

Development of a fuzzy-stochastic programming with Green Z-score criterion method for planning water resources systems with a trading mechanism

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Abstract This study developed a fuzzy-stochastic programming with Green Z-score criterion (FSGZ) method for water resources allocation and water quality management with a trading-mechanism (WAQT) under uncertainties. FSGZ can handle uncertainties expressed as probability distributions, and it can also quantify objective/subjective fuzziness in the decision-making process. Risk-averse attitudes and robustness coefficient are joined to express the relationship between the expected target and outcome under various risk preferences of decision makers and systemic robustness. The developed method is applied to a real-world case of WAQT in the Kaidu-Kongque River Basin in northwest China, where an effective mechanism (e.g., market trading) to simultaneously confront severely diminished water availability and degraded water quality is required. Results of water transaction amounts, water allocation patterns, pollution mitigation schemes, and system benefits under various scenarios are analyzed, which indicate that a trading-mechanism is a more

sustainable method to manage water-environment crisis in the study region. Additionally, consideration of anthropogenic (e.g., a risk-averse attitude) and systemic factors (e.g., the robustness coefficient) can support the generation of a robust plan associated with risk control for WAQT when uncertainty is present. These findings assist local policy and decision makers to gain insights into water-environment capacity planning to balance the basin's social and economic growth with protecting the region's ecosystems.

Keywords Fuzzy programming · Two-stage stochastic programming · Green Z-score criterion · Strategic analysis · Trading-mechanism · Arid basin

Subscript

- j* District: *j* = 1 Kuerla, *j* = 2 Yanqi, *j* = 3 Hejing, *j* = 4 Heshuo, *j* = 5 Bohu and *j* = 6 Yuli;
m Municipal sector: *m* = 1 Residential use, *m* = 2 Municipal services;
n Agriculture sector: *n* = 1 Cearl, *n* = 2 Cotton, *n* = 3 Oil plants, *n* = 4 Vegetable, *n* = 5 Fruit;
i Industrial sector: *i* = 1 Agricultural processing industry, *i* = 2 oil industry, *i* = 3 Chemical Industry;
k Ecological sector: *k* = 1 Forest, *k* = 2 Safe water level of reservoir;
h Water level: *h* = 1 Low, *h* = 2 Medium, *h* = 3 High;

Notation

- f* System benefit without restricted policy (US \$)
 BM_{mj} , BA_{nj} , BI_{ij} , BE_{kj} Net benefit for municipality/agriculture/industry/ecology in district *j* per volume of water being delivered (US \$/ m³)

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$WLM_{mj}, WLA_{nj}, WLI_{ij}, WLE_{kj}$	Water demand target for municipality/agriculture/industry/ecology in district j (m^3)	Q_{jh}^A	Water permit for trading in district j (m^3)
$WLM_{mjmax}, WLA_{njmax}, WLI_{ijmax}, WLE_{kjmax}$	The maximum water demand target for municipality/agriculture/industry/ecology in district j (m^3)	CTM_{mj}, CTI_{ij}	Maximum capacity of recycling for municipality/industry in district j (m^3)
$WLM_{mjmin}, WLA_{njmin}, WLI_{ijmin}, WLE_{kjmin}$	The minimum water demand target for municipality/agriculture/industry/ecology in district j (m^3)	dm_{COD}, di_{COD}	The content of COD per volume of waste water for municipality/industry in district j (%)
$SLM_{mj}, SLA_{nj}, SLI_{ij}, SLE_{kj}$	Water shortage for municipality/agriculture/industry/ecology in district j (m^3)	dm_{TN}, di_{TN}	The content of TN per volume of waste water for municipality/industry in district j (%)
$LM_{mj}, LA_{nj}, LI_{ij}, LE_{kj}$	Loss for municipality/agriculture/industry/ecology in district j per volume of water not being delivered (US \$/ m^3)	dm_{TP}, di_{TP}	The content of TP per volume of waste water for municipality/industry in district j (%)
$YLM_{mj}, YLA_{nj}, YLI_{ij}$	Excessive pollution discharge from municipality/agriculture/industry (ton)	dar_{TP}	Dissolved TN content of runoff corresponding to agricultural activity n in district j (%)
$PM_{mj}, PA_{nj}, PI_{ij}$	Penalty for excessive pollution discharge from municipality/agriculture/industry (US \$/ton)	dar_{TN}	Dissolved TP content of runoff corresponding to agricultural activity i in district j (%)
$POM_{mj}, IRA_{nj}, IRI_{ij}$	The coefficient of waste water discharge per volume of water being used for municipality/agriculture/industry in district j	das_{TN}	TN content of soil corresponding to agricultural activity n in zone j (kg/t)
CM_{mj}, CI_{ij}	Recycling cost for municipality/industry in district j (US \$/ m^3)	das_{TP}	TP content of soil corresponding to agricultural activity n in zone j (kg/t)
$TM_{mj}, TA_{nj}, TI_{ij}, TE_{kj}$	Amount of water trading for municipality/agriculture/industry/ecology in district j (m^3)	ua_{nj}	Soil loss from agricultural activity i in zone j (t/km ²)
$VMC_{mj}, VAC_{nj}, VIC_{ij}, VEC_{kj}$	Trading cost for municipality/agriculture/industry/ecology in district j (US \$/ m^3)	$D_{njh}^{CM}, D_{njh}^{CA}, D_{ijh}^{CI}$	Maximum allowable COD discharge for municipality/agriculture/industry in district j with probability p_{hj} of occurrence under scenario h (ton)
$WM_{mj}, WA_{nj}, WI_{ij}, WE_{kj}$	The initial water permit for municipality/agriculture/industry/ecology in district j (m^3)	$D_{njh}^{NM}, D_{njh}^{NA}, D_{ijh}^{NI}$	Maximum allowable TN discharge for municipality/agriculture/industry in district j with probability p_{hj} of occurrence under scenario h (ton)
p_{hj}	Probability of random water availability QR_{ij} under level h(%)	$D_{njh}^{PM}, D_{njh}^{PA}, D_{ijh}^{PI}$	Maximum allowable TP discharge for municipality/agriculture/industry in district j with probability p_{hj} of occurrence under scenario h (ton)
α, β	Recycling ratio of municipality/industry in district j	SPA_{nj}	Maximum allowable soil loss for agriculture in district j (ton)
δ	The percentage of water availability for initial water right to satisfy basic demand of each water consumer		
Q_{jh}^K	Water availability of district j under probability p_{hj} (m^3)		
Q_{jh}^R	Water flow from river in district j under probability p_{hj} (m^3)		
E_j	Evaporation and infiltration loss of water from river in district j (m^3)		
H_j	Normal water requirement of watercourse in district j (m^3)		

Introduction

Improvements to living standards and the socio-economy have come at the expense of water, in particular water scarcity and deteriorating water quality, leading to a water crisis in many places around the world (Li et al. 2011; Navarro-

Ortega et al. 2012). Although a sound water plan based on an index of water quantity and quality may manage water crisis to some extent, individual governmental regulations (e.g., individual water planning by government) cannot exert efficiency of water resources utilization and conservation at the extreme due to “governance failure.” Thus, a trading-oriented mechanism can be promoted to simultaneously provide more effective guidance to the preservation of valuable water resources and total pollutant control (Millenium 2005). A flexibility mechanism, market-approach (i.e., trading-oriented mechanism) can not only reallocate water rights (permit) from lower- to higher-value to make economic gains but also provide incentives to adopt water saving and pollution abatement practices (Turrall et al. 2005; Zaidi and deMonsabert 2014; Zhang et al. 2015). In a water allocation and quality planning system with a trading-mechanism (WAQT), emission permits have a high correlation with water rights (permit); thus, the interaction of two permits (i.e., water permit and emission permit) become a key to the trading process. However, a variety of uncertainties that incorporate imprecise economic data, varied water policies, random stream flows, and uncertain pollution discharges can influence trading processes (Zeng et al. 2016). For example, variations in the initialization of water right obligations are impacted by stochastic events, which can be expressed as probability distributions around actual water polices and water availabilities instead of certain values. Meanwhile, the varieties of hydrological and climatic regimes can result in inherent difficulties in evaluating economic effects, which are embodied in economic implications of water trading to increase the complexity of the water resource allocation system (Li et al. 2014). Moreover, in water quality planning, uncertainties such as diffusion of pollutants would be highly obscure, which may be expressed as vagueness and impreciseness in the outcome of a random sample (Li and Huang 2009). The aforementioned uncertainties and their interactions would intensify complexities in a WAQT system, which require a more comprehensive, complex, and ambitious plan.

Previously, various mathematical programming models were proposed for supporting water management (including water resources allocation and water quality) under multiple uncertainties (Huang and Loucks 2000; Nasiri et al. 2007; Ward and Pulido-Velázquez 2008; Morais et al. 2014; Kumar et al. 2016; Mombloch et al. 2015; Li et al. 2015). Among them, fuzzy credibility constraint programming (FCP) deemed as one type of fuzzy mathematic programming (FMP) is an effective approach to tackle decision making problems with vagueness/obscure information in the objective functions and constraints (Inuiguchi and Ramík 2000; Li et al. 2006; Inuiguchi 2012). However, it cannot reflect vague risk adaptation of the decision maker in a decision problem, which may impact the “best” outcome among a series of options for each possible future state (Kahneman and Miller 1986). In general,

various fuzziness criteria (e.g., Maximin and Maximax (Wald 1945), Laplace (Laplace 1951), Hurwicz’s (Hurwicz 1951) and Minimax regret (Savage 1951)) in the risk preferences of decision makers would impact potential future outcomes directly. With aim to produce more rational, robust risk control methods in decision-making processes has been developed. Dyer et al. 1992 proposed a synthetic solution named Green Z-score criterion method (GZ) to provide a range of criteria. Each criterion in GZ (i.e., Maximin and Maximax, Laplace, Hurwicz’s and Minimax regret criteria) can be assigned a score to calculate an aggregated score (Green and Weatherhead 2014); then risk-attitudes (i.e., pessimism/optimism) and outcome robustness would be considered. This method can compare various risk-attitudes of decision makers in the decision-making process by using criteria weight and also reflect systemic robustness to promote reliability of decision-making (Amram and Kulatilaka 1999; Ben-Haim 2006). Nevertheless, the above methods cannot deal with uncertainty represented as chance or probability (Li and Huang 2009; Zeng et al. 2014). Thus, two-stage stochastic programming (TSP) is introduced to rectify the initial decision with a probabilistic event. However, few studies focused on coupling hybrid methods (e.g., FCP, TSP and Green Z-score criterion) into a framework to deal with multiple and uncertain information in a WAQT system.

Therefore, the development of a fuzzy-stochastic programming with Green Z-score criterion method (FSGZ) is proposed for WAQT under uncertainties, incorporating FCP, TSP, and GZ into a general framework. FSGZ can not only handle uncertainty expressed as probability distributions but also quantify objective and subjective fuzziness in decision-making processes. Risk-averse attitudes and robustness coefficient are considered to express relationships between expected the target and outcome, which can generate a robust risk control plan under multiple uncertainties. The developed method is applied to a real case of water management on integration of water quantity and quality in the Kaidu-Kongque River Basin in China, which is experiencing atrophic water availability and deteriorating water quality due to the rapid pace of economic and population growth. Results of water transaction amounts, water resources allocation pattern, pollution mitigation efforts, and system benefit under various scenarios are analyzed, which indicate that a trading-mechanism is a more effective and sustainable manner to manage a water crisis in the study region, and also support the adjustment of existing water allocation patterns and pollution discharge schemes in a robust manner.

