. Firstly, this study merely discusses the model's reasonability and applicability in the real case of Henan Province, it neglects the verification in other study areas such as Zhangweinan River Basin, Shanxi Province and Xinjiang Uygur Autonomous Region, thus some comparative analyses shall be further extended (Liu et al., 2016; Wang et al., 2017; Luo et al., 2019). Secondly, in this study, three preference attitudes of decision makers are only divided by the prediction of the future available water resources, which are incapable of analyzing the decision makers' preferences on water demand estimation and economic development in the future. For instance, the domestic water demand may subject to socio-economic factors (population, household size, income, education and life style), climatic characteristics (temperature and humidity) and public water policies and strategies (Makki et al., 2015; Kozłowski et al., 2018). Hence, some sensitivity analyses towards other key parameters (e.g. water demand, water price, water discharge requirement) shall be further adopted in the MIFCP-RWMS model (Jiang et al., 2018; Poirier-Pocovi and Bailey, 2020).

Acknowledgements

This research was supported by the National Natural Science Foundation of China (51809145 and 51909239), the Key Research Project of Henan Higher Education Institution (20A570001), and the Postdoctoral Foundation of Henan Province (1901008). A demo example to clarify the computational procedures of the proposed MIFCP approach as well as the LP, IPP and IFCP methods is available at ??????. Both data and code used in this paper are available from the authors upon request (yulei2018@zzu.edu.cn). The authors are grateful to the editors and the anonymous reviewers for their insightful comments and suggestions.

References

Abdulbaki, D., Al-Hindi, M., Yassinea, A., Najm, M.A., 2017. An optimization model for the allocation of water resources. Journal of Cleaner Production. 164, 994-1006. https://doi.org/10.1016/j.jclepro.2017.07.024

Bi, W., Dandy, G.C., Maier, H.R., 2015. Improved genetic algorithm optimization of water distribution system design by incorporating domain knowledge. Environmental Modelling & Software. 69, 370-381. https://doi.org/10.1016/j.envsoft.2014.09.010

Charnes, A., Cooper, W.W., 1959. Chance-constrained programming. Management Science. 6(1), 73-79. https://doi.org/10.1287/mnsc.6.1.73

Chen, S., Shao, D.G., Gu, W.Q., Xu, B.L., Li, H.X., Fang, L.Z., 2017. An interval multistage water allocation model for crop different growth stages under inputs uncertainty. Agricultural Water Management. 186, 86-97. https://doi.org/10.1016/j.agwat.2017.03.001

Chen, S., Xu, J.J., Li, Q.Q., Tan, X.Z., Nong, X.Z., 2019. A copula-based interval-bistochastic programming method for regional water allocation under uncertainty. Agricultural Water Management. 217, 154-164. https://doi.org/10.1016/j.agwat.2019.02.008

Chang, N.B., Wang, S.F, 1997. A fuzzy goal programming approach for the optimal planning of metropolitan solid waste management systems. European Journal of Operational Research. 99, 303-321. https://doi.org/10.1016/S0377-2217(96)00024-0

Cottle, R.W., Dantzig, G.B., 1970. A generalization of the linear complementarity problem. Journal of Combinatorial Theory. 8(1), 79-90. https://doi.org/10.1016/S0021-9800(70)80010-2

Dai, C., Cai, Y.P., Ren, W., Xie, Y.F., Guo, H.C., 2016. Identification of optimal placements of best management practice through an interval-fuzzy possibilistic programming model. Agricultural Water Management. 165, 108-121. https://doi.org/10.1016/j.agwat.2015.10.016

Dantzig, G.B., 1955. Linear programming under uncertainty. Management Science. 1(3-4):197-206. https://doi.org/10.1287/mnsc.1.3-4.197

Dantzig, G.B., 1982. Reminiscences about the origins of linear programming. Operations Research Letters. 1(2):43-48. https://doi.org/10.1016/0167-6377(82)90043-8

