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A Water Trading Model Based on the Construction of Water Bank with Considering Multiple Uncertain Information

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Abstract. On the context of population growth and industrialization development, water demands of China present an increasing tendency, which results in conflicts between human activities and water resources. Particular in an arid region, the water deficit has attracted policymakers' attentions, which requires a more effective water resources allocation method to satisfy the harmony between human being and natural resources. Thus, a "quasi-market" approach (mixed market approach or government method) is developed for water allocation in an arid region; meanwhile, water bank would be introduced to improve water trading. An interval stochastic-fuzzy programming (ISFP) is introduced to tackle uncertainty by probability distribution and interval number; meanwhile it can hedge the risk by the simulation process of water trading. Based on analysis of feature of arid region, a sustainable water resources strategy and mode can be provided to coordinate the human activity and resources utilization.

1. Introduction

The high speed of population growth and economic development can lead the shrinking of available water resources in China, which would motivate water crisis today. The decision-makers have confronted big challenge for maintaining sustainable between human development and limited water resources, particularly in some arid regions. More efficient schemes for water resources management such as water trading have been required, with aim to allocate water resources optimally [1]. Although trading mechanism can increases the economic productivity of water by encouraging its movement from low to high valued, water is a quasi-good, which can not be allocated by market value completely [2]. Therefore, a "quasi-market" approach (mixed market approach or government method) can be established for water allocation in an arid region; meanwhile, water bank would be introduced to improve water trading [3]. However, multiple uncertainties and corresponding complexities in a water trading system would increase the risk of decision-making, which have essentially placed them beyond the conventional deterministic optimization methods.

System analysis and optimization method can be deemed as effective tools to support decision-making processes in water trading with considering multiple uncertainties [4]. Among these, two-stage stochastic mathematic programming (TSP) is an effective manner to handle randomness characterized by probability distribution (such as water flow), where the expected target can be recoursed by an examination of random water availability [3]. Meanwhile, through the construction of linkage between policies and the economic penalties, TSP can reflect complexities of system uncertainties as well as analyzing policy scenarios when the pre-regulated targets are violated [4], [5]. However, the TSP method has difficulty in identifying the probability distribution of coefficient, which should be traduced an interval parameter mathematic programming into TSP optimization framework [6]. Moreover, many uncertainties (e.g., economic data and water availabilities) are often not obtained as probability distributions, which make deterministic parameters of water availability mislead or bias the decision makers easily. Therefore, credibility constrained programming (CCP) can be introduced to measure in fuzzy water trading system with the confidence levels, which would be useful in the presence of weaker sources of information [6], [7]. Previously, few reports in the consideration of multiple uncertainties previously, which requires a hybrid method to deal with uncertainties and economic penalties in a water trading system based on trading mechanism.

Therefore, an interval stochastic-fuzzy programming (ISFP) for water trading is developed for water resources management in arid regions of China. The proposed method can not only reflect the tradeoffs between resource benefits and penalties, but also deal with uncertainties expressed as intervals, probability distributions and fuzzy membership functions. The ISFP method will be applied to one of the arid regions in Northwest China. The model can help releasing more water resources to join into water trading based on bank, which can reduce the loss of water deficiency and gain a high net system benefit. Local economic targets, the decreasing of water permit and water trading ratio under varied levels of system-failure risk will be generated, which not only help decision makers optimally allocate water resources, but also gain insights into the tradeoffs between water trading and economic objective.

2. Modeling Formulation

In a water trading system, policymakers have allocated water permit target to each user in the beginning of this year according to the situations of water usage last year. However, the random water availability would result in water target being not met, which would be adjusted by policymakers. Since trading mechanism has introduced to improve the productivities of water from low value to high value, water permits can be allocated to by law of price. However, water is a quasi-public good, which should be allocated to satisfy the basic water demand of drink safety and food secure. Thus, water permit can be allocated to satisfy the basic demand of water user, then, the surplus water permit can be traded. Meanwhile, water bank is introduced into water trading, which can provide more water source participating into water market to allocate water more effectively and equally. However, multiple uncertainties may exist in water allocation and trading process, which affect the water resources management planning to be made. Thus, water trading model based on water bank can be formulated as follows:

$$\max f^{\pm} = \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{\pm} W_{ij}^{\pm} - \sum_{i=1}^{I}\sum_{j=1}^{J} BC_{ij}^{\pm} BW_{ij}^{\pm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H} P_h C_{ij}^{\pm} Y_{ijh}^{\pm} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H} P_h (TB_{ij}^{\pm} - TC_{ij}^{\pm}) TY_{ijh}^{\pm} \quad (1)$$