Methodology

Fuzzy credibility constrained programming (FCP) is effective for addressing independent uncertainties in the constraint’s

left- and right-hand sides in decision-making issues and can express the relationship between the satisfaction degree and system-failure risk. However, it is difficult for FCP to reflect a risk-averse attitude and system robustness in the decision-making process. Green Z-score criterion analysis (GZ) was introduced to address that issue by introducing various parameters (i.e., a risk-averse attitude and a robustness coefficient) into FCP to generate a simplified rational model that can be personalized for an individual decision-maker in a robust manner (Hajkowicz 2008). Moreover, FCP is not linked to the economic consequences of policy violations that are pre-

regulated by the authorities by taking recourse actions to correct any infeasibilities (Li and Huang 2009). Two-stage stochastic programming (TSP) can handle such issues by linking an initial decision (first-stage decision) and a random event (second-stage decision) through an action taken as a recourse. Detailed information about the FCP, GZ, and TSP methods is contained in **Appendix 1**. For practical decision-making issues, a hybrid format of uncertainties expressed as probability distributions and fuzzy sets can be addressed by a fuzzy-stochastic programming with a Green Z-score criterion (FS-GZ) as follows:

$$\text{Max } f = \max \left\{ \lambda \cdot \sum_{n=1}^N \frac{f_{\text{out}} - \left[\max_{d \in D} f_{\text{out}} - \left(\max_{d \in D} f_{\text{out}} - \min_{d \in D} f_{\text{out}} \right) \cdot (\alpha/100) \right]}{\max_{d \in D} f_{\text{out}} - \left[\max_{d \in D} f_{\text{out}} - \left(\max_{d \in D} f_{\text{out}} - \min_{d \in D} f_{\text{out}} \right) \cdot (\alpha/100) \right]} - (1-\lambda) \cdot \sum_{n=1}^N \left(f_{\text{out}} / \min_{d \in D} f_{\text{out}} \right) \right\}, \tag{1a}$$

subject to

$$\text{Cr} \left\{ \sum_{i=1}^{I_1} \tilde{e}_i x_i - \sum_{i=1}^{I_2} \sum_{h=1}^H p_h \tilde{s}_i y_{ih} \leq \sum_{n=1}^N \frac{f_{\text{out}} - \left[\max_{d \in D} f_{\text{out}} - \left(\max_{d \in D} f_{\text{out}} - \min_{d \in D} f_{\text{out}} \right) \cdot (\alpha/100) \right]}{\max_{d \in D} f_{\text{out}} - \left[\max_{d \in D} f_{\text{out}} - \left(\max_{d \in D} f_{\text{out}} - \min_{d \in D} f_{\text{out}} \right) \cdot (\alpha/100) \right]} \right\} \geq \eta^{\text{max}f} \tag{1b}$$

$$\text{Cr} \left\{ \sum_{i=1}^{I_1} \tilde{e}_i x_i - \sum_{i=1}^{I_2} \sum_{h=1}^H p_h \tilde{s}_i y_{ih} \geq \sum_{n=1}^N \left(f_{\text{out}} / \min_{d \in D} f_{\text{out}} \right) \right\} \geq \eta^{\text{min}f}, \tag{1c}$$

$$y_{ih} \geq 0, \quad i = 1, 2, \dots, I_1; \quad h = 1, 2, \dots, H. \tag{1g}$$

where objective and subjective fuzziness is quantified according to the processes of decision-making and the risk-averse attitude and robustness coefficient are considered to express the relationship between the expected target and the outcome. Detailed information and the meaning of each symbol are provided in **Appendix 1**. Based on credibility measures (as shown in **Appendix 1**), model (1) can be transformed into:

$$\text{Cr} \left\{ \sum_{i=1}^I a_{ij} x_i \leq \tilde{b}_j \right\} \geq \eta^p, \quad i = 1, 2, \dots, I; \quad j = 1, 2, \dots, J, \tag{1d}$$

$$\sum_{i=1}^{I_1} A_{it} x_i + \sum_{i=1}^{I_2} A'_{it} x_i \geq w_h, \quad t = 1, 2, \dots, J_2; \quad h = 1, 2, \dots, H, \tag{1e}$$

$$x_i \geq 0, \quad i = 1, 2, \dots, I_1, \tag{1f}$$

$$\text{Max } f = \max [(\lambda \cdot OP) - (1-\lambda) \cdot PE], \tag{2a}$$

subject to

$$\sum_{i=1}^{I_1} [e_i^3 + (1-2\eta^{\text{max}f})(e_i^3 - e_i^4)] x_i - \sum_{i=1}^{I_2} \sum_{h=1}^H p_h [s_i^3 + (1-2\eta^{\text{max}f})(s_i^3 - s_i^4)] y_{ih} \leq \sum_{n=1}^N \left\{ f_{\text{out}} - \left[\max_{d \in D} f_{\text{out}} - \left(\max_{d \in D} f_{\text{out}} - \min_{d \in D} f_{\text{out}} \right) \cdot (\alpha/100) \right] \right\} / \left\{ \max_{d \in D} f_{\text{out}} - \left[\max_{d \in D} f_{\text{out}} - \left(\max_{d \in D} f_{\text{out}} - \min_{d \in D} f_{\text{out}} \right) \cdot (\alpha/100) \right] \right\}, \tag{2b}$$

$$\sum_{i=1}^{I_1} [e_i^2 + (1-2\eta^{\min f})(e_i^2 - e_i^1)] x_i - \sum_{h=1}^{I_2} \sum_{i=1}^H p_h [s_i^2 + (1-2\eta^{\min f})(s_i^2 - s_i^1)] y_{ih} \geq \sum_{n=1}^N \left(f_{\text{out}} / \min_{d \in D} f_{\text{out}} \right) \tag{2c}$$

$$A_{ij}x_i \leq b_j^3 + (1-2\eta^b)(b_j^3 - b_j^4), \quad j = 1, 2, \dots, J_1; \quad h = 1, 2, \dots, H, \tag{2d}$$

$$\sum_{i=1}^{I_1} A_{it}x_i + \sum_{i=1}^{I_2} A'_{it}x_i \geq w_h, \quad t = 1, 2, \dots, J_2; \quad h = 1, 2, \dots, H, \tag{2e}$$

$$x_i \geq 0, \quad i = 1, 2, \dots, I_1, \tag{2f}$$

$$y_{ih} \geq 0, \quad i = 1, 2, \dots, I_2; \quad h = 1, 2, \dots, H. \tag{2g}$$

Resolving model (2) can address multiple uncertainties expressed as possibilities or probability distributions existing on the left- and right-hand sides of constraints and in the objective function. A robust object function can be obtained based on the optimism coefficient λ , while a set of solutions associated with the robustness coefficient (i.e., the α level) and the credibility level (i.e., the δ level) for the objective function and decision variables can be obtained.

Application

The Kaidu and Kongque Rivers are tributaries of the Tarim River located from 71° 39" E to 93° 45" E and from 34° 20" N to 43° 39" N, and the Kaidu and Kongque Rivers have a length of 610 and 785 km, respectively. Because the Kaidu-Kongque Basin is formed in the arid monsoon climate zone, it is considered to be a typical semi-arid and arid region in the Tarim River Basin and has low rainfall and high evaporation (Huang et al. 2012). In fact, the distribution of rainfall in the Kaidu-Kongque Basin is uneven; approximately 80 % of the total rainfall occurs in the wet season (4 months) of the year, with an average rainfall of approximately 273 mm per year (SYXUAR 2011). This region has a total area of approximately $62 \times 10^3 \text{ km}^2$, and more than 95 % of the arable land requires irrigation, which not only provides the food supply for a native population of more than 1.2 million but also provides grains for other places in Xinjiang province, even to the northwest of China. Thus, it is deemed to be the most important cotton and grain area in the Tarim Basin and abounds in wheat, corn, tomato, and fruit. In the studied region, more than 90 % of the total water-resources are used for agricultural

irrigation, so the agricultural economy has recently greatly developed because of the water supply. By 2013, the GDP from agriculture was \$ 1.8 billion, implying that agriculture and its corresponding agribusinesses have become the pillars of the studied region (SYXUAR 2013). Additionally, the chemical, fossil oil, textiles, electric power, papermaking, and transportation industries have a high speed development due to the national western development policy (Zeng et al. 2015). All of these changes have greatly increased the standard of living and social material productivity because of accelerated industrialization, urbanization, and population growth. However, a variety of issues, such as an increasing water demand, a limited water supply, and concerns about pollution, have arisen. For instance, from 2000 to 2013, an enormous increase in agricultural production to provide food security resulted in the over-expansion of cultivated land (the increase of the farmed area was $51.15 \times 10^3 \text{ km}^2$), which resulted in increasing severe water deficits (approximately $135.20 \times 10^6 \text{ m}^3$) and soil losses (approximately $1.23 \times 10^9 \text{ ton}$) (SYXUAR 2000, 2013). Additionally, excessive cultivation and fertilization can cause environmental destruction and degeneration. In 2013, the amount of nitrogen fertilizer in agriculture was $3.27 \times 10^6 \text{ ton}$, which resulted in excess discharge of nitrogen and phosphorus (SYXUAR 2000, 2013). Moreover, pollution issues caused by industry are more serious than those from agriculture and urbanization. In 2013, the wastewater discharged from industry exceeded 2.48 million tons and contained abundant pollutant, such as total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD). Although retreatment techniques can recycle 65 % of wastewater, the pollutants discharged into the river still exceeded the amount that the river could tolerate (SYXUAR 2013).

Consequently, local policymakers are facing a number of challenges regarding water resource allocation and water quality management, such as (a) population growth and economic development caused by an increasing water demand that reached the limit of the amount that the natural system could provide; (b) non-point/point source pollution due to excessive cultivation and fertilization and rapid industrialization that resulted in environmental destruction and degeneration and diminished the available water resources, aggravating chronic

severe shortages in the studied basin; (c) rapid urbanization and over exploitation that destroyed the original balanced structure of the water system, leading to a water-environment crisis; and (d) a water-environment crisis index of water deficits and pollution issues became a major obstacle to social and economic development in this region. This situations require an effective water planning/management

methodology (such as market approach/water trading) to resolve the conflicts among water consumers and support the sustainability of the regional water resources and environmental development.

Figure 1 shows the framework of a fuzzy-stochastic programming with Green Z-score criterion (FSGZ) and its application to the Kaidu-Kongque River Basin. In the studied

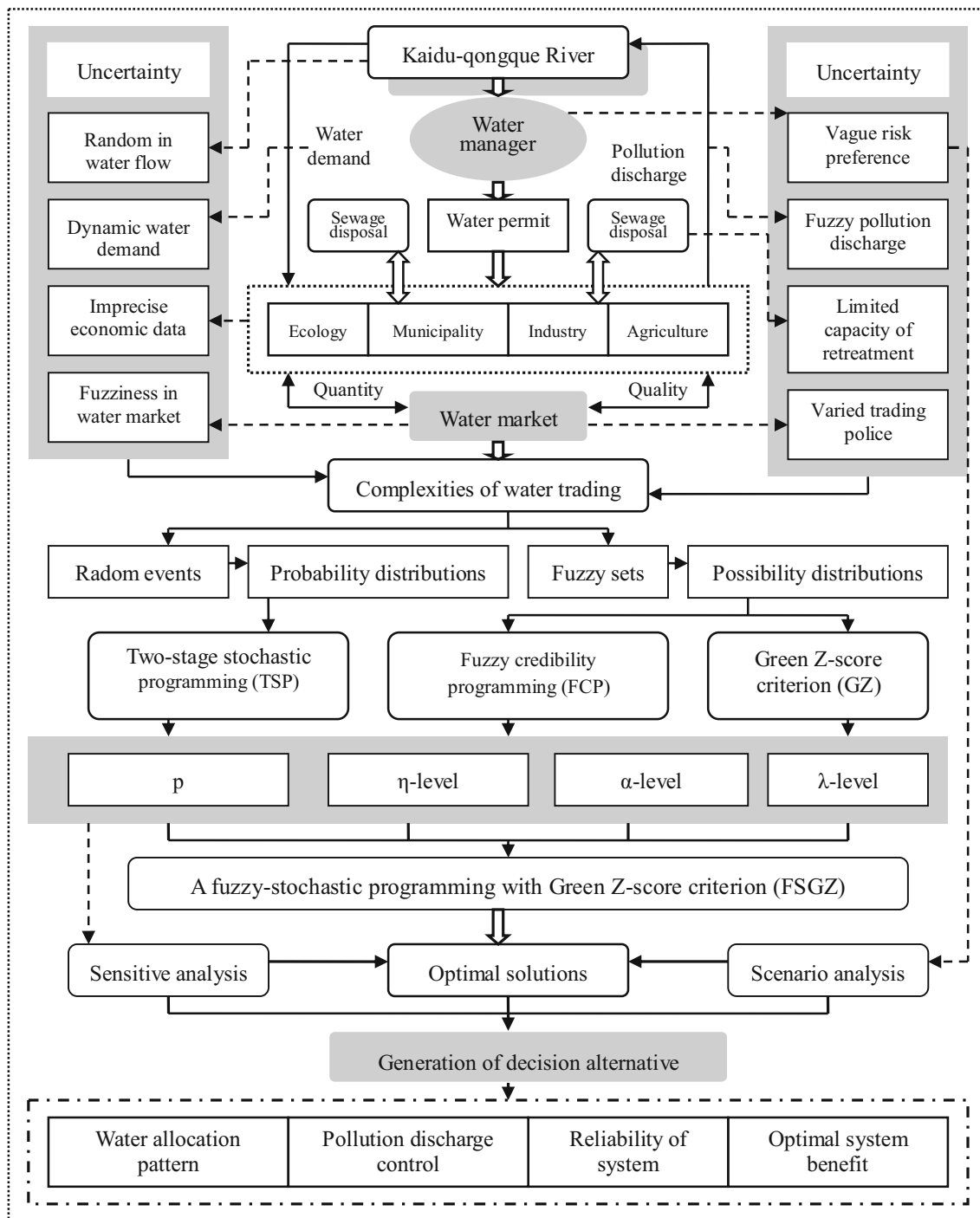


Fig. 1 Framework of a fuzzy-stochastic programming with Green Z-score criterion and its application to Kaidu-kongque River Basin

