A two-stage interval-stochastic water trading model for allocating water resources of Kaidu-Kongque River in northwestern China

X. T. Zeng, Y. P. Li, G. H. Huang and J. Liu

ABSTRACT

In this study, a two-stage interval-stochastic water trading (TIWT) model is developed for reallocating water resources under uncertainty, which integrates techniques of interval-parameter programing and two-stage stochastic programing into a general framework. The TIWT model can provide an effective linkage between system benefit and the associated economic penalty attributed to the violation of the pre-regulated water permit under uncertainties expressed as probabilistic distributions and interval values. The trading scheme is introduced to optimize water allocation of Kaidu-Kongque River in northwestern China. Results obtained suggest that trading program can effectively allocate limited water resources to competitive users by market approach in such an arid area, which improves economic efficiency in the mass (e.g., maximizing system benefits) and remedies water deficiency. A number of policies for water permits are analyzed and reveal that different water permits lead to different water shortages, system benefits, and system-failure risks. Tradeoffs between economic benefit and system-failure risk are also examined under different policies, which support generating an increased robustness in risk control for water resources allocation under uncertainty. The results are helpful for local decision-makers in adjusting the current water allocation pattern optimally.

Key words | interval analysis, market approach, reallocating water, stochastic programing, uncertainty, water trading

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INTRODUCTION

In the past decades, the challenge of water resources management associated with the principle of sustainable development has been of concern to many researchers and managers, due to the pressures of increasing population, developing economy, and changing climate all over the world. Particularly in many semi-arid and arid regions, water shortage and unreliable water supply have been considered major obstacles to sustainable water resources development in watershed systems. Currently, one-third of the world's population is living in countries and regions of water resources limitation (Bates *et al.* 2008). Because of limited water availability imposing strong restrictions on natural and human systems, the management of water resources has become an increasingly pressing issue in semi-arid and arid regions (Huang *et al.* 2012). For example, Tarim River Basin in China is a typical arid region that is characterized by low and irregular rainfall, high temperature, and high evaporation. Water shortage has become an increasingly serious problem, where demand outstrips water resources availability due to chronic severe scarcity. Therefore, the constantly increasing demand for water in terms of both sufficient quantity and satisfied quality, has forced planners to contemplate and propose ever more comprehensive, complex and ambitious plans for water resources systems (Li & Huang 2009).

Previously, a number of systems analysis techniques (e.g., simulation modeling, economic analysis, risk assessment, and optimization method) have been employed for water

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resources management in semi-arid and arid regions in response to such complexities (Bowden *et al.* 2003; Reddy & Kumar 2009; Abdullaev & Rakhmatullaev 2014). For example, Ortega *et al.* (2003) proposed an economic analysis approach to evaluate the effect of water cost on water systems in Spanish semi-arid regions, which could improve the advantage of benefit-cost analysis techniques for effectively managing limited water resources. Benli & Kodal (2003) developed a non-linear optimization model for water amount and income under adequate and limited water in the southeast of Turkey, which could handle the situations of both objective function and constraints without linearity limitation. Masih *et al.* (2009) provided spatio-temporal assessment analysis and trend analysis based on statistical parameters in the semi-arid Karkheh River Basin of Iran, which could improve the correlation between water allocation and streamflow variability, water resources management and the trend of water changes. Burte *et al.* (2009) used a simulation method for predicting multipurpose water availability in the semi-arid Brazilian northeast, which could tackle the complexities of water availability, potential evapotranspiration, water demand under spatial and temporal variations, and different policies. Mahmoud *et al.* (2010) developed a hybrid factors scenario analysis method for water resources planning in an American semi-arid region, in which water policy (e.g., periodic drought policy vs. sustained drought policy, water-conservative population policy vs. water-consumptive population policy, booming economy policy vs. poor economy policy) and impact factors of water systems in response to risk prevention could be reflected. Tabari & Yazdi (2014) proposed a multi-objective optimization method for planning of water in inter-basin and restoration of water in outer-basin, where a non-dominated sorting genetic algorithm was used for solving complexity and non-linearity of objectives and decision variables. In general, the above conventional simulation and optimization methods were effective for planning water resources systems considering a number of impact factors (e.g., economic objective, environmental requirement, and policy regulation).

Water trading is considered an effective way to allocate water resources optimally, which can increase the economic productivity of water by encouraging its movement from low to high valued use. Under the situation of limited water, transition toward trading through water markets is likely to improve economic efficiency in the mass (e.g., maximizing system benefits) (Brill *et al.* 1997). Moreover, since the market mechanism makes inefficient water users consider the opportunity costs of water usage, market trading schemes can provide incentives to adopt water saving (Calatrava & Garrido 2005). Owing to competing users achieving water on the law of value (i.e., price fluctuates around value) in the market, surplus water can be released to gain a high benefit, such that the contradiction between water demand and water deficiency can be mitigated. Water trading can balance limited water resources between human-use allocation and flow stream especially in arid and semi-arid areas, such that several water trading programs have been established worldwide (Luo *et al.* 2010). For example, Huang *et al.* (2005) employed an input/output method to calculate the virtual water trading in northwestern China, which made water as a merchandise achieve a higher value using an economic systematic method. Zaman *et al.* (2009) formulated an economic model to describe demand and supply in an integrated water trading-allocation system in Australia, which could establish a link between paper trades (estimated by economic models) and physical water transfers (estimated by biophysical models). Smajgl *et al.* (2008) developed an agent-based model to create a water trading scheme in Australia, which could tackle the inefficiency of informal self-regulating and formal institutional changes based on simulating the environmental and economic performances of newcomers in water trading processes. Abdelaziz & Frank (2010) characterized hydrologic and economic impacts of water trading in Egypt, through integrating hydrologic, environmental, economic, and institutional constraints within a water trading program. In general, it is commonly recognized that the effectiveness of water trading is explicitly influenced by various uncertainties existing in water resources systems. For example, spatial and temporal variations exist in water trading programs, such as stream flow, water demand, trading ratio, and trading efficiency, and these fluctuations can be associated with the net system benefits that are functions of many stochastic factors (Eugene 2011; Blokker *et al.* 2011). These complexities could become further compounded by not only interactions among the uncertain parameters, but also their economic implications. Particularly in semi-arid and arid regions, these complexities could be amplified by water scarcity, population growth, economic development, and eco-environmental protection, which could intensify the conflict-laden issue of water trading among competing municipal, industrial, agricultural, environmental, and ecological interests (Huang *et al.* 2012). Therefore, the inherent complexities and stochastic uncertainties that exist in a water trading program have essentially placed them beyond the conventional deterministic systems analysis methods.

Two-stage stochastic programing (TSP) is effective for solving decision-making problems associated with randomness, in which an examination of policy scenario is desired and the system data are characterized by probability distribution (Luo *et al.* 2007). TSP can provide an effective linkage between policies and economic penalties, which has advantages in reflecting complexities of system uncertainties as well as analyzing policy scenarios when the pre-regulated targets are violated. Previously, a number of research works have been conducted for dealing with uncertainties in water resources systems through TSP techniques (Maqsood *et al.* 2005; Kenneth 2007; Gómez & Pérez 2012). However, the major problem of stochastic programing methods is that the increased data requirement for specifying the probability distributions of coefficients may affect their practical applicability (Li *et al.* 2008). For example, in a water trading program, although the randomness in water availability can be relatively easy to quantify with probability distribution, many other uncertain components (e.g., economic data, allocation target, and trading ratio) are often not straightforward enough to be expressed as probability distributions. Interval-parameter programing (IPP) is an alternative for dealing with uncertainties existing in the model's left- and/or right-hand sides as well as those that cannot be quantified as membership or distribution functions, since interval numbers are acceptable as its uncertain inputs (Huang 1998; Maqsood & Huang 2003; Li *et al.* 2008; Suo *et al.* 2013; Miao *et al.* 2014; Zeng *et al.* 2014; Zhang *et al.* 2014). One potential approach for better accounting for complex uncertainties is to introduce the IPP technique into the TSP framework.