Fan, Y.R., Huang, G.H., 2012. A robust two-step method for solving interval linear programming problems within an environmental management context. Journal of Environmental Informatics. 19(1), 1-9. https://doi.org/10.3808/jei.201200203

Fu, Y.C., Zhang, J., Zhang, C.L., Zang, W.B., Guo, W.X., Qian, Z., Liu, L.S., Zhao, J.Y., Feng, J., 2018. Payments for ecosystem services for watershed water resource allocations. Journal of Hydrology. 556, 689-700. https://doi.org/10.1016/j.jhydrol.2017.11.051

Garg, N.K., Dadhich, S.M., 2014. Integrated non-linear model for optimal cropping pattern and irrigation scheduling under deficit irrigation. Agricultural Water Management. 140, 1-13. https://doi.org/10.1016/j.agwat.2014.03.008

HSY (Henan Statistical Yearbook), 2017. Statistics Bureau of Henan Province. Henan, China. http://www.ha.stats.gov.cn/hntj/lib/tjnj/2017/indexch.htm.

Huang, G.H., Baetz, B.W., Patry, G.G., 1992. A grey linear programming approach for municipal solid waste management planning under uncertainty. Civil Engineering Systems. 9(4), 319-335. https://doi.org/10.1080/02630259208970657

Huang, G.H., Loucks, D. P., 2000. An inexact two-stage stochastic programming model for water resources management under uncertainty. Civil Engineering Systems. 17(2), 95-118. https://doi.org/10.1080/02630250008970277

Huang, X.X., 2006. Credibility-based chance-constrained integer programming models for capital budgeting with fuzzy parameters. Information Sciences. 176, 2698-2712. https://doi.org/10.1016/j.ins.2005.11.012

HWRB (Henan Water Resources Bulletin), 2017. Henan Hydrological Information Network. Henan, China. http://www.hnssw.com.cn/resources/index.jhtml.

Jiang, L., Li, Y.P., Zhao, X., Tillotson, M.R., Wang, W.C., Zhang, S.S., Sarpong, L., Asmaa, Q., Pan, B.Z., 2018. Parameter uncertainty and sensitivity analysis of water quality model in Lake Taihu, China. Ecological Modelling. 375, 1-12. https://doi.org/10.1016/j.ecolmodel.2018.02.014

Ji, L., Zhang, B.B., Huang, G.H., Xie, Y.L., Niu, D.X., 2018. Explicit cost-risk tradeoff for optimal energy management in CCHP microgrid system under fuzzy-risk preferences. Energy Economics. 70, 525-535. https://doi.org/10.1016/j.eneco.2018.01.017

Kacimov, A.R., Obnosov, Y.V., 2019. Analytic solutions for fresh groundwater lenses floating on saline water under desert dunes: The Kunin-Van Der Veer legacy revisited. Journal of Hydrology. 574, 733-743. https://doi.org/10.1016/j.jhydrol.2019.04.065

Kozłowski, E., Kowalska, B., Kowalski, D., Mazurkiewicz, D., 2018. Water demand forecasting by trend and harmonic analysis. Archives of Civil and Mechanical Engineering. 18, 140-148. https://doi.org/10.1016/j.acme.2017.05.006

Li, C.C., Cai, Y.P., Qian, J.P., 2018. A multi-stage fuzzy stochastic programming method for water resources management with the consideration of ecological water demand. Ecological Indicators. 95, 930-938. https://doi.org/10.1016/j.ecolind.2018.07.029

Li, M., Fu, Q., Singh, V.P., Ji, Y., Liu, D., Zhang, C.L., Li, T.X., 2019b. An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty. Science of the Total Environment. 651, 1416-1434. https://doi.org/10.1016/j.scitotenv.2018.09.291