region, due to the water deficit and discharge of pollution, the goal is the development of an optimal plan that maximizes the benefits from the water system and minimizes the risk associated with water-environment requirements as well as the risk attitudes of policymakers. Water resource deficits and increased pollution have damaged extremely vulnerable ecosystems in the basin, and water crises could be exacerbated by the expansion of human activity. A rational plan for water quality and quantity is required to balance economic development and environmental protection. In general water planning, a temporary allocation plan is usually made by a water manager based on the expected water demand from users in the beginning of the year, which can be considered to be first-stage decision variables. Then, permanent allocation plans would follow (expressed in terms of water deficits) if the general water availability cannot satisfy all of the users, leading to losses due to the water deficit. Additionally, associated pollution from human activities in proportion to actual water consumption would be emitted, leading to environmental deterioration. In traditional planning, water is proportionally allocated to users by their own permits, which could lead to ineffective allocations, with water surpluses and shortages occurring simultaneously. Additionally, a single political plan cannot efficiently allocate water resources and conserve the environment at the extreme due to “governance failure.” Thus, a market approach (trading mechanism) can be introduced to correct these weaknesses, reallocating water rights (permits) from lower- to higher-value to increase economic efficiency but also providing incentives to adopt water-savings and pollution abatement measures (Millennium 2005; Zeng et al. 2015). In a general water allocation and quality planning system with trading-mechanism (WAQT), the study region’s policymakers need a plan to allocate uncertain supplies of water to every consumer and maximize the overall system benefit, as well as satisfy pollution control requirements (Zeng et al. 2014). Since emission permits have a high correlation with water rights, interactions of two permits become key components of trading processes. Based on initial water obligations (rights), water consumers can buy/sell water permits through a water market, thus, remedying a water deficit. Meanwhile, pollution discharges, in proportion to water consumption, would be controlled according to regional environmental load. Thus, the tradeoff between emission permits and water rights can support policymakers generating a comprehensive plan associated with water allocation/consumption and pollution control.

However, due to the temporal variations of available water resources and pollution sources, an optimal scheme for effective allocation and pollution discharge can also vary correspondingly (Li et al. 2011), which means that such a WAQT planning issue can be formulated as a fuzzy-stochastic programming with the Green Z-score criterion (FSGZ) model to resolve the following problems: (i) identifying efficient water allocation and pollution emission schemes; (ii) understanding how the trading-oriented scheme in the WAQT generates an

optimized water-allocation pattern and pollution-control plans according to various policy adjustments; (iii) determining the effects of uncertainties expressed as fuzzy sets and probability distributions on the water-environment structure, system cost and other system components in the WAQT of Kaidu-Kongque Basin; (iv) determining the effects of the link between the risk preference of the decision-makers (i.e., the risk-averse attitude) and the systemic robustness (i.e., the robustness coefficient) on the reliability of WAQT; (v) balancing the relationship between risk attitudes and system benefits.

Based on the fuzzy-stochastic programming with Green Z-score criterion (FSGZ) method proposed in the “**Methodology**” section, an effective water resources allocation and water quality management with trading-mechanism (WAQT) model is formulated. The objective is to maximize the net system benefit (i.e., municipal, agricultural, industrial and ecological outcomes). Meanwhile, uncertain information would reflect the system disruption risk attributable to uncertainties. The total system benefit would equal benefits from outcome from water allocations for municipal, agricultural, industrial and ecological activities and benefit from water trading minus loss of water deficit, cost of excess pollution discharge, cost for environmental retreatment, and cost of trading. In this study, three water consumers (i.e., municipal, agricultural and industrial users) from human activities (e.g., residential, municipal services, cereal/cotton/oil plants/vegetable/fruit irrigation, and industries such as agricultural processing, oil and chemicals) deemed as non- and point source would discharge pollutants (the main factors being nitrogen, phosphorus and biochemical oxygen demand discharges). Available water is highly uncertain and expressed as probabilistic distribution and/or fuzzy set. Water deficit and pollution are fluctuated with randomness (low, medium, and high) and fuzziness in water availability. Meanwhile, four scenarios associated with various risk-attitudes for water demands of human activities (shown in Table 3) are considered. In addition, additional uncertain information associated with other parameters such as economic data may come from measurement errors, which can be expressed as fuzzy sets.

The constraints include a number of inequalities/equalities which define the relationships among the water quantity, water supply capacity, water permits, water quantity, water trading, wastewater treatment capacity, nitrogen/phosphorus/COD discharge, and technique as follows:

- (1) Constraints of water availability: water availability from the surface, watercourses, and underground water, all of which must maintain a minimum level requirement (m^3).
- (2) Constraints of water permits: the total initial water permits can be assigned to each water consumer based on various policies that do not exceed the actual water availability.
- (3) Constraints of water trading: water trading can be performed to satisfy water demands in a two-stage context after the initial water permit assignment, and the amount

- of trading when the flow levels are low, medium, and high occur based on a random variable (i.e., water availability).
- (4) Constraints of water quantity: although a water deficit would bring an adverse impact to water demand, water trading can remit such a conflict through a market-approach, which could encourage water from low value to high value based on price value regulation.
 - (5) Constraints of waste water treatment capacity: wastewater generation from the point source (mainly from human-daily life and industrial-production processes) should be less than the maximum wastewater treatment capacity.
 - (6) Constraints of the COD discharge: although wastewater can be retreated by sewage facilities, the ultimate COD discharges from urban sources and industry would enter the river, so the allowable COD discharge level (based on environmental load in study region) must not be exceeded.
 - (7) Constraints of nitrogen discharge: nitrogen discharge restrictions on point and nonpoint sources would be regulated by allowance thresholds.
 - (8) Constraints of phosphorus discharge: point and nonpoint sources of phosphorus discharges would be restricted by allowance thresholds based on the environmental load.
 - (9) Constraints of soil loss: imposed according to a sediment load permit to limit soil erosion.
 - (10) Constraints of cropland resources: the amount of irrigation in the studied region.
 - (11) Constraints of the industrial production scale: industrial production should be restricted to maintain a rational pace.
 - (12) Constraints of population growth: the population growth should maintain a rate based on the water availability and the environmental load in the studied region.
 - (13) Constraints of Non-negativity: some benefits are non-negative
- Detailed objective functions and constraints are provided in **Appendix 2**, where the rationalities for the equations and inequalities are explained.

Table 1 Economic data

Sector		District					
		j = 1 Kuerla	j = 2 Yanqi	j = 3 Hejing	j = 4 Heshuo	j = 5 Bohu	j = 6 Yuli
Unit net benefits (US \$/10 ³ m ³)							
Municipality	Residential	(660, 675, 713)	(403, 415, 435)	(305, 317, 319)	(348, 352, 258)	(349, 355, 362)	(360, 369, 372)
	Municipal	(580, 595, 612)	(557, 597, 652)	(445, 477, 499)	(535, 543, 562)	(481, 492, 519)	(481, 492, 522)
Agriculture	Cearl	(249, 258, 263)	(161, 172, 185)	(191, 202, 211)	(229, 234, 241)	(202, 207, 212)	(241, 253, 262)
	Cotton	(267, 277, 289)	(172, 182, 198)	(288, 195, 205)	(258, 263, 272)	(215, 222, 234)	(262, 271, 282)
	Oil plants	(269, 272, 283)	(223, 256, 269)	(162, 167, 172)	(224, 239, 251)	(205, 215, 222)	(259, 271, 275)
	Vegetable	(244, 250, 259)	(148, 156, 162)	(167, 177, 186)	(210, 218, 222)	(188, 191, 200)	(231, 234, 245)
	Fruit	(267, 279, 282)	(165, 171, 174)	(188, 197, 205)	(258, 260, 272)	(212, 224, 248)	(252, 261, 274)
Industry	Processing oil	(452, 459, 466)	(278, 282, 292)	(359, 362, 388)	(332, 344, 361)	(342, 355, 377)	(313, 327, 343)
	oil	(522, 534, 539)	(312, 322, 338)	(292, 419, 440)	(358, 378, 418)	(392, 411, 432)	(362, 378, 397)
	Chemistry	(483, 490, 515)	(308, 312, 323)	(392, 400, 420)	(259, 361, 399)	(387, 393, 412)	(354, 361, 379)
Ecology	Forest	(235, 245, 252)	(205, 212, 233)	(192, 196, 206)	(202, 213, 224)	(212, 220, 231)	(208, 219, 230)
	River/reservoir	(208, 218, 222)	(185, 189, 199)	(169, 175, 183)	(190, 197, 200)	(192, 196, 206)	(188, 195, 205)
Loss of water shortage (US \$/10 ³ m ³)							
Municipality	Residential	(821, 840, 882)	(467, 507, 533)	(392, 403, 423)	(454, 488, 465)	(412, 428, 450)	(413, 420, 464)
	Municipal	(702, 722, 798)	(657, 698, 723)	(525, 547, 575)	(593, 630, 662)	(556, 581, 610)	(567, 598, 630)
Agriculture	Cearl	(291, 295, 310)	(179, 183, 193)	(211, 219, 230)	(269, 275, 289)	(232, 236, 248)	(277, 289, 304)
	Cotton	(299, 300, 332)	(188, 197, 206)	(223, 234, 246)	(284, 295, 310)	(242, 253, 266)	(292, 310, 325)
	Oil plants	(292, 307, 323)	(298, 200, 228)	(220, 228, 239)	(278, 286, 301)	(224, 235, 242)	(292, 301, 316)
	Vegetable	(272, 286, 300)	(172, 178, 187)	(209, 212, 223)	(262, 267, 280)	(222, 229, 241)	(287, 294, 301)
	Fruit	(302, 319, 335)	(198, 202, 208)	(224, 237, 248)	(287, 298, 313)	(251, 256, 268)	(302, 313, 329)
Industry	Processing oil	(502, 532, 559)	(323, 334, 351)	(424, 434, 456)	(402, 413, 433)	(412, 426, 448)	(387, 392, 412)
	oil	(592, 616, 647)	(376, 387, 406)	(487, 503, 526)	(456, 478, 502)	(476, 494, 518)	(434, 454, 477)
	Chemistry	(555, 588, 618)	(359, 368, 383)	(456, 480, 500)	(446, 450, 479)	(445, 473, 492)	(402, 431, 459)
Ecology	Forest	(278, 283, 295)	(243, 252, 263)	(229, 236, 246)	(249, 253, 264)	(254, 260, 271)	(252, 259, 270)
	River/reservoir	(240, 248, 258)	(219, 229, 239)	(200, 205, 213)	(213, 220, 230)	(227, 236, 246)	(223, 235, 245)
Cost of sewage retreatment (US \$/10 ³ m ³)							
Municipality		(834, 858, 880)	(592, 610, 670)	(489, 530, 680)	(554, 579, 594)	(499, 535, 567)	(534, 552, 583.5)
Agriculture		(467, 489, 512)	(419, 423, 456)	(424, 434, 489)	(399, 412, 424)]	(440, 445, 490)	(424, 434, 478)
Industry plants		(865, 874, 916)	(645, 674, 716)	(543, 553, 615)	(644, 666, 718)	(545, 565, 618)	(545, 561, 608)
Cost of trading (US \$/10 ³ m ³)							
Municipality		(134, 158, 180)	(134, 158, 180)	(134, 158, 180)	(134, 158, 180)	(134, 158, 180)	(134, 158, 180)
Agriculture		(267, 289, 312)	(267, 289, 312)	(267, 289, 312)	(267, 289, 312)	(267, 289, 312)	(267, 289, 312)
Industry plants		(285, 294, 316)	(285, 294, 316)	(285, 294, 316)	(285, 294, 316)	(285, 294, 316)	((285, 294, 316)

Table 2 Allowance pollution discharges

Pollutant	Water flow level	Probability	Allowance amount
COD (10 ³ ton)	Low	0.583	(7.05, 7.28, 7.65)
	Medium	0.342	(7.35, 7.93, 8.44)
	High	0.185	(7.82, 8.67, 9.06)
TN (10 ³ ton)	Low	0.583	(1.01, 1.26, 1.47)
	Medium	0.342	(1.31, 1.72, 2.07)
	High	0.185	(1.42, 1.83, 2.26)
TP (10 ³ ton)	Low	0.583	(0.24, 0.65, 0.95)
	Medium	0.342	(0.33, 0.88, 1.02)
	High	0.185	(0.47, 0.87, 1.15)

The parameters for the formulation of the model were calculated based on government reports, statistical yearbooks, and related research (Huang et al. 2012). Table 1 shows the economic data, such as net benefit/loss of unit of water and cost of sewage retreatment / trading, which were calculated from the regional statistical yearbook considering the social-economic development (SYXUAR from 2000 to 2013). In this study, the water availability level was obtained via statistical analyses using the results of the annual stream flow of the Kaidu-Kongque River (2005–2012). Since concentrated precipitation occurs from May to September (80 %), the total water availability can be categorized into three levels (i.e., low, medium and high) with respective probabilities of 0.5, 0.3 and 0.2, where the available water values are expressed as fuzzy values (i.e., (712, 725, 734), (854, 863, 889), and (998, 1001, 1012) × 10⁶ m³). Table 2 shows the pollution discharge allowances for the Kaidu-Kongque River Basin for the probabilities of the various levels, which are expressed as intervals with associated varying probabilities. To compare various effects of the risk-averse attitude, the threshold of acceptability and the robustness coefficient in a WAQT, four scenarios were designed to reflect different risk attitudes to relationships between the water-environment and socio-economic development, including the Laplace, Hurwicz, Minmax regret and Maxmin scenarios (as shown in Table 3).