Therefore, this study aims to develop a two-stage interval-stochastic water trading (TIWT) model, through integrating the techniques of TSP and IPP into a general framework. It can not only handle uncertainties expressed as probability distributions and interval values in a water trading program, but also provide a link between water allocation schemes and economic penalties caused by improper policy due to existing uncertainties. The TIWT model will be applied to identifying an optimal water allocation pattern for Kaidu-Kongque River in Tarim River Basin, China. A number of strategies that are associated with different water permits will be analyzed, which can help decision-makers not only allocate water resources optimally, but also gain insight into the tradeoff between water trading and economic objective.

MODELING FORMULATION

A manager (e.g., water resources bureau) is responsible for allocating water resources to multiple users (e.g., residential, industrial, agricultural, and ecological) in semi-arid and/or arid regions, with the goals of maximizing the overall system benefit, satisfying users' demand and reducing water shortage. The manager needs to create a plan to effectively allocate the water to each user while simultaneously considering the system disruption risk attributable to the uncertainties. On the basis of the local management policy, water permits will be allocated to each competitive user in different districts. In the situation of water without trading, water for each user will be limited by its own permit proportionally (Luo *et al.* 2007). Given a water demand that is promised to each user, if the pre-regulated water demand is satisfied, it results in benefit to the local economy (i.e., targeted income). However, when the available water resources cannot satisfy the water demand, a recourse action has to be undertaken to minimize the reduction of system benefit (i.e., deficiency loss). The objective of the function is to choose the first decision variables in a way that the expected value of the random second-stage function is optimized (Birge & Louveaux 1988), which results in optimization of the state of the system. The study problem can be formulated as an interval two-stage stochastic programing (ITSP) model, through integrating techniques of TSP and IPP into a general framework (Appendix, available online at http://www.iwaponline.com/jh/017/090.pdf). The ITSP model can support medium- to long-term planning problems effectively where decisions need to be made dynamically (e.g., raising water demand) to get the optimized expected value of objectives. Thus, when water is not tradable, ITSP model can be formulated as follows:

$$\max f_1^{\pm} = \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{\pm} W_{ij}^{\pm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H} P_h C_{ij}^{\pm} Y_{ijh}^{\pm} \tag{1a}$$

subject to

$$W_{ij}^{\pm} - Y_{ijh}^{\pm} \le Q_{ijh}^{\pm} * T_{ij}^{\pm} / \sum_{i=1}^{I}\sum_{j=1}^{J} T_{ij}^{\pm}, \quad \forall i, j, h \tag{1b}$$

$$0 \le Y_{ijh}^{\pm} \le W_{ij}^{\pm} \le W_{ij\max}^{\pm}, \quad \forall i, j, h \tag{1c}$$

$$0 \le Y_{ijh}^{\pm} \le Q_{ijh}^{\pm}, \quad \forall i, j, h \tag{1d}$$

$$M_{ij}^{\pm} \ge 0, \quad \forall i, j \tag{1e}$$

where i denotes type of user ($i = 1, 2, \ldots, I$); j denotes name of district ($j = 1, 2, \ldots, J$); h denotes probability level of random water availability ($h = 1, 2, \ldots, H$); the objective of model (1), $f_1^{\pm}$ presents net benefit of the entire system without trading (\$); $B_{ij}^{\pm}$ is net benefit to user i in district j per volume of water being delivered (\$/10^3 m^3); $W_{ij}^{\pm}$ is pre-regulated water demand target to user i in district j (10^3 m^3) based on annual water demand in the last years, which is a first-stage decision variable made before the realization of uncertain $Q_{ijh}^{\pm}$. In a practical water allocation problem, $W_{ij}^{\pm}$ has been pre-regulated to each competitive user in different districts at the beginning of the year, which was based on water demands in the past. $W_{ij\max}^{\pm}$ is the maximum annual water requirement to user i in district j (10^3 m^3), which is constrained by the user's water consumption capacity; $Q_{ijh}^{\pm}$ is total water availability of the entire system under probability P_h (10^3 m^3); P_h denotes probability of random water availability $Q_{ijh}^{\pm}$ under level h (%); $C_{ij}^{\pm}$ is economic loss to user i in district j per volume of water not being delivered (\$/10^3 m^3); $Y_{ijh}^{\pm}$ is water deficiency to user i in district j by which water demand is not met when water availability is $Q_{ijh}^{\pm}$ (10^3 m^3). $Y_{ijh}^{\pm}$ is two-stage decision variable, which indicates a recourse action would take place after occurrence of uncertain $Q_{ijh}^{\pm}$; $T_{ij}^{\pm}$ is allowable water permit to user i in district j (10^3 m^3). One of the main advantages of the ITSP model is its capability of incorporating multiple policies of water resources management within the optimization framework through the first-stage variables (i.e., $W_{ij}^{\pm}$).

Since water is allocated to each user by its own permit proportionally, constraint (1b) reflects the water allocation without trading (i.e., water can be allocated to each user in proportion to the user's water permit when total water availability is in shortage). Constraint (1c) ensures that each user's water requirement is constrained by the user's water consumption capacity; since water allocation equals to the difference between pre-regulated water target and water deficiency (i.e., water allocation = target − deficiency), pre-regulated water target is greater than water deficiency to ensure the positive value of water allocation. Meanwhile, constraint (1d) reflects water availability can satisfy water demand target mainly, which cannot lead to an extensive deficiency (e.g., the scale of water deficiency exceeds water availability) in the study area. Constraint (1e) reflects the water permit is non-negative.

Model (1) reflects the water allocation without a trading scheme, which indicates that water should be allocated to each user in proportion to the user's water permit when total water availability is uncertain. With the purpose of more effective water allocation, a water trading program can be established. In the situation of limited water, trading can not only make water move from low value to high value, but also reduce the loss of water deficiency and maximize its economic benefit through the market scheme. In a water trading program, a target quantity of water is measured according to users' needs and water permit is allocated according to water availability. If water target is satisfied, a net system benefit would be obtained; if water target exceeds the water availability, water shortage would be generated and thus result in economic penalty. On the other hand, if water permit for each user is regulated too low, surplus water would be generated. In such a situation, each user can sell surplus water permits or buy water permits to gain a higher profitability through water trading. When water is tradable, all users are no longer constrained by their own water permit but theoretically by both the aggregate supply of the total water availability and total water permit of the entire system (Luo *et al.* 2007). It means that water permits being traded to higher value are a substitute for being allocated cubic meters to each user.