Where $f^{\pm}$ is total system benefit; i is type of water user (1 is municipal; 2 is agricultural; 3 is industrial; 4 is ecological; j represent various district; h is water level (1 to 3 are high, medium and high level); $B_{ij}^{\pm}$ is the net benefit of one volume water being delivered to user i in district j; $W_{ij}^{\pm}$ is water target of user i in district j; $C_{ij}^{\pm}$ is loss of one volume water not being delivered to user i in district j; P_h is probability of water shortage; $Y_{ijh}^{\pm}$ is amount of water shortage; $BW_{ij}^{\pm}$ is initial water permit to satisfy the basic water demand in district j; $BC_{ij}^{\pm}$ is delivering cost; $TY_{ijh}^{\pm}$ is trading amount; $TB_{ij}^{\pm}$ is remedying cost from water trading; $TC_{ij}^{\pm}$ is trading cost.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} (Q_{ijh}^{\pm} - BW_{ijh}^{\pm}) \le T_{ij}^{\pm}, \quad \forall i, j \quad (2a)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} TY_{ijh}^{\pm} \le T_{ij}^{\pm}, \quad \forall i, j \quad (2b)$$

$$TC_{ij}^{\pm} + TS_{ij}^{\pm} \le C_{ij}^{\pm}, \quad \forall i, j \quad (2c)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} (W_{ij}^{\pm} - Y_{ijh}^{\pm} + TY_{ijh}^{\pm}) \le Q_{ijh}^{\pm}, \quad \forall i, j, h \quad (2d)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} TY_{ijh}^{\pm} \le (1-g) * \sum_{i=1}^{I}\sum_{j=1}^{J} S_{ijh}^{\pm} \le T_{ij}^{\pm}, \quad \forall i, j, h \quad (2e)$$

$$S_{ijh}^{\pm} \leq (R_{ij}^{\pm} + V_{hij}^{\pm} - E_{ij}^{\pm}) - R_{ij\min}^{\pm}, \quad \forall i, j, h \tag{2f}$$

$$0 \leq Y_{ij}^{\pm} \leq Q_{ijh}^{\pm}, \quad \forall i, j \tag{2g}$$

$$W_{ij}^{\pm}, BW_{ij}^{\pm} \geq 0, \quad \forall i, j \tag{2h}$$

Where $T_{ij}^{\pm}$ is available water permit for trading; g is the reducing percent of water trading from water bank; $S_{ij}^{\pm}$ is available water from water bank under various water level; $R_{ij}^{\pm}$ is initial value of water in water bank; $V_{ijh}^{\pm}$ is water inflow into water bank; $E_{ij}^{\pm}$ is water loss in water bank; $R_{ijm\text{in}}^{\pm}$ is minimum water demand for water bank.

3. Case Study

Kaidu-kongque River Basin contains six counties with area of 62 $\times 10^3 km^2$, which has the population more than one million [8]. It is a typical arid region, where the water supply capacity of river is quite low due to extremely dry climate, low rainfall, and high evaporation, which can not satisfy water demands of 4 users in 6 counties easily. Water trading based on water bank can solve conflicts caused by water shortage, which not only improve the net system benefit. In study basin, under allocated water permit, since trading can release surplus water to join into water bank, water bank include three types of water (e.g., underground water, reservoir water and released surplus water). Competitive four users (e.g., municipal, agricultural, industrial, and environmental users) in six counties will sell released water or buy water from water bank to remedy water shortages and gain higher benefits. **Figure 1** present the relationship between water manager and users in water trading based on water bank.