Results and discussion

System benefit under various λ, α and η levels

Figure 2 shows the optimized net system benefits with trading schemes when λ, α and η levels are varied. In this study, since

different risk-averse attitudes (e.g., coefficient of optimism λ-level), credibility-satisfaction levels (i.e., η-level) and robustness coefficient (i.e., α-level) are joined into FSGZ, six levels for α (i.e. 0.01, 1, 10, 50, 80 and 100), two levels for η (i.e. 0.6 and 0.99), and six levels for λ (i.e. 0.01, 0.1, 0.2, 0.5, 0.8, 1) were considered, leading to a total of 72 scenarios. The results show higher λ values would result in higher system benefit, due to its positive effects presented in FSGZ. For example, the system benefit with trading-mechanism would vary from \$ 1.08 × 10⁹ to \$ 1.34 × 10⁹ when λ is from 0.01 to 1, when η-level is 0.6 and α-level is 100. Meanwhile, η-level reflects the satisfaction and risk-violated levels through credibility measures in the constraints of water availability, thus, system benefits would decrease as the η-level is raised. For instance, system benefit with trading scheme would range from \$ 1.34 × 10⁹ to \$ 1.21 × 10⁹ when η levels are from 0.6 to 0.99, when λ and α levels are 1 and 100, respectively. The system benefits would decrease with α level rising, which indicates that higher system-reliability levels would result in lower system benefits.

Water shortage under various scenarios

Figure 3 presents water shortage under various special scenarios (concluding Laplace, Hurwicz, Minmax regret, and Maxmin scenarios in Table 3) with a trading-mechanism scheme when η level is 0.6. The results present that various special scenarios (corresponding to various λ and α levels) would lead to different water shortages. For example, when water flow is medium (η = 0.6), water shortage of municipal users in Yanqi county (j = 2) would be 3.55 × 10⁶ m³, 3.27 × 10⁶ m³, 3.27 × 10⁶ m³, 3.27 × 10⁶ m³ under cases 1, 2, 3, and 4, corresponding to Maxmax, Minmax regret, Laplace, and Hurwicz scenarios. It implies that Green Z-score criterion is a robust method to express various special scenarios (i.e., Minmax regret, Maxmax, Hurwicz and Laplace) directly by various coefficients of optimism (e.g., λ-level), coefficients of robustness (i.e., α-level), and thresholds of acceptability (i.e., h-level).

Water trading among various water consumers / districts

Figure 4 shows water trading among various consumers / districts when λ, α, and η levels are 1, 100, and 0.99 respectively. From the results, several indications can be obtained. These include (a) The expected water trading of a buyer (e.g., water consumer) is higher than actual released water from the seller (i.e., the local water authority) due to scarce water availability,

Table 3 Special scenarios in Green Z-score criterion

Corresponding decision criterion Decision maker	Maximin Pessimist	Minmax regret Neutral	Laplace Neutral	Hurwicz Optimist-pessimist
Coefficient of optimism (λ)	0.01	0.5	0.5	0.5
Coefficient of robustness (α)	100	100	100	0.01

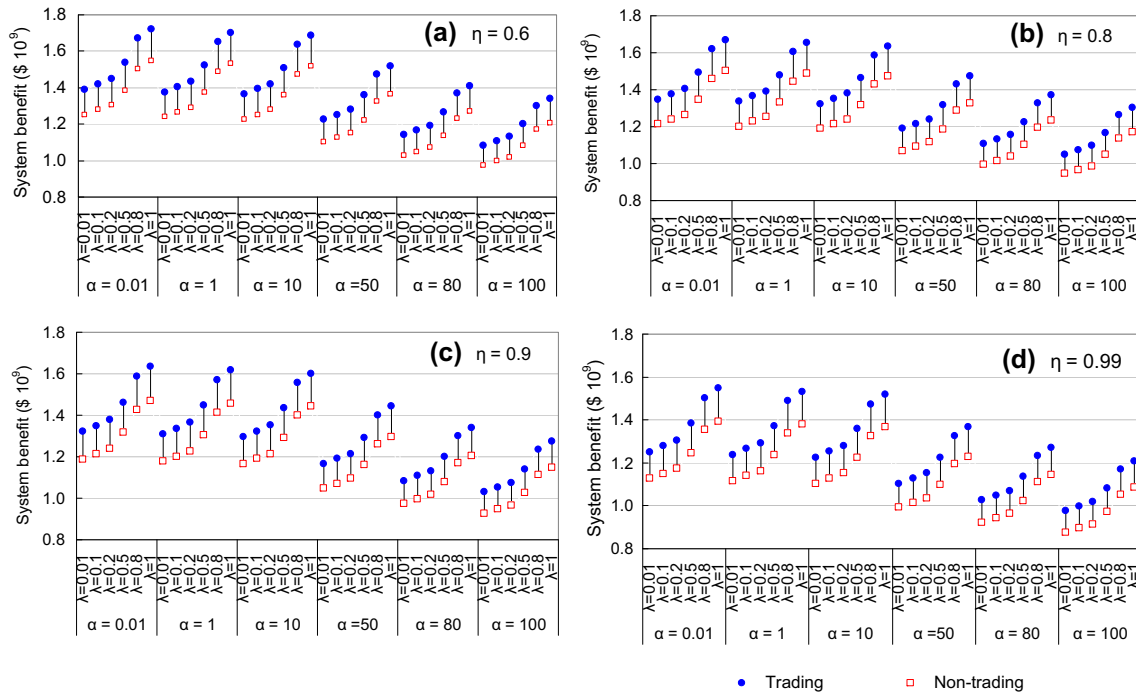


Fig. 2 System benefits under with trading- and non-trading scheme when λ , α , and η levels are varied

especially when available water flow is low. For example, when the water availability level is low, the total expected amount of water trading for a buyer (industry user) in Zone 1 (i.e., Kuerla county) would be $298.37 \times 10^6 \text{ m}^3$, while the actual released water permit that can be traded (sold) would be $148.45 \times 10^6 \text{ m}^3$, which is far below what buyer expected to trade. (b) Water trading would vary with different water availability levels over a two-stage context. It implies that the vast amount of water

trading occurs in a dry season to remedy serious water shortages, while amount of trading would decrease in a wet season. (c) In comparison of total trading amounts of six districts, the results indicate that amount of water trading is Zone 1 > Zone 2 > Zone 6 > Zone 3 > Zone 5 > Zone 4. With the rapid pace of urbanization and population growth, Kuerla county (i.e., Zone 1) would require more food security, which results in rapid expansion of farmland. In this situation, water demand for agriculture

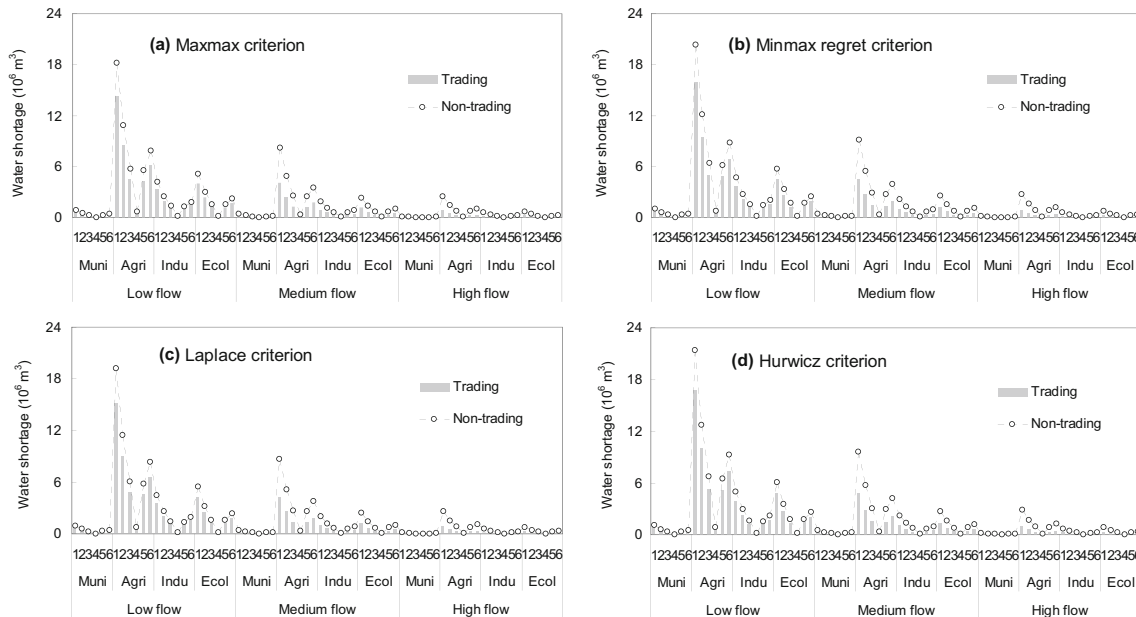


Fig. 3 Water shortage under various especial scenarios with trading- and non-trading scheme when η level is 0.6 (where “1” denoted as “Kuerla county,” “2” denoted as “Yanqi county,” “3” denoted as “Hejing county,”

“4” denoted as “Heshuo county,” “5” denoted as “Bohu county,” “6” denoted as “Yuli county”)