Under the trading scheme, the manager can reduce the water permit to release appropriate water permits to trade water in the market according to actual water requirement, such that a maximized system benefit could be achieved. Therefore, when water is tradable, a two-stage inexact water trading (TIWT) model can be formulated as follows:

$$\max f_2^{\pm} = \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{\pm} W_{ij}^{\pm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H} P_h C_{ij}^{\pm} Y_{ijh}^{\pm} + \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{\pm} L_{ijh}^{\pm} - \sum_{i=1}^{I}\sum_{j=1}^{J} (FC_{ij}^{\pm} + VC_{ij}^{\pm}) L_{ijh}^{\pm} \quad (2a)$$

subject to

$$\sum_{i=1}^{I}\sum_{j=1}^{J} M_{ij}^{\pm} \le (1-d) * \sum_{i=1}^{I}\sum_{j=1}^{J} T_{ij}^{\pm}, \quad \forall i, j \quad (2b)$$

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

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

$$FC_{ij}^{\pm} + VC_{ij}^{\pm} \le C_{ij}^{\pm}, \quad \forall i, j \quad (2e)$$

$$L_{ijh}^{\pm} \le Y_{ijh}^{\pm} - N_{ijh}^{\pm}, \quad \forall i, j \quad (2f)$$

$$0 \le Y_{ij}^{\pm} \le Q_{ijh}^{\pm}, \quad \forall i, j \quad (2g)$$

$$0 \le Y_{ijh}^{\pm} \le W_{ij}^{\pm} \le W_{ij\max}^{\pm}, \quad \forall i, j, h \quad (2h)$$

$$M_{ij}^{\pm} \ge 0, \quad \forall i, j \quad (2i)$$

$$W_{ij}^{\pm} \ge 0, \quad \forall i, j \quad (2j)$$

where $f_2^{\pm}$ presents the net benefit of the entire system under the trading mechanism ($); d is the percentage of reduced total allowable water allocation (i.e., mitigation level); $M_{ij}^{\pm}$ is reallocated allowable water permit to user i in district j with trading scheme (10^3 m^3); $N_{ijh}^{\pm}$ is released water to user i in district j when total water availability exceeds allowable water reallocation with trading scheme (10^3 m^3); $FC_{ij}^{\pm}$ is trading fix cost to user i in district j with trading scheme ($/$10^3$ m^3); $VC_{ij}^{\pm}$ is trading variable cost to user i in district j with trading scheme ($/$10^3$ m^3); $L_{ijh}^{\pm}$ is the amount of water trading from other sources to user i in district j under h level when water availability is $Q_{ijh}^{\pm}$ with trading scheme (10^3 m^3). Constraint (2b) indicates that total actual reallocated water permits of the entire system in the trading scheme are constrained by total allocated water permits. The water manager can adjust total water permits to reallocate to water users based on a policy of regional development. Since water demand target is pre-regulated at the beginning of the year based on annual water availability in the past, pre-regulated water target is not equal to current water availability, which results in recourse problems. Constraint (2c) reflects that a recourse action has to be undertaken to minimize the reduction of system benefit (i.e., deficiency loss) with the trading scheme, when the available water resources cannot satisfy the water demand. Meanwhile, since the water permit is estimated in a similar manner to water demand target, constraint (2d) reflects released water is obtained based on recourse actions between current water availability and reallocated water permit. Released water can be obtained when water availability is greater than reallocated water permit, then it can join in water trading to remedy water deficiency by water market. Constraint (2f) reflects the trading process, where water deficiency can be remedied by released water and other sources. Constraint (2e) reflects that fixed and variable trading costs are constrained by losses of water deficiency, which ensures net system benefits with the trading scheme should not be less than that without trading scheme. The implications of constraints (2g)–(2j) are similar to constraints (1c)–(1e).

In the TIWT model, when the target of water for each user in each district ($W_{ij}^{\pm}$) is expressed as an interval number, decision variable z_{ij} is introduced to identify the optimal target value. Let $W_{ij}^{\pm} = W_{ij}^{-} + \Delta W_{ij} z_{ij}$, where $\Delta W_{ij} = W_{ij}^{+} - W_{ij}^{-}$ and $z_{ij} \in [0, 1]$. Thus, when $W_{ij}^{\pm}$ reach their upper bounds, a higher net benefit of the water system would be achieved. When $W_{ij}^{\pm}$ reach their lower bounds, the system may generate a lower net benefit with a low risk of water deficiency loss. Thus, model (2) can be transformed into two deterministic linear programing submodels, which correspond to the lower and upper bounds of the desired objective as follows (Huang 1998).

Submodel (1)

$$\max f_2^{+} = \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{+}(W_{ij}^{-} + \Delta W_{ij} z_{ij}) - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H} P_h C_{ij}^{-} Y_{ijh}^{-} + \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{+} L_{ijh}^{+} - \sum_{i=1}^{I}\sum_{j=1}^{J} (FC_{ij}^{-} + VC_{ij}^{-}) L_{ijh}^{+} \tag{3a}$$

subject to

$$\sum_{i=1}^{I}\sum_{j=1}^{J} M_{ij}^{+} \le (1-d)* \sum_{i=1}^{I}\sum_{j=1}^{J} T_{ij}^{+}, \quad \forall i, j \tag{3b}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} (W_{ij}^{-} + \Delta W_{ij} z_{ij} - Y_{ijh}^{-}) \le Q_{ijh}^{+}, \quad \forall i, j, h \tag{3c}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} (Q_{ijh}^{+} - N_{ijh}^{-}) \le M_{ij}^{+}, \quad \forall i, j \tag{3d}$$

$$FC_{ij}^{-} + VC_{ij}^{-} \le C_{ij}^{-}, \quad \forall i, j \tag{3e}$$

$$L_{ijh}^{+} \le Y_{ijh}^{-} - N_{ijh}^{-}, \quad \forall i, j, h \tag{3f}$$

$$0 \le Y_{ijh}^{-} \le Q_{ijh}^{+}, \quad \forall i, j \tag{3g}$$

$$0 \le Y_{ijh}^{-} \le W_{ij}^{-} + \Delta W_{ij} z_{ij} \le W_{ij\max}^{+}, \quad \forall i, j, h, \quad \forall i, j, h \tag{3h}$$

$$M_{ij}^{+} \ge 0, \quad \forall i, j \tag{3i}$$

$$W_{ij}^{+} \ge 0, \quad \forall i, j \tag{3j}$$

where submodel (1) corresponding to f_2^{+} is first desired to maximize $f_2^{\pm}$; where Equation (3a) and constraints (3b)–(3j) are corresponding to upper bounds of the desired objective. Then, the optimal solutions (e.g.,$Y_{ijh\text{opt}}^{-}$, $N_{ijh\text{opt}}^{-}$, $L_{ijh\text{opt}}^{+}$, and $z_{ij\text{opt}}$) can be obtained through solving submodel (1), which can also be imported into submodel (2) to acquire f_2^{-} as follows.

Submodel (2)

$$\max f_2^{-} = \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{-}(W_{ij}^{-} + \Delta W_{ij} z_{ij}) - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{h=1}^{H} P_h C_{ij}^{+} Y_{ijh}^{+} + \sum_{i=1}^{I}\sum_{j=1}^{J} B_{ij}^{-} L_{ijh}^{-} - \sum_{i=1}^{I}\sum_{j=1}^{J} (FC_{ij}^{+} + VC_{ij}^{+}) L_{ijh}^{-} \tag{4a}$$

subject to

$$\sum_{i=1}^{I}\sum_{j=1}^{J} M_{ij}^{-} \le (1-d)* \sum_{i=1}^{I}\sum_{j=1}^{J} T_{ij}^{-}, \quad \forall i, j \tag{4b}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} (W_{ij}^{-} - \Delta W_{ij} z_{ij\text{opt}} - Y_{ijh}^{+}) \le Q_{ijh}^{-}, \quad \forall i, j, h \tag{4c}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} (Q_{ijh}^{-} - N_{ijh}^{+}) \le M_{ij}^{-}, \quad \forall i, j \tag{4d}$$