Li, X.M., Lu, H.W., Li, J., Du, P., Xu, M., He, L., 2015. A modified fuzzy credibility constrained programming approach for agricultural water resources management-A case study in Urumqi, China. Agricultural Water Management. 156, 79-89. https://doi.org/10.1016/j.agwat.2015.03.005

Li, Y.P., Huang, G.H., Yang, Z.F., Nie, S.L., 2008. IFMP: Interval-fuzzy multistage programming for water resources management under uncertainty. Resources, Conservation and Recycling. 52, 800-812. https://doi.org/10.1016/j.resconrec.2007.11.007

Li, Y.Y., Cui, Q., Li, C.H., Wang, X., Cai, Y.P., Cui, G., Yang, Z.F., 2016. An improved multi-objective optimization model for supporting reservoir operation of china's South-to-North Water Diversion Project. Science of the Total Environment. 575, 970-981. https://doi.org/10.1016/j.scitotenv.2016.09.165

Li, Z., Huang, G.H., Guo, L., Fan, Y.R., Chen, J.P., 2019a. A fuzzy gradient chance-constrained evacuation model for managing risks of nuclear power plants under multiple uncertainties. Journal of Environmental Informatics. 33(2), 129-138. https://doi:10.3808/jei.201500315

Li, Z., Huang, G.H., Zhang, Y.M., Li, Y.P., 2013. Inexact two-stage stochastic credibility constrained programming for water quality management. Resources, Conservation and Recycling. 73, 122-132. https://doi.org/10.1016/j.resconrec.2013.01.008

Li, Z.W., Majozi, T., 2018. Optimal Synthesis of Batch Water Networks with a Flexible Scheduling Framework Using Dynamic Programming. Computer Aided Chemical Engineering. 44, 205-210. https://doi.org/10.1016/B978-0-444-64241-7.50029-X

Liu, B.D., Liu, Y.K., 2002. Expected value of fuzzy variable and fuzzy expected value models. IEEE Transactions on Fuzzy Systems. 10, 445-450.

https://doi.org/10.1109/TFUZZ.2002.800692

Liu, D.D., Guo, S.L, Shao, Q.X., Liu, P., Xiong, L.H., Wang, L., Hong, X.J., Xu, Y., Wang, Z.L., 2018. Assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions. Journal of Hydrology. 556, 759-774. https://doi.org/10.1016/j.jhydrol.2017.12.002

Liu, J., Li, Y.P., Huang, G.H., Zhuang, X.W., Fu, H.Y., 2017. Assessment of uncertainty effects on crop planning and irrigation water supply using a Monte Carlo simulation based dual-interval stochastic programming method. Journal of Cleaner Production. 149, 945-967. https://doi.org/10.1016/j.jclepro.2017.02.100

Liu, J.H., Gao, X.R., Shao, W.W., Han, J.Y., Gong, J.G., Niu, C.W., 2016. Water Resources Monitoring System Construction in Shanxi Province, China. Procedia Engineering. 154, 326-333. https://doi.org/10.1016/j.proeng.2016.07.484

Liu, Z., Huang, Y.L., 2013. Sustainable distributed biodiesel manufacturing under uncertainty: An interval-parameter-programming-based approach. Chemical Engineering Science. 93, 429-444. https://doi.org/10.1016/j.ces.2013.02.024

Luo, M., Liu, T., Meng, F.H., Duan, Y.C., Bao, A.M., Xing, W., Feng, X.W., Maeyer, P.D., Frankl, A., 2019. Identifying climate change impacts on water resources in Xinjiang, China. Science of the Total Environment. 676, 613-626. https://doi.org/10.1016/j.scitotenv.2019.04.297

Makki, A.A., Stewart, R.A., Beal, C.D., Panuwatwanich, K., 2015. Novel bottom-up urban water demand forecasting model: Revealing the determinants, drivers and predictors of residential indoor end-use consumption. Resources, Conservation and Recycling. 95, 15-37. https://doi.org/10.1016/j.resconrec.2014.11.009