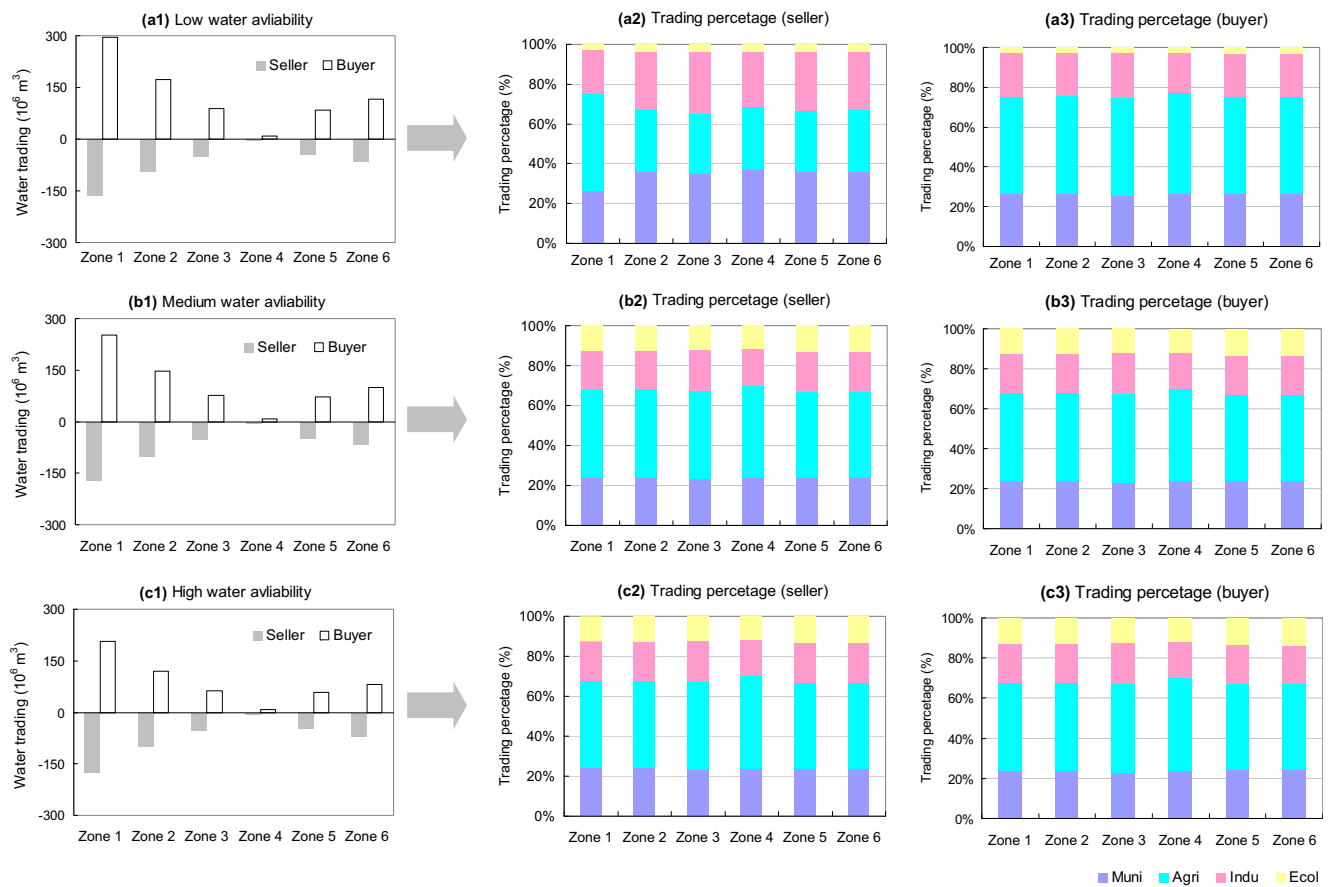


Fig. 4 Water trading among of various consumers/districts when λ , α , and η levels are 1, 100, and 0.99

in Kuerla county would be much more than other four districts. However, the characteristics of an arid region, inefficient agricultural development and deteriorated farmland quality would result in a vicious circle of water demand and supply. (d) In comparison of trading amounts among various water consumers, it illustrates that the highest trading amount would occur in agriculture due to its high water deficit and support policies based on food security. However, with a market-based approach, the water deficit of a municipality would be remedied completely, which can satisfy the requirement of drinking water safety.

Total water allocation under various water flow levels

Figure 5 presents the solutions for total water allocation for four water consumers of different counties when η levels are 0.6 and 0.99 ($\lambda = 1, \alpha = 100$). In this study, since water demand targets were regulated before random water flows were known, a recourse action would occur between targets and random water availability, generating water allocations. Thus, the results indicate that water allocations would float with random variables (i.e., total water availability) in the study area. For example, water shortages are severe in a dry season, leading to lower allocations; while water shortages are greater than during a wet season, leading to higher allocations. Although agriculture

deemed as the largest water consumer encounters the most severe water deficit, enormous water allocations would occur in agriculture. Meanwhile, the highest water allocation would occur in Zone 1 (i.e., Kuerla county), and the lowest allocation in Zone 4 (i.e., Heshuo county). Moreover, different η -levels (corresponding to varied water-availability levels and changed net benefit/penalty) would generate various system-violated risks, thus resulting in different water-allocation plans. For example, water allocation for municipal, agricultural, industrial, and ecological users (in Bohu county, $j = 5$) would be 4.95, 97.75, 21.85 and $28.75 \times 10^6 \text{ m}^3$, respectively, when η is 0.6, while allocation would be 3.82, 90.75, 18.28, and $21.3 \times 10^6 \text{ m}^3$ when η is 0.99.

Pollution discharge based on water trading scheme

After water is allocated, pollutants would discharge in proportion to actual water consumption. Figure 6 shows the distribution of total pollution discharges of various counties when λ, α and η levels are 1, 100 and 0.99. The results show that agricultural activities are the main source of TN and TP pollutants, their discharge amounts reach 68.7 and 72.3 %. In the study region, agriculture has been expanded in recent years, and an irrational irrigation program and fertilization regime generates excessive

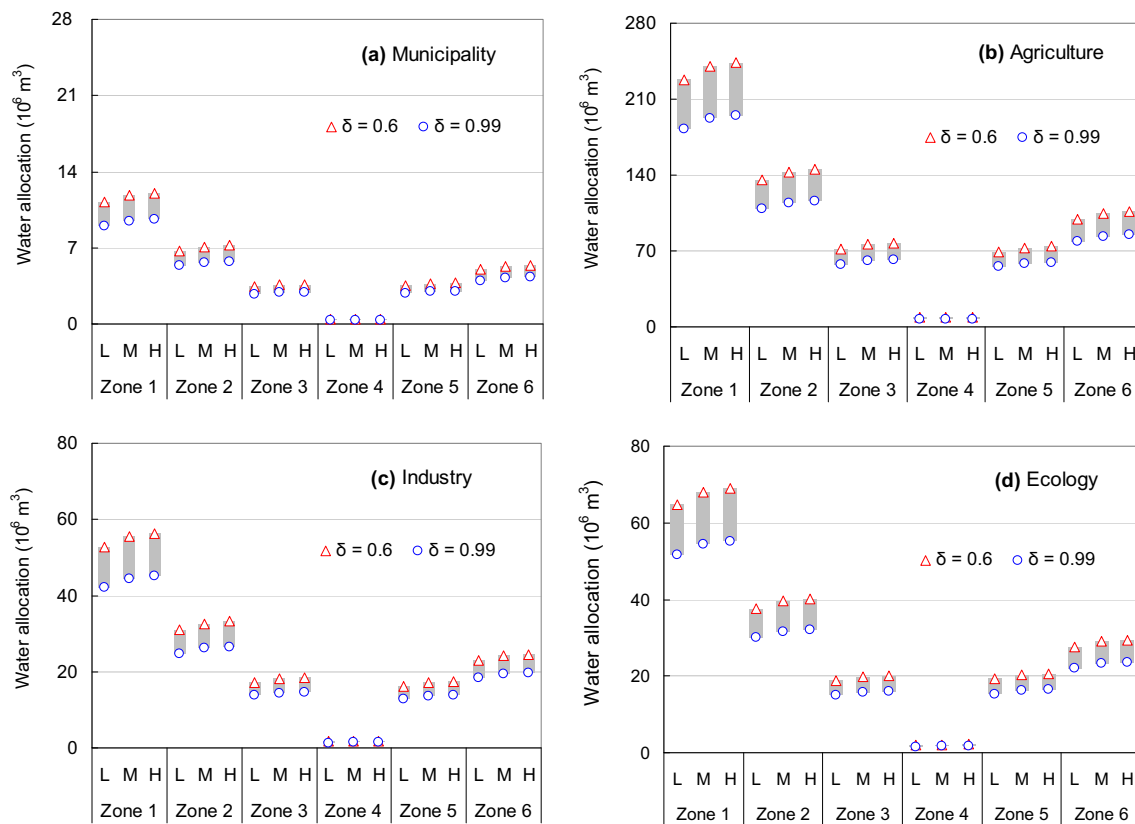


Fig. 5 Total water allocations for four water consumers of different counties when η levels are 0.6 and 0.99 ($\lambda = 1$, $\alpha = 100$)

fertilization and pesticide applications, resulting in high nitrogen and phosphorus concentrations in the soil. With high runoff and soil loss, the TN and TP discharges from farming make their way directly into the river, resulting in pollution. Meanwhile, the results show that COD are generated from industry, its discharge amounts have reached 55.4 % at highest; especially, chemical plants are the largest ones among all sources, occupying 35.4 % of the total COD discharges. Moreover, the results indicate that tighter control of pollutant discharge (i.e., lower allowance discharge) would result in a higher excess discharge, while a looser discharge limit would result in an opposite one.

Figure 7 presents excess TN discharges among agriculture and municipalities with a trading mechanism when λ , α , and η levels are 1, 100, and 0.99. Since the pollutant emissions would be in proportion to water consumption, excess TN discharge would be influenced by actual water trading/allocation. Meanwhile, the results show that excess of TN discharge for agriculture would decrease with trading-oriented mechanisms, while for municipalities it would increase. This implies that more water being reallocated to municipality from agriculture, more excess TN discharge for municipalities would occur. Figure 8 presents excess TP discharges for municipalities under different robustness when η and λ are 0.99 and 1 ($h = 0$). The results demonstrate that excess TP discharges would decrease as α -level is raised. Figure 9 presents COD discharges for industry with trading mechanisms under different λ , α , and η levels

($h = 0$). The results present that the amount of excess COD discharges of each industrial plant under each scenario/ η -cut level is Kuerla > Yanqi > Hejing > Bohu > Yuli > Heshuo, which is affected by various locations of industry throughout the study region. Kuerla county has the highest degree of industrialization, and leading highest COD; meanwhile, the rapid speed of development would result in zone 1 encountering severe pollution issues. Moreover, the results indicate that chemical plants and the oil industry generate more excess COD discharge than the agricultural processing industry, due to its relatively lower treatment efficiency, higher wastewater-generation rate, and higher concentration of raw wastewater.

Discussion

To analyze the efficiencies of trade-oriented mechanisms for water management in the region, different water management schemes (i.e., non-trading and trading scheme) were investigated using the FSGZ model. Figure 2 shows the optimized net system benefits for trading and non-trading schemes. The results indicate that a trading mechanism is superior to a non-trading one, which can increase and improve the economic efficiency on the whole, thus leading to higher benefits. For instance, at λ , α , and η levels of 0.5, 0.6, and 0.6, respectively, the system benefits with a trading scheme (1.81×10^9 \$) were much higher than those with a non-trading scheme (1.81×10^9 \$). The relative efficiencies of

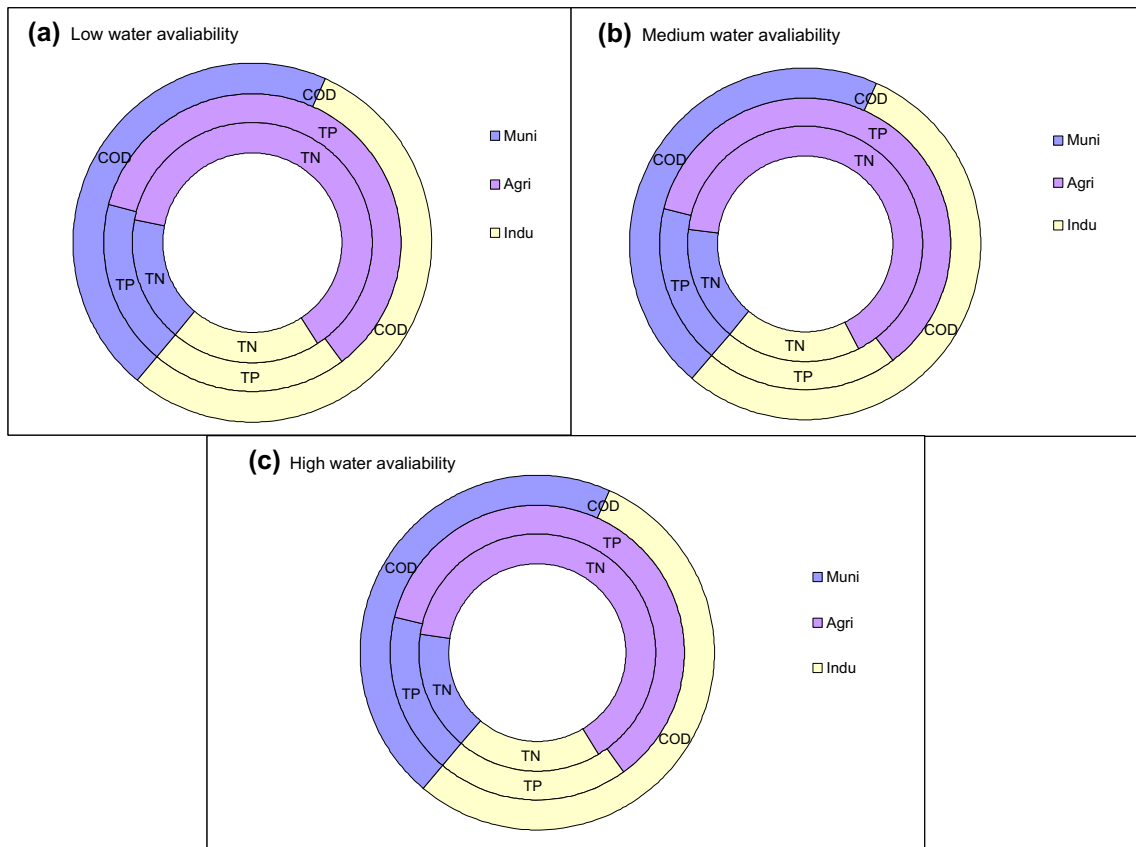


Fig. 6 Total pollution discharges of various counties when λ , α , and η levels are 1, 100, and 0.99

trading versus non-trading imply that trading via water markets is likely to increase and improve economic returns on the whole. Additionally, water shortages would be remedied by water trading because trading encourages the release of water from a low value to high value via a market approach (as shown in Fig. 3). In

addition, Fig. 7 shows excess pollution discharges for agriculture and urban sources with trading- and non-trading mechanisms. The trading mechanism relocates more water municipalities than to agriculture, so more excess pollutant discharge would be generated from urban sources, but pollutant discharge from