$$FC_{ij}^{+} + VC_{ij}^{+} \le C_{ij}^{+}, \quad \forall i, j \tag{4e}$$

$$L_{ijh}^{-} \le Y_{ijh}^{+} - N_{ijh}^{+}, \quad \forall i, j, h \tag{4f}$$

$$0 \le Y_{ijh\text{opt}}^{-} \le Y_{ijh}^{+} \le Q_{ijh}^{-}, \quad \forall i, j \tag{4g}$$

$$0 \le Y_{ijh\text{opt}}^{-} \le Y_{ijh}^{+} \le W_{ij}^{-} + \Delta W_{ij} z_{ij\text{opt}} \le W_{ij\max}^{-}, \quad \forall i, j, h, \quad \forall i, j, h \tag{4h}$$

$$N_{ijh\text{opt}}^{-} \le N_{ijh}^{+} \quad \forall i, j \tag{4i}$$

$$L_{ijh}^{-} \le L_{ijh\text{opt}}^{+} \quad \forall i, j \tag{4j}$$

$$M_{ij}^{-} \geq 0, \quad \forall i, j \tag{4k}$$

$$W_{ij}^{-} \geq 0, \quad \forall i, j \tag{4l}$$

Since the optimal solutions (e.g., $Y_{ijh\text{opt}}^{-}$, $N_{ijh\text{opt}}^{-}$, $L_{ijh\text{opt}}^{+}$, and $z_{ij\text{opt}}$) of f_2^{+} can be imported into submodel (2), lower bound of system benefit (i.e., f_2^{-}) corresponding to their optimal solutions (e.g.,Y_{ijh}^{+}, N_{ijh}^{+}, and L_{ijh}^{-}) can be restricted by upper bound results. Thus, constraints (4g)–(4j) express the interval relationship between lower and upper bound of water deficiency, released water, and water trading. When solving the above two submodels, the solutions of model (2) can be acquired as follows:

$$f_{2\text{opt}}^{\pm} = [f_{2\text{opt}}^{-}, f_{2\text{opt}}^{+}] \tag{5a}$$

$$Y_{ijh\text{opt}}^{\pm} = [Y_{ijh\text{opt}}^{-}, Y_{ijh\text{opt}}^{+}] \tag{5b}$$

$$L_{ijh\text{opt}}^{\pm} = [L_{ijh\text{opt}}^{-}, L_{ijh\text{opt}}^{+}] \tag{5c}$$

$$N_{ijh\text{opt}}^{\pm} = [N_{ijh\text{opt}}^{-}, N_{ijh\text{opt}}^{+}] \tag{5d}$$

CASE STUDY

The Kaidu-Kongque River (71°39″E-93°45″'E, 34°20″'N-43°39″) is a branch of the Tarim River from the middle of mountain Tian to Lake Bositeng; the Kaidu River is about 610 km long and the Kongque River is about 785 km long (The Statistical Yearbook of Xinjiang Uygur Autonomous Region in Uygur Autonomous Region 2005–2012). The Kaidu-Kongque River Basin is located in the middle reach of the Tarim River Basin, and is approximately 62×10^3 km^2. It is a typical arid region, where nearly one-third of the catchment in the downstream of Tarim River has become dried out due to climate change, population growth, agricultural exploration, and economic development. The topography of the basin is complex and consists of 55% mountainous areas and 45% plain areas. The maximum temperature of the basin is around 27 °C and the minimum temperature is around −13 °C. The climate in the basin is extremely dry with an average annual precipitation of 273 mm/year. More than 80% of the total annual precipitation falls from May to September, and less than 20% of the total falls from November to April (Huang *et al.* 2012).

Kaidu-Kongque River Basin includes six counties (i.e., Kuerle, Yanqi, Hejing, Heshuo, Bohu, and Yuli), which have a population of more than one million (The Statistical Yearbook of Xinjiang Uygur Autonomous Region in Uygur Autonomous Region 2005–2012). The study area is suitable for the growth of crops such as wheat, corn, sugar beet, tomatoes, and fruit, and is becoming an important cotton and grain production region in Xinjiang. Profitable planting and breeding mean that agricultural products' processing and manufacturing play an important role in the economy, which accelerates the process of agricultural industrialization. Moreover, the rich mineral and oil resources of the basin form an industrial structure dominated by mining, the chemical industry, and fossil oil industry, while textiles, electric power, papermaking, and transportation are keeping pace with the development of the mainstay industry. In recent years, the development of the economy and society in the basin has brought about industry and agriculture in combination with an integrated economic system, which also takes ecological protection and municipal administration into account.

The river's streamflow is mainly from its upstream, snow melting, and rainfall, which supplies municipal, industrial, and agricultural users; as well, the streamflow is the most important source for ecosystem recovery of the lower reaches of the Tarim River Basin. Owing to dry climate, low rainfall, and high evaporation, the water supply capacity of the study river is quite low, and it has difficulty in satisfying the water demands from the six counties. For example, the available water for six counties is about 9 billion m^3 per year, but the annual water demand exceeds 12 billion m^3 in the past decade. Particularly in recent years, the population has grown rapidly due to urbanization, which has led to water demand of municipalities increasing; industry and agriculture are developing rapidly in response to the national west development strategy, which has led to the water demands of industrial and agricultural users growing sustainably; and ecological water demand is taken seriously because of human activity and excessive environmental exploration, all of which add to the pressures of water supply capacity enormously. Meanwhile, water availability is reducing in response to climate change and environmental deterioration, which leads to chronic severe shortages in the study basin. Therefore, the demand for water has reached the limits of what the natural system can provide in recent years, and water shortage has become a major obstacle to social and economic development for this region (Huang *et al.* 2012). Water shortage caused by inadequate water flow and unreliable water availability makes the conflict between water demand and supply serious, and calls for an efficient tool to solve such issues. Unfortunately, in the studied basin, there is a lack of effective tools for facilitating efficient, equitable, and sustainable water resources management and planning.

Water trading schemes can solve conflicts caused by water shortage (Richard *et al.* 2012), and not only improve the net system benefit, but also save water while respecting hydrologic, environmental, food security, economic development, population growth, and institutional constraints. Under allocated water permits, trading can release surplus water to remedy the losses of water deficiency, and achieve a higher profitability. Four competitive users (e.g., municipal, agricultural, industrial, and ecological) in the six counties can gain a maximized profitability through water trading (as shown in Figure 1). The trading program can break the constraints by water permit proportionally with optimal water allocation based on the law of value. Moreover, a number of variations caused by factitious factors and natural factors exist in the trading system, which brings more complexities and uncertainties into the water trading system. For example, less observation and insufficient data produce uncertainties in data inputting, and natural uncertainties produce many stochastic factors in the trading system, such as stream flow water, demand and water allocation targets, and fluctuations can be associated with the net system benefits. These complexities could become further compounded not only by interactions among the uncertain parameters, but also their economic implications (Huang *et al.* 2010a). Therefore, the proposed TIWT model can be used for optimally allocating limited water to facilitate the regional sustainability with a maximized system benefit.

The parameters for the TIWT model in the Kaiduo-Kongque River Basin have been obtained based on field surveys, statistical data, and related research works (Ma *et al.* 2005; Huang *et al.* 2012). Table 1 shows basic economic data and trading costs, which are estimated indirectly based on The Statistical Yearbook of Xinjiang Uygur Autonomous Region in Uygur Autonomous Region (2005–2012) and water price of Xinjiang Autonomous Region. Values of $B_{ij}^{\pm}$ and $C_{ij}^{\pm}$ are estimated according to different users' gross national product in different counties indirectly. $FC_{ij}^{\pm}$ is a basic form of trading cost, which is estimated by the actual price of excess water for trading in the watershed. $VC_{ij}^{\pm}$ is estimated according to the opportunity cost of water, which is affected by a number of factors, such as scarcity of water resources, relationship between supply and demand, and socio-economic development status.