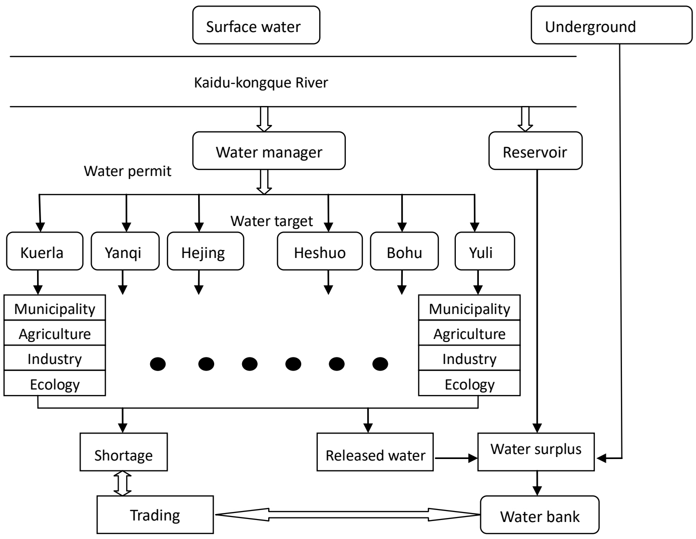

Figure 1. Framework of water trading based on water bank

However, a number of variations caused by factitious factors and natural factors exist in the trading system, which brings more complexities and uncertainties in water trading system. These complexities could become further compounded by not only interactions among the uncertain parameters but also their economic implications. The proposed ISFP model can be used for optimally allocating limited water to facilitate the regional sustainability. The parameters inputs for ISFP is based on calculation from field surveys, statistical data, and related research works previously. Table 1 shows water policy data and water target, in which is acquired by the water permit of water authority of Uygur Autonomous Region from 2005 to 2010 directly [8]. Table 2 shows economic data and trading costs. In order to appraise diverse net system benefits under different water permit and trading ratio in water trading system, numbers of scenarios with water permits (i.e., the value will change from 0% to 20%) and trading ratio (i.e., the value will change from 100% to 10%) will be assumed.

Table 1. Water targets and water permits

District		User			
		i = 1 Municipality	i = 2 Agriculture	i = 3 Industry	i = 4 Ecology
Water target (unit: 10^6 m^3)					
j = 1	Kuerle county	[8.80, 14.00]	[258.00, 275.00]	[53.30, 620.00]	[56.00, 76.00]
j = 2	Yanqi county	[6.00, 8.20]	[158.00, 165.00]	[28.00, 39.00]	[31.00, 47.00]
j = 3	Hejing county	[2.40, 4.30]	[81.00, 88.00]	[16.00, 20.10]	[14.70, 23.00]
j = 4	Heshuo county	[0.24, 0.50]	[9.70, 10.10]	[1.78, 2.25]	[1.28, 2.60]
j = 5	Bohu county	[2.20, 4.30]	[75.00, 85.00]	[15.60, 19.00]	[13.70, 23.00]
j = 6	Yuli county	[4.60, 6.00]	[110.00, 120.00]	[21.60, 27.00]	[24.00, 33.00]
Allocated allowable water permit (unit: 10^6 m^3)					
j = 1	Kuerle county	[9.72, 13.75]	[261.60, 275.08]	[55.44, 61.89]	[59.56, 75.65]
j = 2	Yanqi county	[[6.64, 8.14]	[158.33, 162.87]	[30.31, 36.65]	[32.26, 44.79]
j = 3	Hejing county	[2.89, 4.23]	[82.22, 84.50]	[15.70, 19.01]	[17.08, 23.24]
j = 4	Heshuo county	[0.36, 0.53]	[9.11, 9.38]	[1.89, 2.11]	[1.69, 2.70]
j = 5	Bohu county	[2.56, 4.09]	[78.89, 81.84]	[15.78, 18.41]	[15.58, 22.58]
j = 6	Yuli county	[4.94, 5.87]	[110.56, 117.41]	[22.33, 26.42]	[25.56, 32.29]