Maqsood, I., Huang, G.H., Yeomans, J.S., 2005. An interval-parameter fuzzy two-stage stochastic program for water resources management under uncertainty. European Journal of Operational Research. 167, 208-225. https://doi.org/10.1016/j.ejor.2003.08.068

Martinsen, G., Liu, S.X., Mo, X.G., Bauer-Gottwein, P., 2019. Joint optimization of water allocation and water quality management in Haihe River basin. Science of the Total Environment. 654, 72-84. https://doi.org/10.1016/j.scitotenv.2018.11.036

Milan, S.G., Roozbahani, A., Banihabib, A.E., 2018. Fuzzy optimization model and fuzzy inference system for conjunctive use of surface and groundwater resources. Journal of Hydrology. 566, 421-434. https://doi.org/10.1016/j.jhydrol.2018.08.078

(ND) National data, 2017. National Bureau of Statistics of China. Henan, China. http://data.stats.gov.cn

Poirier-Pocovi, M., Bailey, B.N., 2020. Sensitivity analysis of four crop water stress indices to ambient environmental conditions and stomatal conductance. Scientia Horticulturae. 259, 108825. https://doi.org/10.1016/j.scienta.2019.108825

Rani, D., Gulati, T.R., Garg, H., 2016. Multi-objective non-linear programming problem in intuitionisticx fuzzy environment: Optimistic and pessimistic view point. 64, 228-238. https://doi.org/10.1016/j.eswa.2016.07.034

Ren, C.F., Guo, P., Tan, Q., Zhang, L.D., 2017. A multi-objective fuzzy programming model for optimal use of irrigation water and land resources under uncertainty in Gansu Province, China. Journal of Cleaner Production. 164, 85-94. https://doi.org/10.1016/j.jclepro.2017.06.185

Rong, A., Lahdelma, R., 2008. Fuzzy chance constrained linear programming model for optimizing the scrap charge in steel production. European Journal of Operational Research. 186(3), 953-964. https://doi.org/10.1016/j.ejor.2007.02.017

Karterakis, S.M., Karatzas, G.P., Ioannis K. Nikolos, I.K., Papadopoulou, M.P., 2007. Application of linear programming and differential evolutionary optimization methodologies for the solution of coastal subsurface water management problems subject to environmental criteria. Journal of Hydrology. 342, 270-282. https://doi.org/10.1016/j.jhydrol.2007.05.027

Sasikumar, K., Mujumdar, P.P., 2000. Application of fuzzy probability in water quality management of a river system. International Journal of Systems Science. 31, 575-91. https://doi.org/10.1080/002077200290894

Singh, A., 2012. An overview of the optimization modelling applications. Journal of Hydrology. 466-467, 167-182. https://doi.org/10.1016/j.jhydrol.2012.08.004

Singh, A., 2015. Land and water management planning for increasing farm incoming in irrigated dry areas. Land Use Policy. 42, 244-250. https://doi.org/10.1016/j.landusepol.2014.08.006

Singh, S.K., Yadav, S.P., 2015. Modeling and optimization of multi objective non-linear programming problem in intuitionistic fuzzy environment. Applied Mathematical Modelling, 39(16), 4617-4629. http://dx.doi.org/10.1016/j.apm.2015.03.064

Sun, J., Li, Y.P., Suo, C., Liu, Y.R., 2019. Impacts of irrigation efficiency on agricultural water-land nexus system management under multiple uncertainties-A case study in Amu Darya River basin, Central Asia. Agricultural Water Management. 216, 76-88. https://doi.org/10.1016/j.agwat.2019.01.025

Tu, Y., Zhou, X.Y., Gang, J., Liechty, M., Xu, J.P., Lev, B., 2015. Administrative and market-based allocation mechanism for regional water resources planning. Resources, Conservation and Recycling. 95, 156-173. https://doi.org/10.1016/j.resconrec.2014.12.011

Uche, J., Martínez-Gracia, A., Círez, F., Carmona, U., 2015. Environmental impact of water supply and water use in a Mediterranean water stressed region. Journal of Cleaner Production.