Table 2 shows policy data $T_{ij}^{\pm}$, which were acquired by the water permit of the water authority of Uygur Autonomous Region from 2005 to 2012 indirectly. Water target $W_{ij}^{\pm}$ is estimated by users' actual water use in recent years, which takes the situation of economic development into consideration. To appraise diverse net system benefits under different water permits in the water trading system, a number of policy scenarios with different decreasing levels with different allowable water permits are examined (i.e., the value of water permit will change from 0 to 20%), which are shown in Table 3. In addition, Table 4 provides the total water availability, which is acquired through statistical analyses with the results of the annual stream flow of the Kaidu-Kongque River (2005–2012). In the study area, the annual precipitation of water flow ranges from 250 to 550 mm and the average value reaches 273 mm (Huang *et al.* 2010b). Owing to spatial and temporal variability, the seasonal distribution of precipitation is uneven; several probability distribution functions (PDF) (i.e., gamma distribution, normal distribution, and logarithmic distribution) are often used to fit FDP of random variables, respectively. It found that the gamma distribution is the best fit for FDP of random variables (Huang *et al.* 2010b). After the FDP of random variable $Q_{ijh}^{\pm}$ are determined, the discretization value with different probability levels can be calculated (Huang *et al.* 2010b). Around 50% of annual stream flow is less than the average value even to zero (denoted as 'low' level), 37% of annual stream flow

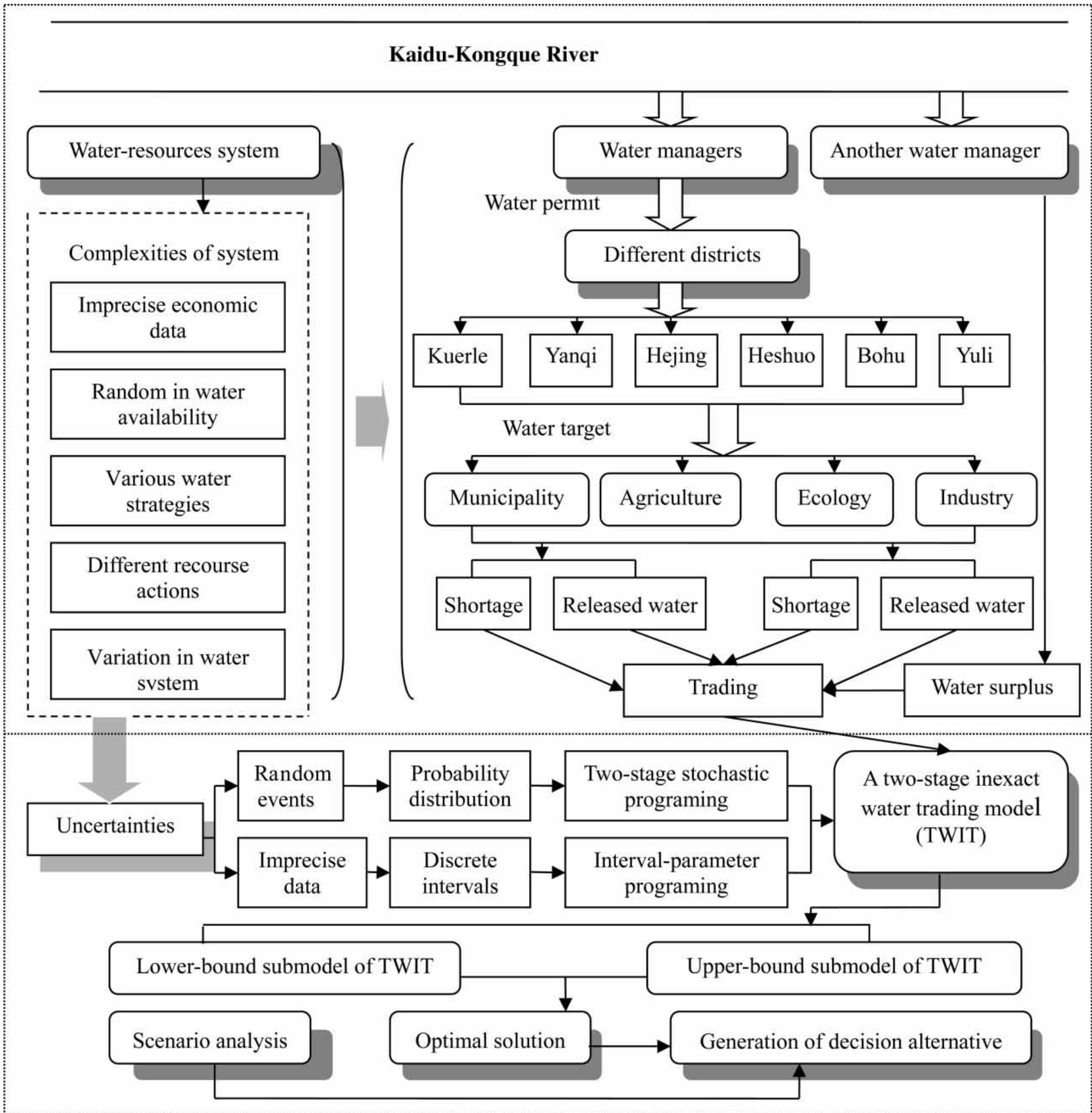

Figure 1 | Regional water quantity trading relationship.

fluctuates to an average value (denoted as 'medium' level), and 13% of annual stream flow is more than the average value even to highest (denoted as 'high' level).

RESULTS ANALYSIS

In this study, five scenarios corresponding to different water permit levels were examined by the ITWT model in Kaiduo-Kongque River Basin. Figure 2 shows the solutions for optimized net system benefit obtained from the ITWT model, which are the sum of the first-stage benefit from the water allocation and the second-stage random losses of water deficiency. The lower-bound system benefits could result in a lower risk of violating the allowable water permit. Reversely, a higher benefit would lead to a higher probability of violating the allowance. Consequently, there is a tradeoff between the net system benefits and water permit violation risk. In addition, different water permits would result in varied system benefits. For example, net system benefits

Table 1 | Economic data and trading costs

District	User $i=1$ Municipality	 $i=2$ Agriculture	 $i=3$ Industry	 $i=4$ Ecology
Net benefit (unit: US$/$10^3$ m^3)				
$j=1$ Kuerle county	[6,030, 6,670]	[2,320, 2,520]	[4,530, 4,670]	[1,960, 2,120]
$j=2$ Yanqi county	[5,500, 6,040]	[1,420, 1,560]	[2,600, 2,930]	[1,680, 1,930]
$j=3$ Hejing county	[4,670, 4,800]	[1,530, 1,860]	[3,730, 3,810]	[1,540, 1,780]
$j=4$ Heshuo county	[5,300, 5,530]	[2,010, 2,340]	[3,440, 3,620]	[1,660, 1,940]
$j=5$ Bohu county	[4,910, 5,100]	[1,780, 2,010]	[3,620, 3,740]	[1,530, 1,840]
$j=6$ Yuli county	[4,600, 5,260]	[2,230, 2,460]	[3,220, 3,440]	[1,690, 1,990]
Penalty (unit: US$/$10^3$ m^3)				
$j=1$ Kuerle county	[7,240, 8,000]	[2,780, 3,010]	[5,440, 5,600]	[2,350, 2,540]
$j=2$ Yanqi county	[6,600, 7,250]	[1,700, 1,870]	[3,120, 3,520]	[2,020, 2,320]
$j=3$ Hejing county	[5,600, 5,760]	[1,840, 2,230]	[4,480, 4,570]	[1,850, 2,140]
$j=4$ Heshuo county	[6,360, 6,640]	[2,410, 2,810]	[4,130, 4,340]	[1,990, 2,330]
$j=5$ Bohu county	[5,890, 6,120]	[2,140, 2,410]	[4,340, 4,490]	[1,840, 2,210]
$j=6$ Yuli county	[5,520, 6,310]	[2,680, 2,950]	[3,860, 4,130]	[2,030, 2,390]
Trading fix cost (unit: US$/$10^3$ m^3)				
$j=1$–6	[3,050, 3,150]	[550, 650]	[2,400, 2,500]	[280, 350]
Trading variable cost (unit: US$/$10^3$ m^3)				
$j=1$–6	[1,200, 1,300]	[700, 800]	[150, 200]	[100, 150]