Table 2. Economic data

District	User			
	i = 1 Municipality	i = 2 Agriculture	i = 3 Industry	i = 4 Ecology
Trading fix cost (unit: US$/$10^3$ m^3)				
j = 1 to 6	[3050, 3150]	[550, 650]	[2400, 2600]	[280, 350]
Trading variable cost (unit: US$/$10^3$ m^3)				
j = 1 to 6	[1200, 1350]	[700, 800]	[150, 200]	[100, 150]

4. Result Analysis

In this study, five scenarios corresponding to different water permit levels and ten scenarios corresponding to different water trading ratio levels were examined by the ISFP model in Kaiduo-kongque River Basin. Different λ levels achieved different water availabilities, water targets, and varied water shortage. In general, actual water allocation would be target minus shortage, which can be impacted by random stream condition with an associated probability level. **Figure 2** shows that a higher λ level (higher credibility satisfaction) can lead lower water availability, which results in a lower allocation, leading a lower benefit, vice versa. Solutions for optimized net system benefits show that the sum of the first-stage benefit from the water allocation and the second-stage random losses of water deficiency.

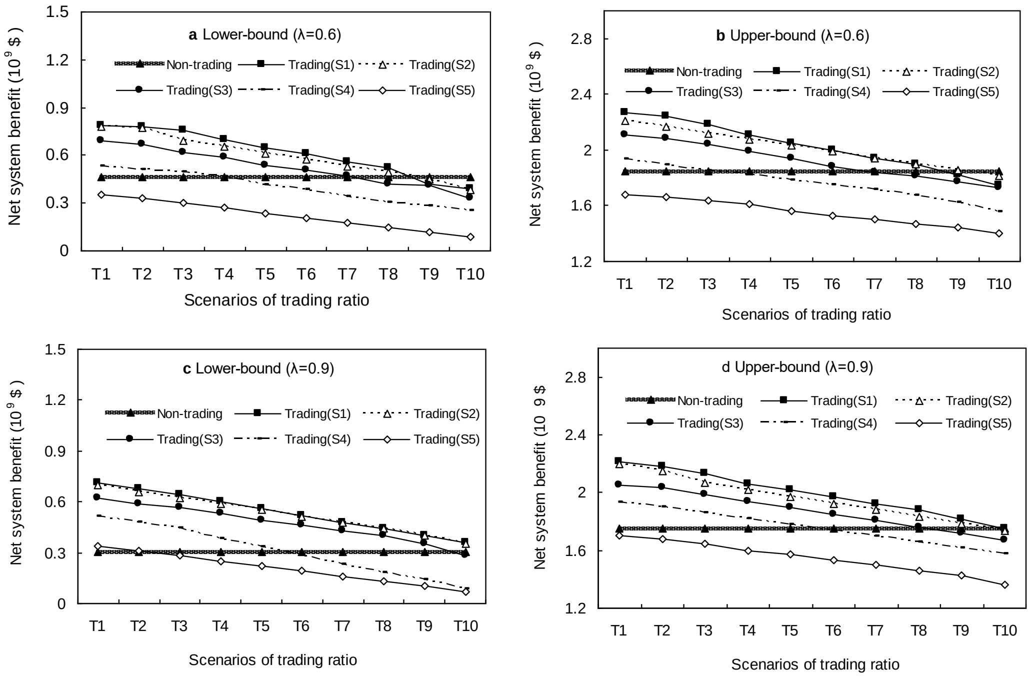

Figure 2. System benefits under various decreasing water permit levels / trading ratio (λ=0.6 and 0.9)

Figure 3 presents water shortages under various policy cases (S1 and S4). Due to water deficiency in study region, water permits have been allocated in advance to satisfy the basic water demand; then the surplus can be traded based on water bank, so as to saving more water or getting higher benefits. By the decreasing of water permits, less water would be allowanced but more water would be released to trade, which led much more shortage under lower water permit than that under higher water permit.