88, 196-204. https://doi.org/10.1016/j.jclepro.2014.04.076

Wang, C.X., Li, Y.P., Huang, G.H., 2017. Taguchi-factorial type-2 fuzzy random optimization model for planning conjunctive water management with compound uncertainties. Environmental Modelling & Software. 97, 184-200. https://doi.org/10.1016/j.envsoft.2017.08.007

Wang, S., Huang, G.H., 2012. Identifying optimal water resources allocation strategies through an interactive multi-stage stochastic fuzzy programming approach. Water Resources Management. 26, 2015-2038. https://doi.org/10.1007/s11269-012-9996-1

Wang, Y.M., Yang, J., Chang, J.X., 2019. Development of a coupled quantity-quality-environment water allocation model applying the optimization-simulation method. Journal of Cleaner Production. 213, 944-955. https://doi.org/10.1016/j.jclepro.2018.12.065

WPN (Water Price Network), 2017. E20 Environment Platform. Henan, China. http://www.h2o-china.com/price/list?pid=16, cited 13.5.2019.

Xie, Y.L., Xia, D.H., Huang, G.H., Ji, L., 2018. Inexact stochastic optimization model for industrial water resources allocation under considering pollution charges and revenue-risk control. Journal of Cleaner Production. 203, 109-124. https://doi.org/10.1016/j.jclepro.2018.08.245

Xu, J.X., Huang, G.H., Li, Z., Chen, J.P., 2017. A two-stage fuzzy chance-constrained water management model. Environment Science and Pollution Research. 24, 12437-12454. https://doi.org/10.1007/s11356-017-8725-y

Yang, J., Chang, J.X., Wang, Y.M., Li, Y.Y., Hu, H., Chen, Y.T., Huang, Q., Yao, J., 2018. Comprehensive drought characteristics analysis based on a nonlinear multivariate drought index. Journal of Hydrology. 557, 651-667. https://doi.org/10.1016/j.jhydrol.2017.12.055

Yan, Z.Q., Zhou, Z.H., Sang, X.F., Wang, H., 2018. Water replenishment for ecological flow with an improved water resources allocation model. Science of the Total Environment. 643, 1152-1165. https://doi.org/10.1016/j.scitotenv.2018.06.085

Ye, Q.L., Li, Y., Zhuo, L., Zhang, W.L., Xiong, W., Wang, C.,Wang, P.F., 2018. Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: A case study for Beijing, China. Water Research. 129, 264-276. https://doi.org/10.1016/j.watres.2017.11.036

Yu, L., Li, Y.P., 2019. A flexible-possibilistic stochastic programming method for planning municipal-scale energy system through introducing renewable energies and electric vehicles. Journal of Cleaner Production. 207, 772-787. https://doi.org/10.1016/j.jclepro.2018.10.006

Yu, L., Li, Y.P., Huang, G.H., 2016. A fuzzy-stochastic simulation-optimization model for planning electric power systems with considering peak-electricity demand: A case study of Qingdao, China. Energy. 98, 190-203. https://doi.org/10.1016/j.energy.2016.01.021

Yu, L., Li, Y.P., Shan, B.G., Huang, G.H., Xu, L.P., 2018. A scenario-based interval-stochastic basic-possibilistic programming method for planning sustainable energy system under uncertainty: A case study of Beijing, China. Journal of Cleaner Production. 197, 1454-1471. https://doi.org/10.1016/j.jclepro.2018.06.248

Zhang, C.L., Guo, P., 2017. A generalized fuzzy credibility-constrained linear fractional programming approach for optimal irrigation water allocation under uncertainty. Journal of Hydrology. 553, 735-749. https://doi.org/10.1016/j.jhydrol.2017.08.008