would be achieved (i.e., US$[1.15, 2.28] $\times 10^9$, US$[1.12, 2.22] $\times 10^9$, US$[1.01, 2.11] $\times 10^9$, US$[0.80, 1.93] $\times 10^9$, and US$[0.55, 1.68] $\times 10^9$) under the different water permit levels (i.e., 100% water permit, 95% water permit, 90% water permit, 85% water permit, 80% water permit) in the trading scheme. Results indicate that the system benefits under trading would decrease along with the water permits. The highest net system benefit would be achieved (i.e., US$[1.15, 2.28] $\times 10^9$) under the highest water permit level, when water is in the trading scheme. By decreasing water permits, the net system benefit under trading would drop, with the intervals of net system benefits changing from mild to acute.

Figure 3 shows the results of optimal water allocation for municipal, agricultural, industrial, and ecological users in six counties of the study basin with trading scheme under scenario 1 (i.e., $d = 0\%$). Results indicate that shortage in water supply would be generated if the pre-regulated target (i.e., $W_{ij}^{\pm}$) was not satisfied (i.e., shortage = targeted value – available inflow). In such a situation, the actual water allocation would be the difference between the pre-regulated target and the probabilistic shortage (i.e., allocation = target – shortage). Solutions from Figure 3 show each allocated water flow is the difference between the promised target and the probabilistic shortage under a given flow condition with an associated probability level, which indicates that different violation levels would result in varied water allocation patterns. For example, under scenario 1, the optimized targets of municipal, agricultural, industrial, and ecological users (in Bohu county, $j = 5$) were 4.45×10^6 m^3, 87.98×10^6 m^3, 19.67×10^6 m^3, and 28.75×10^6 m^3, respectively. When inflow is low, shortages would be [0.75, 1.71] $\times 10^6$ m^3, [13.88, 22.19] $\times 10^6$ m^3, [1.53, 4.65] $\times 10^6$ m^3, and [9.54, 12.44] $\times 10^6$ m^3; correspondingly, the actual allocations would be [2.75, 3.71] $\times 10^6$ m^3, [65.79, 74.10] $\times 10^6$ m^3, [15.02, 18.14] $\times 10^6$ m^3, [16.31, 19.22] $\times 10^6$ m^3, respectively. The total amount of allocated water to Bohu county would be [99.68, 115.17] $\times 10^6$ m^3 when inflow is low. However, the total optimized water

Table 2 | 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	[14.49,16.10]	[288.77, 320.85]	[64.17, 71.30]	[80.73, 89.70]
$j=2$ Yanqi county	[8.49, 9.43]	[173.88, 193.20]	[42.17, 46.85]	[48.65, 54.05]
$j=3$ Hejing county	[4.45, 4.95]	[91.08, 101.20]	[20.80, 23.12]	[26.91, 29.90]
$j=4$ Heshuo county	[0.52, 0.58]	[10.45, 11.62]	[2.33, 2.59]	[3.10, 3.45]
$j=5$ Bohu county	[4.45, 4.95]	[87.98, 97.75]	[19.67, 21.85]	[25.88, 28.75]
$j=6$ Yuli county	[6.21, 6.90]	[124.20, 13.80]	[27.95, 31.05]	[36.23, 40.25]
Maximum water target (unit: 10^6 m^3)				
$j=1$ Kuerle county	17.00	350.00	75.00	95.00
$j=2$ Yanqi county	9.5	200.00	50.00	57.00
$j=3$ Hejing county	5.00	110.00	25.00	32.00
$j=4$ Heshuo county	0.6	13.00	3.00	4.00
$j=5$ Bohu county	5.00	100.00	24.00	30.00
$j=6$ Yuli county	7.00	15.00	32.00	45.00
Allocated allowable water permit (unit: 10^6 m^3)				
$j=1$ Kuerle county	[12.28, 14.44]	[245.51, 288.84]	[55.24, 64.99]	[67.52, 79.43]
$j=2$ Yanqi county	[7.28, 8.55]	[145.37, 171.02]	[32.71, 38.48]	[39.98, 47.03]
$j=3$ Hejing county	[3.77, 4.44]	[75.42, 88.73]	[16.97, 19.96]	[20.74, 24.40]
$j=4$ Heshuo county	[0.48, 0.56]	[8.38, 9.85]	[1.88, 2.22]	[2.41, 2.84]
$j=5$ Bohu county	[3.65, 4.29]	[73.04, 85.93]	[16.44, 19.34]	[20.15, 23.71]
$j=6$ Yuli county	[5.24, 6.16]	[104.78, 123.28]	[23.58, 27.74]	[28.82, 33.90]

Table 3 | Lists of scenarios

Abbreviation	Trading scheme
S1	Scenario 1 with 0% decreasing of total allowable water permit
S2	Scenario 2 with 5% decreasing of total allowable water permit
S3	Scenario 3 with 10% decreasing of total allowable water permit
S4	Scenario 4 with 15% decreasing of total allowable water permit
S5	Scenario 5 with 20% decreasing of total allowable water permit

demand would be 140.85×10^6 m^3, which indicates a serious shortage when inflow is low. When inflows are middle or high, the shortages would be alleviated, whereas each user would have to obtain water from other sources to satisfy its essential demands. The solutions for water shortage and allocation of other different counties and under the other scenarios can be similarly interpreted based on the results presented in Figure 3.

By inputting the interval numbers of stream flow and the economic data, water shortages of four users in six counties were obtained. Water shortages would occur if the available water resource could not meet the regulated target, which indicates that the shortage was the difference between the target and water availability. Figure 4 presents water shortages of four users in six counties in the study basin under different water permit levels with trading scheme. By the decreasing of water permit, less water would be allocated but more water would be released to trade, which leads to different shortages under different water permit levels. For example, under scenario 2 (S2), water shortages of municipal users in Yanqi county ($j=2$) would be [0.84,