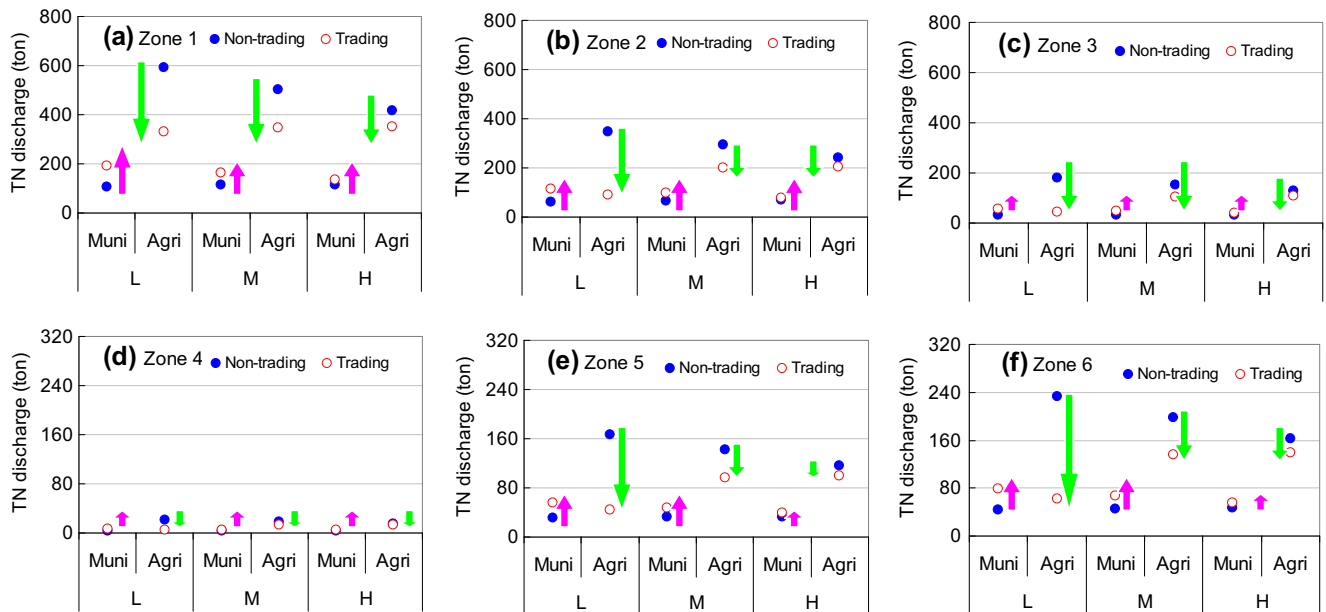


Fig. 7 Excess TN discharges among agriculture and municipality with trading- and non-trading mechanism when λ , α , and η levels are 1, 100, and 0.99

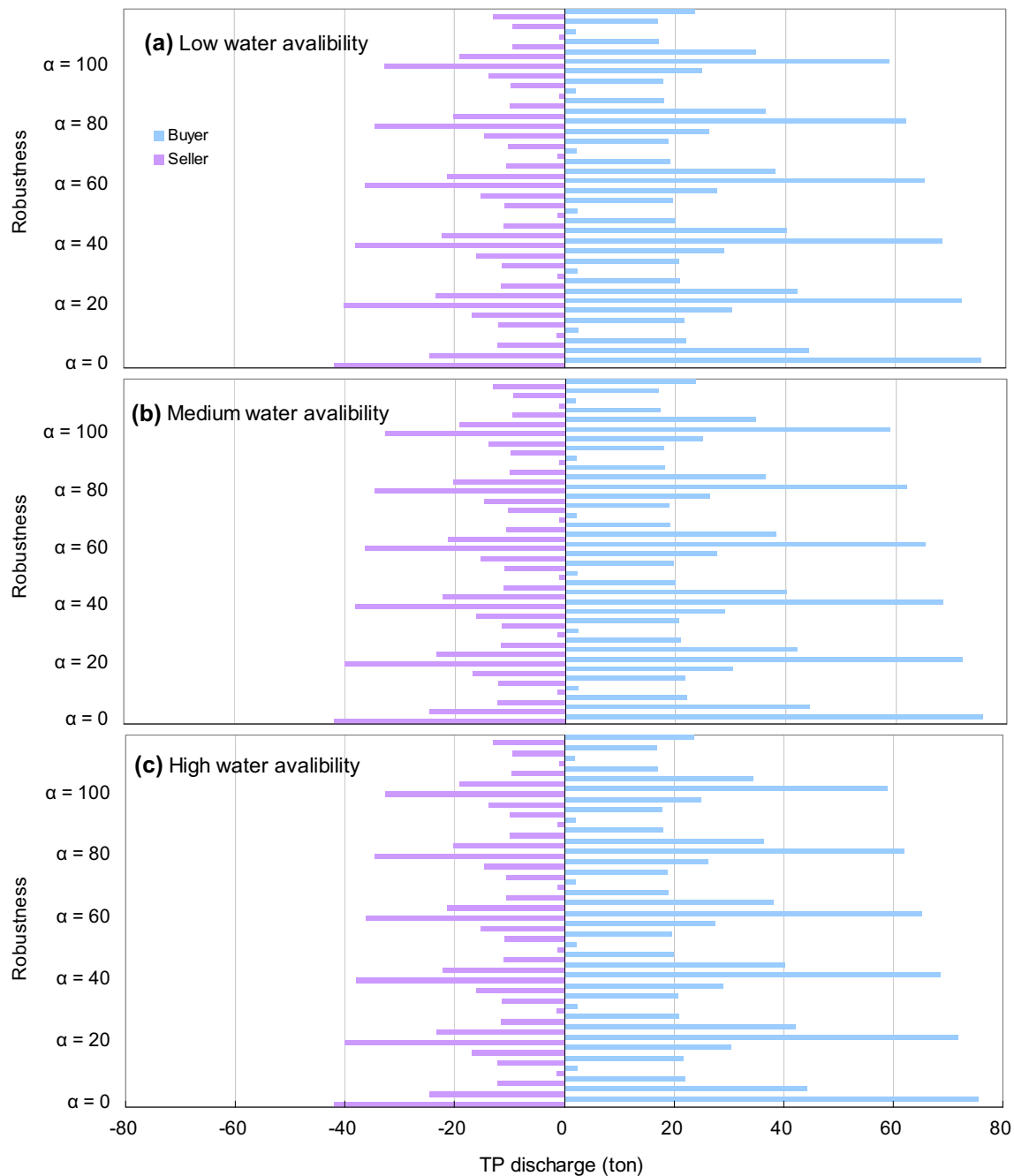


Fig. 8 Excess TP discharges for municipality with trading mechanism under different robustness when η and λ are 0.99 and 1

agriculture would decrease with a trading-oriented mechanism due to lower water allocation, while the opposite results would occur in the municipalities. Figure 8 demonstrates that trading and non-trading mechanisms can result in different N discharges based on the actual water allocation. For instance, the P discharge from urban sources with the trading scheme would be greater than that with the non-trading scheme because more water would be allocated to municipalities via a market-approach, and the opposite results would occur in agriculture. On the whole, the pollutant discharges with the trading mechanism would be relatively lower than those with the non-trading scheme.

The calculated results lead to the following findings: (a) results discover that severe water deficit has negative effects on drinking water security, food security, and economic development in the region. The reasons for water deficits include several factors, such as climate change, irrational water allocation plans, inefficient water-usage, behindhand water consumption concept, and unscientific risk option. (b) The results find that unreasonable industrial structure and excessive production has enhanced water deficits, even leading to severe pollution issues. A laissez-faire policy of overexploitation by agriculture and the overdevelopment of industry would result in an excessive water demand

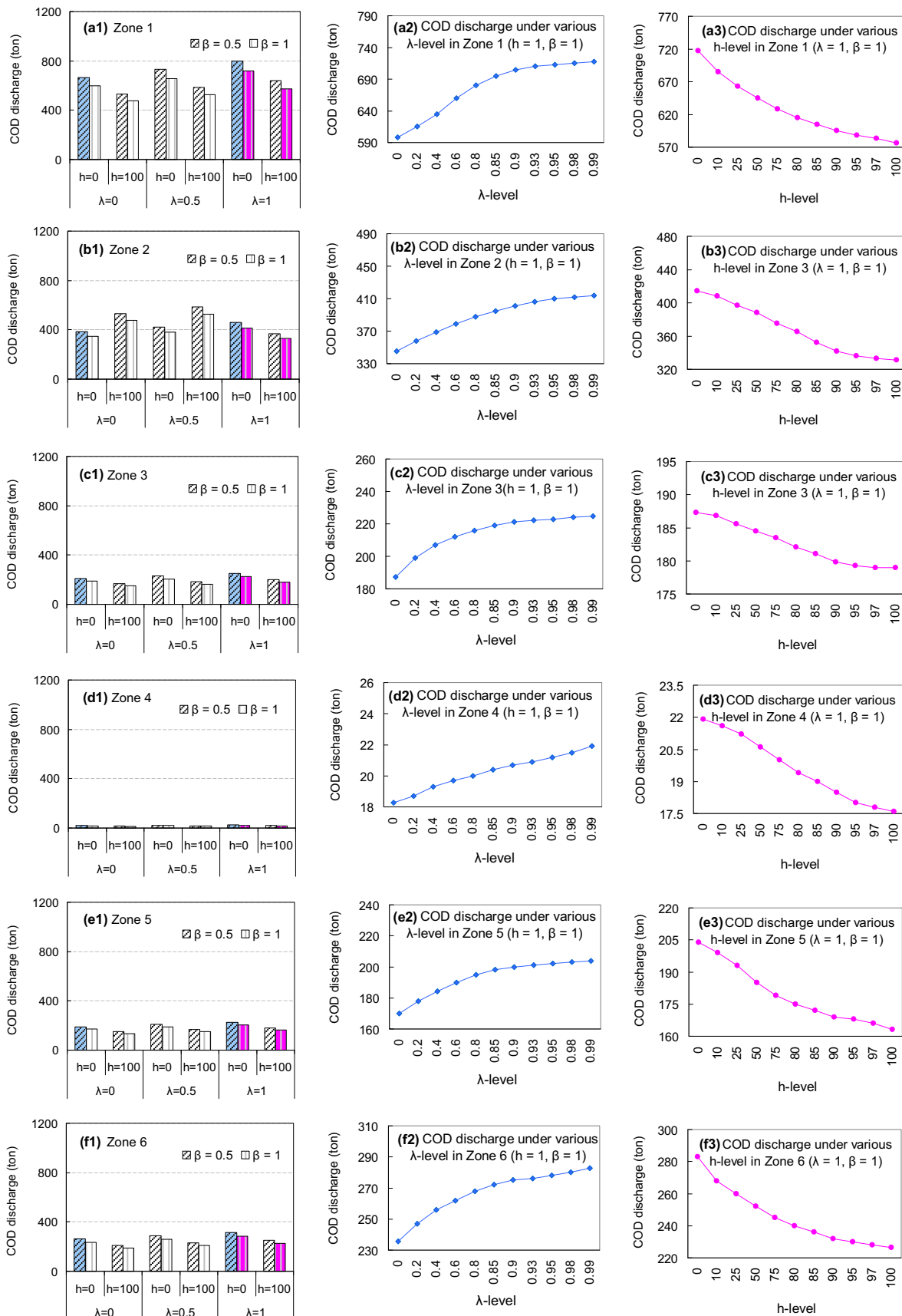


Fig. 9 COD discharges for industry with trading mechanism under different λ , α , and η levels

exceeding the natural capacity, and inefficient water usage, outdated recycling and retreatment techniques would aggravate pollution issues. (c) Inadequate fertilization management and irrigation regimes can degrade water resources and the environment, leading to a water-environment crisis. (d) A trading mechanism is more effective and can improve the efficiency of water allocation on the whole. (e) An unscientific risk choice (including confidence levels and scenario planning) in a decision process with uncertainties can affect WAQT plans, which adversely affects the policymaker leading to neither adventurous nor conservative decisions. Correspondingly, specific suggestions to the authorities are summarized as follows: (a) an adjustment of the local water-user structure and improvement of water-use efficiency could lessen water deficits and promote system benefits, as well as satisfying the local increasing water demand. (b) Adjusting the location of industries and limiting excess production can improve the efficiency of water consumption and lessen the impact of pollution. Additionally, wastewater recycling/treatment technologies should be promoted; more advanced techniques should be encouraged to improve the efficiency of pollutant removal. (c) Improving irrigation regimes and fertilizer regulation can simultaneously promote the efficiency of agricultural water-usage and lessen discharge. (d) Improving market construction/market behavior can improve the efficiency of water trading (including the water-user structure and water-use efficiency) to satisfy an increasing water demand. (e) Consciousness (including risk caused by natural and artificial uncertainties) should be accounted for in the policy making process and can fortify the reliability of land utilization plans in WAQT plans.