Zhang, C.L., Li, X.M., Guo, P., Huo, Z.L., 2020. An improved interval-based fuzzy credibility-constrained programming approach for supporting optimal irrigation water management under uncertainty. Agricultural Water Management. 238, 106185. https://doi.org/10.1016/j.agwat.2020.106185

Zhang, F., Engel, B.A., Zhang, C.L., Guo, S.S., Guo, P., Wang, S.F., 2019b. Agricultural production planning approach based on interval fuzzy credibility-constrained bi-level programming and Nerlove supply response theory. Journal of Cleaner Production. 233, 1158-1169. https://doi.org/10.1016/j.jclepro.2019.06.096

Zhang, F., Zhang, C.L., Yan, Z.H., Guo, S.S., Wang, Y.Z., Guo, P., 2018. An interval nonlinear multiobjective programming model with fuzzy-interval credibility constraint for crop monthly water allocation. Agricultural Water Management. 209, 123-133. https://doi.org/10.1016/j.agwat.2018.07.026

Zhang, J.L., Li, Y.P., Zeng, X.T., Huang, G.H., Li, Y., Zhu, Y., Kong, F.L., Xi, M., Liu, J., 2019a. Effluent trading planning and its application in water quality management: A factor-interaction perspective. Environmental Research. 168, 286-305. https://doi.org/10.1016/j.envres.2018.09.029

Zhang, Y.M., Huang, G.H., 2010. Fuzzy Robust Credibility-Constrained Programming for Environmental Management and Planning. Journal of the Air & Waste Management Association. 60, 711-721. https://doi.org/10.3155/1047-3289.60.6.711

Zhang, Y.M., Huang, G.H., 2011a. Inexact credibility constrained programming for environmental system management. Resources, Conservation and Recycling. 55, 441-447. https://doi.org/10.1016/j.resconrec.2010.11.007

Zhang, Y.M., Huang, G.H., 2011b. Optimal water resource planning under fixed budget by interval-parameter credibility constrained programming. Engineering Optimization. 43(8), 879-889. https://doi.org/10.1080/0305215X.2010.522709

Zhang, Y.M., Huang, G.H., Lin, Q.G., Lu H.W., 2012. Integer fuzzy credibility constrained programming for power system management. Energy. 38, 398-405. https://doi.org/10.1016/j.energy.2011.11.035

Zomorodian, M., Lai, S.H., Homayounfar, M., Ibrahim, S., Fatemi, S.E., El-Shafie, A., 2018. The state-of-the-art system dynamics application in integrated water resources modeling. Journal of Environmental Management. 227, 294-304. https://doi.org/10.1016/j.jenvman.2018.08.097

List of Table Captions

Table 1. Water supply in 18 cities of Henan Province in 2017 (10^9 m^3).

Table 2. Water demand in 18 cities of Henan Province in 2017 (10^9 m^3).

List of Figure Captions

Figure 1 The study area

Figure 2 The framework of MIFCP-RWMS model

Figure 3 The curves of α-cut level and relative credibility level under the attitudes of three types of decision makers

Figure 4 Amount of water supply under three attitudes of decision makers during the total planning periods under $\alpha = 0.5$ (10^6 m^3)

Figure 5 Amount of water resources supply under three attitudes of decision makers (10^9 m^3)

Figure 6 Amount of water allocation under three attitudes of decision makers in different cities under $\alpha = 0.5$ (10^9 m^3)

Figure 7 Amount of water allocation under three attitudes of decision makers under $\alpha = 0.5$ (10^9 m^3)

Figure 8 Amount of main pollutants under different attitudes of decision makers under $\alpha = 0.5$

Figure 9 System benefits under three attitudes of decision makers with different α-cut levels (10^{12} ¥)

Figure 10 Compared results among MIFCP, LP, IPP and IFCP and under $\alpha = 0.8$