Table 4 | Total water availabilities

District	Level	Probability	User $i=1$ Municipality	 $i=2$ Agriculture	 $i=3$ Industry	 $i=4$ Ecology
Total water availability (unit: 10^3 m^3)						
$j=1$ Kuerle county	$h=1$(low)	0.502	[8,237, 13,177]	[224,238, 235,600]	[49,429, 52,923]	[59,660, 61,750]
	$h=2$(medium)	0.370	[8,670, 13,870]	[236,040, 248,000]	[52,030, 55,708]	[62,800, 65,000]
	$h=3$(high)	0.128	[9,537, 15,257]	[259,644, 272,800]	[57,233, 61,279]	[69,080, 71,500]
$j=2$ Yanqi county	$h=1$(low)	0.502	[5,287, 7,648]	[133,000, 140,600]	[25,337, 34,846]	[35,701, 37,525]
	$h=2$(medium)	0.370	[5,565, 8,050]	[140,000, 148,000]	[26,670, 36,680]	[37,580, 39,500]
	$h=3$(high)	0.128	[6,121, 8,855]	[154,000, 162,800]	[29,337, 40,348]	[41,338, 43,450]
$j=3$ Hejing county	$h=1$(low)	0.502	[2,095, 3,781]	[71,250, 75,525]	[14,364, 18,145]	[15,661, 18,145]
	$h=2$(medium)	0.370	[2,205, 3,980]	[75,000, 79,500]	[15,120, 19,100]	[16,485, 19,800]
	$h=3$(high)	0.128	[2,426, 4,378]	[82,500, 87,450]	[16,632, 21,010]	[18,134, 21,780]
$j=4$ Heshuo county	$h=1$(low)	0.502	[209, 456]	[8,550, 8,978]	[1,546, 1,710]	[1,738, 2,005]
	$h=2$(medium)	0.370	[221, 480]	[9,000, 9,450]	[1,628, 1,800]	[1,829, 2,111]
	$h=3$(high)	0.128	[243, 528]	[9,900, 10,395]	[1,790, 1,980]	[2,012, 2,322]
$j=5$ Bohu county	$h=1$(low)	0.502	[2,745, 3,705]	[65,788, 74,100]	[15,015, 18,135]	[16,312, 19,215]
	$h=2$(medium)	0.370	[2,890, 3,900]	[69,250, 78,000]	[15,805, 19,089]	[17,170, 20,226]
	$h=3$(high)	0.128	[3,179, 4,290]	[76,175, 85,800]	[17,386,20,998]	[18,887, 22,249]
$j=6$ Yuli county	$h=1$(low)	0.502	[4,446, 5,672]	[96,259, 108,533]	[19,551, 24,899]	[26,196, 27,550]
	$h=2$(medium)	0.370	[4,680, 5,970]	[101,325, 114,245]	[20,580, 26,209]	[27,575, 29,000]
	$h=3$(high)	0.128	[5,148, 6,567]	[111,458, 125,670]	[22,638, 28,830]	[30,333, 31,900]

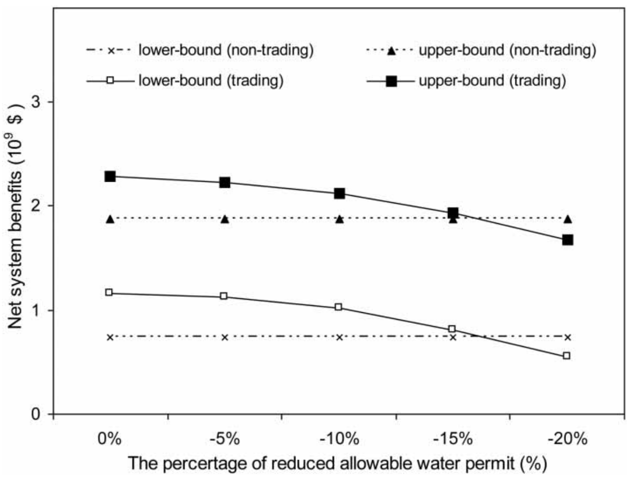

Figure 2 | System benefits under different water permits.

3.20] × 10^6 m^3 at low level, [0.44, 2.92] × 10^6 m^3 at medium level, and [0.73, 2.37] × 10^6 m^3 at high level. In comparison, under scenario 4 (S4), municipal water shortages in Yanqi county would be [1.19, 3.55] × 10^6 m^3 at low level, [0.78, 3.27] × 10^6 m^3 at medium level, and [1.59, 2.19] × 10^6 m^3 at high level. Shortages under S4 are all higher than those under S2 due to decreasing water permit. Moreover, shortages are affected by the randomness of water availabilities. For example, shortages of industrial users in Heshuo county ($j=4$) would be [0.62, 0.78] × 10^6 m^3 in the dry season and [0.35, 0.54] × 10^6 m^3 in the wet season under scenario 2. The results indicate that, when the flow is high in the wet season, the shortage may be relatively low under advantageous conditions, and would be raised when the flow is low in the dry season. The solutions for water shortage under other scenarios could be similarly interpreted based on the results presented in Figure 4.

Water could be transferred to the most valuable users through trading, and substituted for being allocated to each user proportionally. In this study, since allocation targets and related losses of different users vary from each other, released water could remedy losses of water deficiencies to get a higher benefit, which could encourage

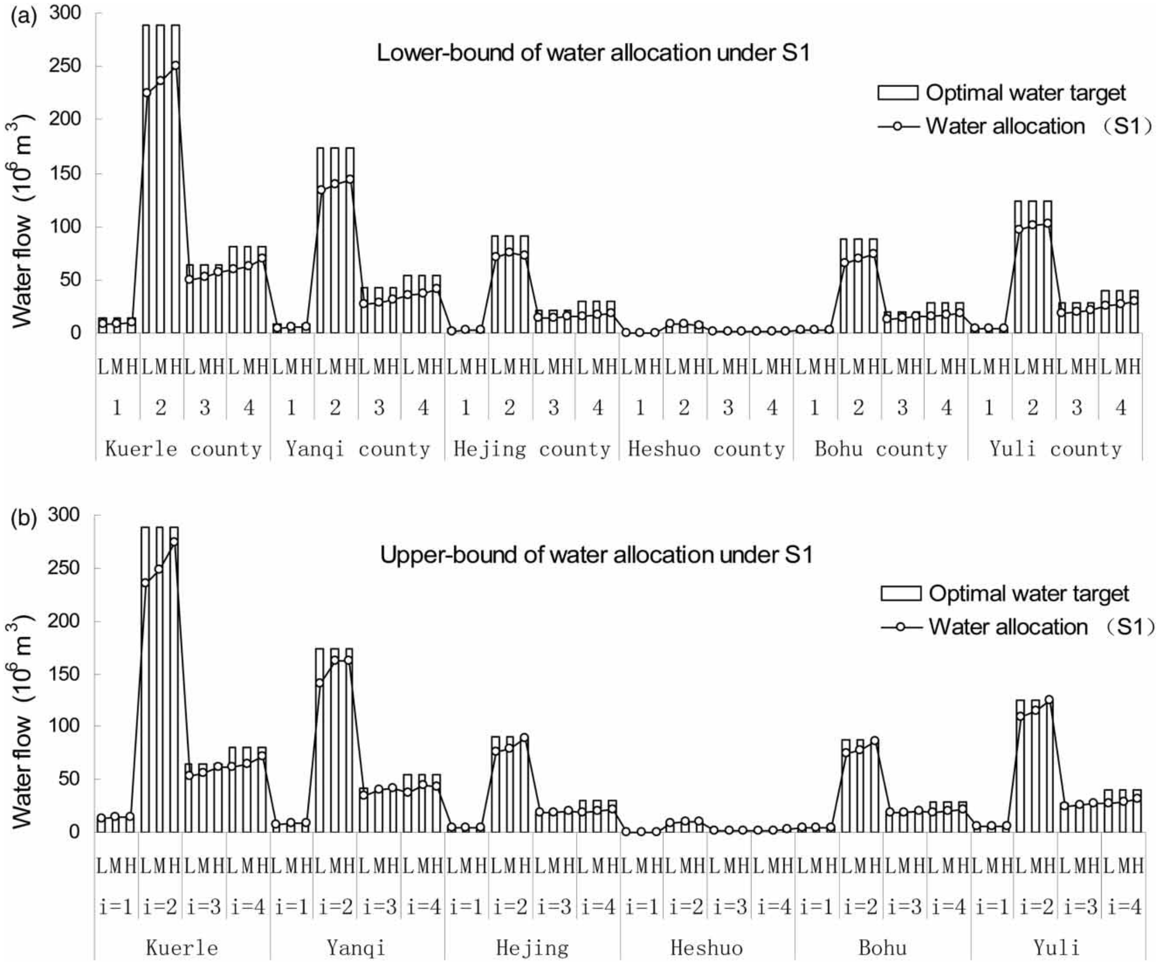

Figure 3 | Solutions for optimal water target and water allocation in scenario 1.