Conclusions

In this study, a fuzzy-stochastic programming with Green Z-score criterion (FSGZ) method is proposed for water resources allocation and water quality management with a trading-mechanism (WAQT) under multiple uncertainties. The developed FSGZ method is applied to a real world case study of WAQT in the Kaidu-Kongque River Basin, which is one of the most arid regions in northwest China. FSGZ incorporates Green Z-score criterion, and FP and TSP within a general framework. The advantages of this method are as follows: (a) FSGZ can realize recourse actions when random events occur; (b) it tackles fuzziness in objective function and constraint synchronously; (c) Green Z-score criterion is introduced for reflecting relationships between expected the target and outcome expressed as a hybrid and robust manner concluding the risk-averse attitude and robustness coefficient; (d) it can incorporate a trading mechanism, water allocation patterns, pollution control and economic growth into a compound management system to support policymakers in their sustainable water-environment plans / strategy; and (f) it can generate robust plans associated with risk control for policymakers to establish sustainable water allocation and

pollution control patterns under uncertainties. Although the FSGZ method is an attempt for WAQT under uncertainties, there are some limitations of the proposed method which would be improved in the future. For example, uncertainties presented as possibility and probability distributions cannot be tackled through FSGZ, which need to couple interval-parameter programming (deemed as other robust optimization techniques) to handle multiple formats of uncertainties.

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Appendix 1

In decision-making issues, fuzzy credibility constrained programming (FCP) is an effective manner to tackle independent fuzzy uncertainties in the constraint’s left- and right-hand sides, which can reflect relationship between satisfaction degree and system-failure risk as follows:

$$\text{Max } f = \sum_{i=1}^I a_i x_i \tag{A1 - 1a}$$

subject to

$$\text{Cr} \left\{ \sum_{i=1}^I u_{ij} x_i \leq \tilde{v}_j \right\} \geq \eta, \quad i = 1, 2, \dots, I; \quad j = 1, 2, \dots, J \tag{A1 - 1b}$$

$$x_i \geq 0, \quad i = 1, 2, \dots, I \tag{A1 - 1c}$$

where $x = (x_1, x_2, \dots, x_I)$ is a vector of non-fuzzy decision variables, a_i , u_{ij} and v_j are cost, technical and right-hand side coefficients respectively. η is credibility level which present a chance of a fuzzy event, In general, credibility of satisfying $\sum_{i=1}^I a_{ij} x_i \leq \tilde{b}_j$ should be greater than or equal to credibility level η (Zhang et al. 2015). Based on concept of credibility, the credibility measure (Cr) is obtained, which equal to an average of the possibility measure and the necessity measure as follow (Pishvae et al. 2012):

$$\text{Cr}\{\xi \leq r\} = \frac{1}{2} (\text{Pos}\{\xi \leq r\} + \text{Nec}\{\xi \leq r\}) \tag{A1 - 2}$$

In formula (A-2), $Pos\{\xi \leq r\} = \sup_{u \leq r} \mu(u)$ and $Nec\{\xi \leq r\} = 1 - \sup_{u > r} \mu(u)$ are possibility and necessity measure, which represent the possibility and necessity of a fuzzy event occur. Where ξ is a fuzzy variable with membership function μ , and μ and r are real numbers. (Trumbo and McComas 2003). Based on trapezoidal fuzzy number method, let $\delta = (\delta_1, \delta_2, \delta_3, \delta_4)$. The expected value of δ (i.e., $(\delta_1, \delta_2, \delta_3, \delta_4)/4$) and its corresponding credibility measures can be obtained. Since credibility measure is greater than 0.5 in response to avoiding improper unsatisfactions and violated risks (Pishvae et al. 2012; Zeng et al. 2014), when $\gamma > 0.5$, the credibility measure can be transformed to as follow:

$$Cr\{\delta \leq r\} \geq \gamma \Leftrightarrow r \geq (2-2\gamma)\delta_3 + (2\gamma-1)\delta_4 \Leftrightarrow \delta_3 + (1-2\gamma)(\delta_3-\delta_4) \tag{A1-3a}$$

$$Cr\{\delta \geq r\} \geq \gamma \Leftrightarrow r \geq (2-2\gamma)\delta_2 + (2\gamma-1)\delta_1 \Leftrightarrow \delta_2 + (1-2\gamma)(\delta_2-\delta_1) \tag{A1-3b}$$

However, FCP has difficulties in reflecting risk-averse attitude and robustness of system in decision-making process. Green Z-score criterion analysis (GZ) is an efficient manner to tackle such a problem, where various parameters (i.e., risk-averse attitude and robustness coefficient) are introduced into FCP to generate a simplified rational model that can be personalized to the individual decision maker with robust manners (Hajkowicz 2008). Thus, a fuzzy credibility constrained programming with Green Z-score criterion (FCP-GZ) can be formulated as follows:

$$\text{Max } f = \max[(\lambda \cdot OP) - (1-\lambda) \cdot PE] \tag{A1-4a}$$

subject to

$$OP = \sum_{n=1}^N \left[(f_{out} - \varphi) / \left(\max_{d \in D} f_{out} - \varphi \right) \right] \tag{A1-4b}$$

$$PE = \sum_{n=1}^N \left(f_{out} / \min_{d \in D} f_{out} \right) \tag{A1-4c}$$

$$Cr \left\{ \sum_{i=1}^I a_{ij} x_i \leq \tilde{b}_j \right\} \geq \eta^b, \quad i = 1, 2, \dots, I; \quad j = 1, 2, \dots, J \tag{A1-4d}$$

$$x_i \geq 0, \quad i = 1, 2, \dots, I \tag{A1-4e}$$

where λ ($0 \leq \lambda \leq 1$) is the optimism coefficient, which can reflect pessimism/optimism attitudes of decision makers, where λ and $(1-\lambda)$ represent the measure of decision maker's optimism and pessimism respectively. In FCP-GZ, a range (i.e., difference between maximum and minimum outcome across all options) would be assigned value (i.e., φ), where $\varphi = 0$ represents the worst outcome and $\varphi = 1$ means the best one (Green and Weatherhead 2014). Meanwhile, α is coefficient of robustness would be introduced into FCP-GZ; thus, we have:

$$\varphi = \max_{d \in D} f_{out} - \left[\left(\max_{d \in D} f_{out} - \min_{d \in D} f_{out} \right) \cdot (\alpha/100) \right] \tag{A1-5}$$

Thus, model (A-1) can be transferred into:

$$\text{Max } f = \max \left\{ \lambda \cdot \sum_{n=1}^N \frac{f_{out} - \left[\max_{d \in D} f_{out} - \left(\max_{d \in D} f_{out} - \min_{d \in D} f_{out} \right) \cdot (\alpha/100) \right]}{\max_{d \in D} f_{out} - \left[\max_{d \in D} f_{out} - \left(\max_{d \in D} f_{out} - \min_{d \in D} f_{out} \right) \cdot (\alpha/100) \right]} - (1-\lambda) \cdot \sum_{n=1}^N \left(f_{out} / \min_{d \in D} f_{out} \right) \right\} \tag{A1-6a}$$

subject to

$$Cr \left\{ \sum_{i=1}^I a_{ij} x_i \leq \tilde{b}_j \right\} \geq \eta^b, \quad i = 1, 2, \dots, I; \quad j = 1, 2, \dots, J \tag{A1-6b}$$

$$x_i \geq 0, \quad i = 1, 2, \dots, I \tag{A1-6c}$$

where coefficient of robustness, $\alpha/100$ (where $0 < \alpha < 100$) can increase the robustness of FCP-GZ.

However, FCP-GZ has difficulties in tackling uncertainties expressed as random variables in a non-fuzzy

decision space (Inuiguchi 2012); moreover, it is lack of linkage to economic consequences of violated policies pre-regulated by authorities through taking recourse actions in order to correct any infeasibilities (Li and Huang 2009). TSP can handle such issue, which can contribute linkages between initial decision (first-stage decision) and random event (second-stage decision) through a recourse action as follows (Li et al. 2006):

$$\text{Max } f = \sum_{i=1}^{I_1} e_i x_i - \sum_{i=1}^{I_2} \sum_{h=1}^H p_h s_i v_{ih} \tag{A1-7a}$$

subject to

$$\sum_{i=1}^{I_1} A_{ij}x_i \leq b_j, \quad j = 1, 2, \dots, J_1 \tag{A1 - 7b}$$

$$\sum_{i=1}^{I_1} A_{it}x_i + \sum_{i=1}^{I_2} A'_{it}x_i \geq w_h, \quad t = 1, 2, \dots, J_2; \quad h = 1, 2, \dots, H \tag{A1 - 7c}$$

$$x_i \geq 0, \quad i = 1, 2, \dots, I_1 \tag{A1 - 7d}$$

$$y_{ih} \geq 0, \quad i = 1, 2, \dots, I_2; \quad h = 1, 2, \dots, H \tag{A1 - 7e}$$

where x_i (first-stage decision variables) have been regulated before the random event occur, leading $e_i x_i$ (first-stage benefits); p_h is probability of random event; y_{ih} (second-stage decision variables) would recourse under the occurrence of event, leading $\sum_{h=1}^H p_h s_i y_{ih}$ (second-stage penalties) (Li et al. 2006); w_h are random variables with probability levels p_h .

Appendix 2

Based on the FSGZ approach, an effective water resources allocation and water quality management with trading-mechanism (WQT) model is formulated. The objective is to maximize the net system benefit (i.e., municipal, agricultural, industrial, and ecological incomes); meanwhile uncertain information would be considered into plans to reflect the system disruption risk attributable to uncertainties. Thus, the objective function can be presented as follows:

$$\bar{f}_{out} = (1)-(2)-(3)-(4) + (5)-(6) \tag{A2 - 1a}$$

- (1) Income from water allocations for municipal, agricultural, industrial and ecological activities:

$$\begin{aligned} & \sum_{m=1}^2 \sum_{j=6}^6 \overline{BM}_{mj} \cdot WLM_{mj} + \sum_{n=1}^5 \sum_{j=1}^6 \overline{BA}_{nj} \cdot WLA_{nj} \\ & + \sum_{i=1}^3 \sum_{j=1}^6 \overline{BI}_{ij} \cdot WLI_{ij} + \sum_{k=1}^2 \sum_{j=1}^6 \overline{BE}_{kj} \cdot WLE_{kj} \end{aligned} \tag{A2 - 1b}$$

- (2) Loss from water shortages for municipal, agricultural, industrial and ecological activities):

$$\begin{aligned} & \sum_{m=1}^2 \sum_{j=6}^6 \overline{LM}_{mj} \cdot SLM_{mj} + \sum_{n=1}^5 \sum_{j=1}^6 \overline{LA}_{nj} \cdot SLA_{nj} \\ & + \sum_{i=1}^3 \sum_{j=1}^6 \overline{LI}_{ij} \cdot SLI_{ij} + \sum_{k=1}^2 \sum_{j=1}^6 \overline{LE}_{kj} \cdot SLE_{kj} \end{aligned} \tag{A2 - 1c}$$