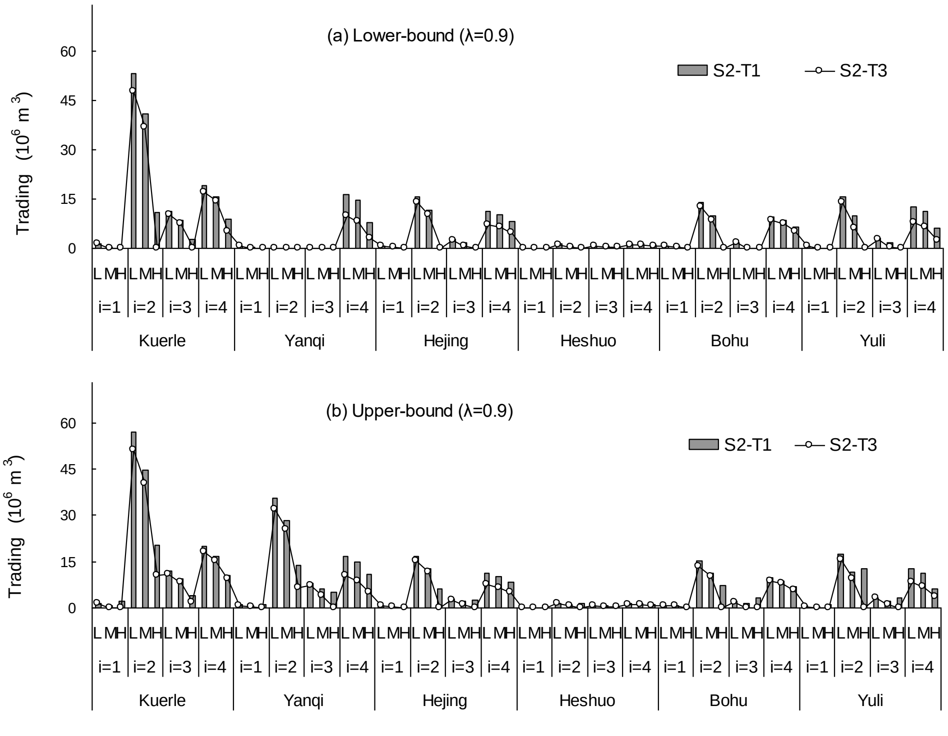

Figure 3. water trading from water bank under S1-T1 and S4-T1 (λ=0.6)

With S2-T1, amount of water trading of ecological users in Kuerle county (j = 1) would be [18.98, 19.97], [15.73, 16.77] and [8.92, 10.37] $\times 10^6 m^3$ at low, medium and high levels under S2-T1 (λ = 0.6), while it would be [17.07, 17.98], [14.16, 15.09] and [4.99, 9.34] $\times 10^6 m^3$ under S3-T2. The results indicated the more water surplus remedy water shortage, the less water trading from water bank. Meanwhile, the results demonstrate that net system benefits under trading were much higher than non-trading when decreasing permit levels were from 0 to 15%, but lower than non-trading when decreasing permit exceeded 15%. It implied that markets can provide incentives to adopt water-saving, since market prices make the opportunity cost of water explicit to users. Therefore, water trading was considered an effective way to not only reduce the shortages of water systems, but also gain a higher net system benefit in arid region.

5. Conclusions

In this study, an interval stochastic-fuzzy programming (ISFP) has been developed to quantify the effectiveness of water trading, which can deal with system uncertainties between allocation policy and violated risk. The developed method has been applied to Kaidu-kongque watershed for water trading under uncertainties of water supply and demand, which a number of scenarios were listed to compare net system benefits and water shortages. Because trading can reduce the "penalty", but increase "trading cost", system net benefit needed to be compared to get the optimal results based on the actual need such as saving water or maximizing system net benefit. The analysis shows that the effectiveness of a trading program is sensitive to water permit and trading ratio. Modeling results indicated that trading is more effective than non-trading under some designated situations. Although application of ISFP model to water trading is a new attempt, which could also be improved by introducing other advanced optimization methods to tackle more uncertainties and complexities in the future.

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