- (3) Penalty for excessive emissions from municipal, agricultural, industrial and ecological activities:

$$\begin{aligned} & \sum_{m=1}^2 \sum_{j=6}^6 \overline{PM}_{mj} \cdot YLM_{mj} \cdot POM_{mj} \\ & + \sum_{n=1}^5 \sum_{j=1}^6 \overline{PA}_{nj} \cdot YLA_{nj} \cdot IRA_{nj} \\ & + \sum_{i=1}^3 \sum_{j=1}^6 \overline{PI}_{ij} \cdot YLI_{ij} \cdot RI_{ij} \end{aligned} \tag{A2 - 1d}$$

- (4) Cost for environmental retreatment from municipal, agricultural and industrial activities:

$$\begin{aligned} & \sum_{m=1}^2 \sum_{j=6}^6 \overline{CM}_{mj} \cdot (WLM_{mj} - SLM_{mj}) \cdot POM_{mj} \cdot (1 - \alpha) \\ & + \sum_{i=1}^3 \sum_{j=6}^6 \overline{CI}_{ij} \cdot (WLI_{ij} - SLI_{ij}) \cdot RI_{ij} \cdot (1 - \eta) \end{aligned} \tag{A2 - 1e}$$

- (5) System benefits from water trading:

$$\begin{aligned} & \sum_{n=1}^5 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TA_{nj} \cdot \overline{BA}_{nj} \\ & + \sum_{k=1}^2 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TE_{kj} \cdot \overline{BE}_{kj} \\ & + \sum_{m=1}^2 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TM_{mj} \cdot \overline{BM}_{mj} \\ & + \sum_{i=1}^3 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TI_{ij} \cdot \overline{BI}_{ij} \end{aligned} \tag{A2 - 1f}$$

(6) Costs of water trading:

$$\begin{aligned} & \sum_{m=1}^2 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TM_{mj} \cdot \overline{VMC}_{mj} \\ & + \sum_{n=1}^5 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TA_{nj} \cdot \overline{VAC}_{nj} \\ & + \sum_{k=1}^2 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TE_{kj} \cdot \overline{VEC}_{kj} \\ & + \sum_{i=1}^3 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TI_{ij} \cdot \overline{VIC}_{ij} \end{aligned} \tag{A2 - 1g}$$

where f_{out} is the total system benefit, equaling to the total benefits/returns minus the total costs. The detailed nomenclatures for the variables and parameters are provided in Notation and Subscript. In this study, 12 water activities/consumers in four sectors (i.e., municipal, agricultural, industrial, and ecological sectors) are competitors in water demands. After water allocation, actual pollutant would discharge in proportion to water consumption. Five main point sources scatter along the river stretch, including two municipal plants (i.e, residential use and municipal services), three industrial plants (i.e., agricultural processing industry, oil industry, and chemical industry); meanwhile five non-point sources plants (i.e., pearl, cotton, oil plants, vegetable, and fruit) from agricultural zones due to manure/fertilizer applications are also taken into consideration. Three water availability levels (i.e., low, medium and high levels) are selected, due to their high vagueness. Since economic data are can be both impacted by objective and subjective factors, a hybrid format of uncertainties expressed as probability distributions and fuzzy sets can be tackled by a fuzzy-stochastic programming with Green Z-score criterion (FS-GZ) (the solutions as shown in “**Methodology**” section).

Meanwhile, some water-environment related constraints include a number of inequalities/equalities which define relationships among water availability, water permit, water quantity, water trading, wastewater retreatment capacity, nitrogen/phosphorus/COD discharges and technique constraints as follows:

(1) Constraints of water availability:

$$Cr \left\{ \tilde{Q}_{jh}^K = \tilde{Q}_{jh}^R - E_{jh} - H_{jh} \right\} \geq \eta \tag{A2 - 2a}$$

Equality (A2-2a) presents water availabilities from surface, watercourse and underground water, all of which need to maintain the minimum level requirement respectively (m^3). Since the

amount of available water in the future can be both impacted by spatio-temporal and artificial factors, a hybrid fuzzy-stochastic format can be introduced to express such a hybrid uncertainty. The other uncertainties in water availabilities from objectives and constraints can refer to this expression.

(2) Constraints of water permit

$$Cr \left\{ (1-\delta) \cdot \tilde{Q}_{jh}^K = \tilde{Q}_{jh}^A \right\} \geq \eta \tag{A2 - 2b}$$

Inequality (A2-2b) means that the sum of initial water permit can be assigned to each water consumer based on policy associated with initial water permit assignment, which would not exceed actual water availability. δ is maximum percentage for initial water permit assignment for each water consumer to satisfy basic demand.

(3) Constraints of water trading:

$$Cr \left\{ \begin{aligned} & \left[\sum_{m=1}^2 \sum_{j=1}^6 (WLM_{mj} - WM_{mj}) - \sum_{m=1}^2 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TM_{mj} \right] \\ & + \left[\sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - WA_{nj}) - \sum_{n=1}^5 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TA_{nj} \right] \\ & + \left[\sum_{i=1}^3 \sum_{j=1}^6 (WLI_{ij} - WI_{ij}) - \sum_{i=1}^3 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TI_{ij} \right] \\ & + \left[\sum_{k=1}^2 \sum_{j=1}^6 (WLE_{kj} - WE_{kj}) - \sum_{k=1}^2 \sum_{j=1}^6 \sum_{h=1}^3 p_{jh} \cdot TE_{kj} \right] \geq \tilde{Q}_{jh}^A \end{aligned} \right\} \geq \eta \tag{A2 - 2c}$$

(4) Constraints of water quantity:

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\begin{aligned} & \sum_{m=1}^2 \sum_{j=6}^6 (WLM_{mj} - SLM_{mj} + TM_{mj}) \\ & + \sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{nj}) \\ & + \sum_{i=1}^3 \sum_{j=1}^6 (WLI_{ij} - SLI_{ij} + TI_{ij}) \\ & + \sum_{k=1}^2 \sum_{j=1}^6 (WLE_{kj} - SLE_{kj} + TE_{kj}) \end{aligned} \right] \leq \tilde{Q}_{jh}^K \right\} \geq \eta \tag{A2 - 2d}$$

Inequality (A2-2c) presents that water trading can be satisfy water demand in the mass in a two-stage context after initial water permit assignment, where trading amount (when flow levels are low, medium and high) would occur based on random variables (i.e., water

availabilities). Inequality (A2-2d) presents although water deficit would bring about adverse impact to water demand, water trading can remit such conflict through market-approach, which could encourage water from low value to high one based on price value regulation.

(5) Constraints of waste water treatment capacity:

$$\sum_{h=1}^3 p_{hj} \left[\sum_{m=1}^2 \sum_{j=6}^6 (WLM_{mj} - SLM_{mj} + TM_{mj}) \cdot POM_{mj} \cdot \alpha \right] \leq CTM_{mj} \tag{A2 - 2e}$$

$$\sum_{h=1}^3 p_{hj} \left[\sum_{i=1}^3 \sum_{j=1}^6 (WLI_{ij} - SLI_{ij} + TI_{ij}) \cdot RI_{ij} \cdot \beta \right] \leq CTI_{ij} \tag{A2 - 2f}$$

Inequalities (A2-2e) to (A2-2f) guarantee that the wastewater generation from point source (main from human-daily life and industrial-production process) should be less than maximum wastewater treatment capacity.

(6) Constraints of COD discharge:

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\sum_{m=1}^2 \sum_{j=6}^6 (WLM_{mj} - SLM_{mj} + TM_{mj}) \cdot POM_{mj} \cdot (1-\alpha) \cdot dm_{COD} + \sum_{i=1}^3 \sum_{j=6}^6 (WLI_{ij} - SLI_{ij} + TI_{ij}) \cdot RI_{ij} \cdot (1-\eta) \cdot di_{COD} \right] \leq \tilde{D}_{mj}^{CM} + \tilde{D}_{ij}^{CI} \right\} \geq 0 \tag{A2 - 2g}$$

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{nj}) \cdot IRA_{nj} \cdot da_{COD} \right] \leq \tilde{D}_{njh}^{CA} \right\} \geq \eta \tag{A2 - 2h}$$

allowable COD discharge level (based on environmental load in study region).

(7) Constraints of nitrogen discharge:

Inequalities (A2-2g) and (A2-2h) present that although wastewater can be retreated by sewage facilities, ultimate COD discharges from municipality and industry would be entered into the river, which requires not exceeding the

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\sum_{m=1}^2 \sum_{j=6}^6 (WLM_{mj} - SLM_{mj} + TM_{mj}) \cdot POM_{mj} \cdot (1-\alpha) \cdot dm_{TN} + \sum_{i=1}^3 \sum_{j=6}^6 (WLI_{ij} - SLI_{ij} + TI_{ij}) \cdot RI_{ij} \cdot (1-\eta) \cdot di_{TN} \right] \leq \tilde{D}_{mjh}^{NM} + \tilde{D}_{ijh}^{NI} \right\} \geq \eta \tag{A2 - 2i}$$

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{nj}) \cdot ua_{nj} \cdot IRA_{nj} \cdot dar_{TN} + \sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{nj}) \cdot SA_{nj} \cdot das_{TN} \right] \leq \tilde{D}_{njh}^{NA} \right\} \geq \eta \tag{A2 - 2j}$$

(8) Constraints of phosphorus discharge:

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\sum_{m=1}^2 \sum_{j=6}^6 (WLM_{mj} - SLM_{mj} + TM_{mj}) \cdot POM_{mj} \cdot (1-\alpha) \cdot dm_{TP} + \sum_{i=1}^3 \sum_{j=6}^6 (WLI_{ij} - SLI_{ij} + TI_{ij}) \cdot RI_{ij} \cdot (1-\eta) \cdot di_{TP} \right] \leq \tilde{D}_{mjh}^{PM} + \tilde{D}_{ijh}^{PI} \right\} \geq \eta \tag{A2 - 2k}$$

In study region, since excessive chemical fertilization and expanding chemical commodity consumption are required with rapid of economic development, vestigial nutrients are transported to water body through soil erosion and surface runoff, leading pollution issues. Inequalities (A2-2i) and (A2-2j) show that nitrogen discharge restrictions, which indicate that point and non-point sources of nitrogen discharges would be regulated by allowance thresholds.

$$Cr \left\{ \sum_{h=1}^3 p_{hj} \left[\sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{nj}) \cdot ua_{nj} \cdot IRA_{nj} \cdot dar_{TP} + \sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{nj}) \cdot SA_{nj} \cdot das_{TP} \right] \leq \tilde{D}_{njh}^{PA} \right\} \geq \eta \tag{A2 - 2l}$$

Inequalities (A2-2k) and (A2-2l) shows that phosphorus discharges restrictions, which indicates that point and non-point sources of phosphorus discharges would be restricted by allowance thresholds based on environmental load.

(9) Constraints of soil loss:

$$\sum_{h=1}^3 P_{hj} \left[\sum_{n=1}^5 \sum_{j=1}^6 (WLA_{nj} - SLA_{nj} + TA_{njh}) \cdot ua_{nj} \right] \leq SPA_{nj} \tag{A2 - 2m}$$

Inequality (A2-2m) shows that the catchment possesses would be potential for generating soil erosion and surface runoff due to its special geography, which may result in effluent discharge into the river directly. Thus, it imposed allowance sediment load permit to restrict soil erosion.

(10) Constraints of cropland resources:

$$WLA_{njmin} \leq WLA_{nj} \leq WLA_{njmax} \tag{A2 - 2n}$$

(11) Constraints of industrial production scale:

$$WLI_{njmin} \leq WLI_{nj} \leq WLI_{njmax} \tag{A2 - 2o}$$

(12) Constraints of population growth scale:

$$WLM_{njmin} \leq WLM_{nj} \leq WLM_{njmax} \tag{A2 - 2p}$$

Inequality (A2-2n) presents restrictions of irrigation developing scale in study region, which means that planning crop area would less than the limited tillable land resources; meanwhile it would be greater than minimum farmland areas regulated by policymakers. Inequality (A2-2o) shows that scale of industrial production should be restricted to maintain a rational pace. Inequality (A2-2p) presents population growth scale, which indicates that the population growth should maintain a speed based on how the water / environmental load in study region.

(13) Constraints of non-negative:

$$\begin{matrix} SLM_{mj}, SLA_{nj}, SLI_{ij}, SLE_{kj} \geq 0 & BM_{mj}, BA_{njb}, BI_{ij}, BE_{kj} \geq 0 \\ C M_{mj}, C A_{nj}, C I_{ij}, C E_{kj} \geq 0 \end{matrix} \tag{A2 - 2q}$$

Inequality (A2-2q) is non-negativity restriction, which assures that only positive activities would be considered in the solution, eliminating infeasibilities while calculating the solution.

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