the further implementation of the water trading scheme. When the losses of water shortages are generated, each user would have to obtain water from released water and other sources to satisfy its essential demands. Figure 5 presents solutions for trading from released water in Kuerle county under scenarios 2 and 4. The results implied that although the amounts of released water can remedy water shortage to an extent, they are less than the amount of expected purchasing water in the study region due to the arid characteristics. For example, under scenario 2, for the industrial user in Kuerle county ($j = 1$), the amounts of released water would be $[2.09, 5.57] \times 10^6$ m^3 at high level, while the amount of expected purchasing water would be $[6.94, 8.6] \times 10^6$ m^3. Figure 6 shows that the solutions of water trading under scenarios 2 and 4 in association varied by reallocated water permit levels. The results indicate that more water would be released by decreasing water permits under trading, while shortage would be remedied by released water, which leads to amounts of water trading from other sources decreasing. For example, under scenario 2, for ecological user in Yuli county ($j = 6$), the amounts of water obtained from trading would be 12.70×10^6 m^3 at low level, 11.25×10^6 m^3 at medium level, and $[6.96, 8.35] \times 10^6$ m^3 at high level, while amounts of water from trading for scenario 4 would be $[12.35, 12.70] \times 10^6$ m^3 at low level, $[9.59, 11.07] \times 10^6$ m^3 at medium level, and $[4.08, 5.27] \times 10^6$ m^3 at high level. The obtained results indicate that amounts of water trading under S4 are lower than those under S2 due to decreasing water permit. Meanwhile, solutions from Figure 6 also indicate that amounts of water trading are influenced by the randomness in the total water availabilities. For example, amounts of water trading from

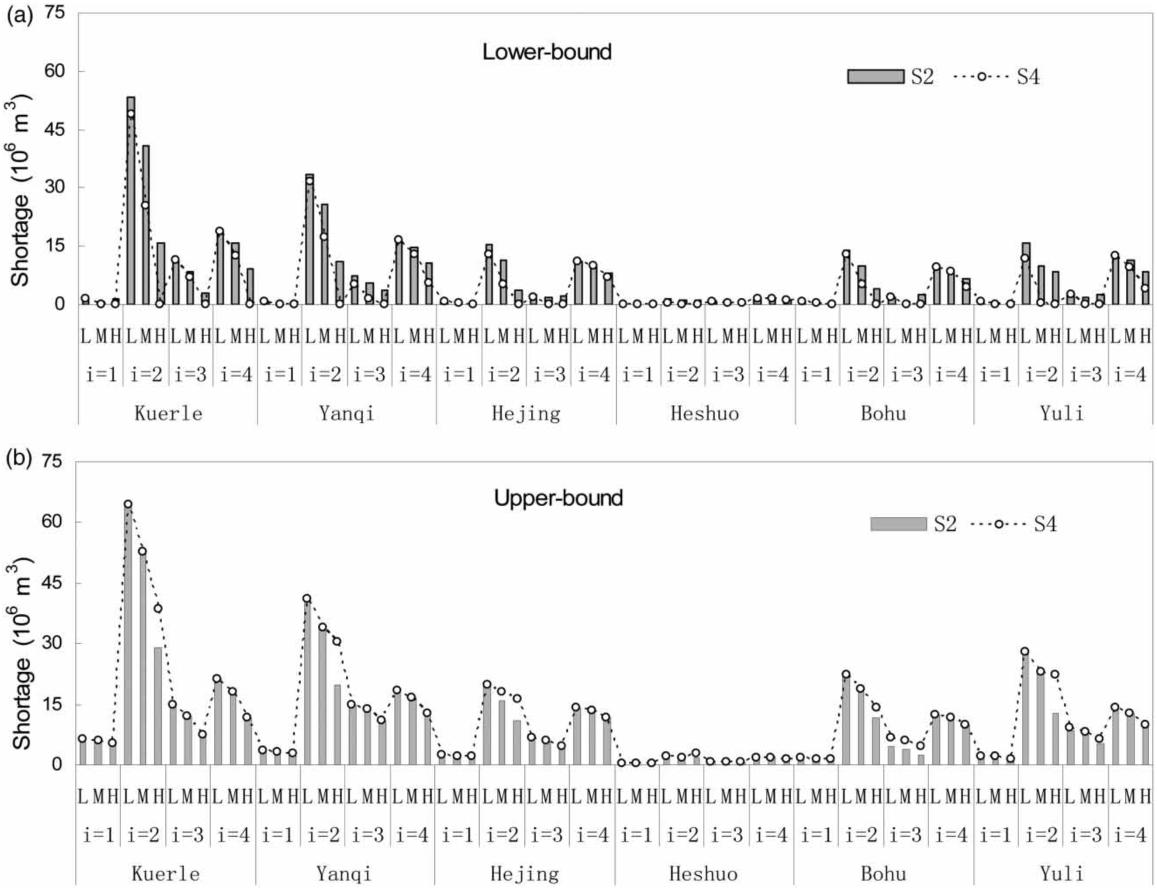

Figure 4 | Solutions for water shortage in scenarios 2 and 4.

other sources to agricultural users in Kuerle county ($j = 1$) county in Figure 6 would be $[48.97, 53.17] \times 10^6$ m^3 in the dry season and zero in the wet season under scenario 4, which indicates trading from other sources in the dry season is much bigger than in the wet season. The solutions for water trading under other scenarios could be similarly interpreted based on the results presented in Figure 6.

In this study, different trading schemes (i.e., non-trading and trading scheme) were examined by the ITSP model, for the sake of comparing differences between the two schemes. Figure 2 shows the system benefits are the sum of the first-stage benefit from the target allocation and the second-stage random loss of water deficit. In Figure 2, solid lines represent the benefit obtained from trading scheme, and dashed lines represent the benefit obtained from non-trading scheme. Solid lines show that the intervals of net system benefits under trading are changed by the decreasing of water permit. However, dashed lines standing for net system benefits under non-trading do not change, due to the fact that the water target and total available was not changed although the water permit decreased. The results demonstrate that net system benefits under trading were much higher than non-trading when decreasing permit levels were from 0 to 15% (in scenario 1–4), but lower than non-trading when decreasing permit exceeded 15% (scenario 5). For example, with scenario 1–4, the net system benefit under trading (i.e., the optimized system benefits would be US$$[1.16, 2.28] \times 10^9$ in S1, US$$[1.12, 2.23] \times 10^9$ in S2, US$$[1.01, 2.12] \times 10^9$ in S3, and US$$[0.81, 1.93] \times 10^9$ in S4) would be higher than that under non-trading (i.e., the optimized system benefits would be US$$[0.74, 1.88] \times 10^9$ in S1–S4). In practice, transaction costs, which include the costs of creating, monitoring, and enforcing water rights, need to be considered when establishing a trading system; the trading cost could reduce the total net system benefit. Therefore, in scenario 5, the net system

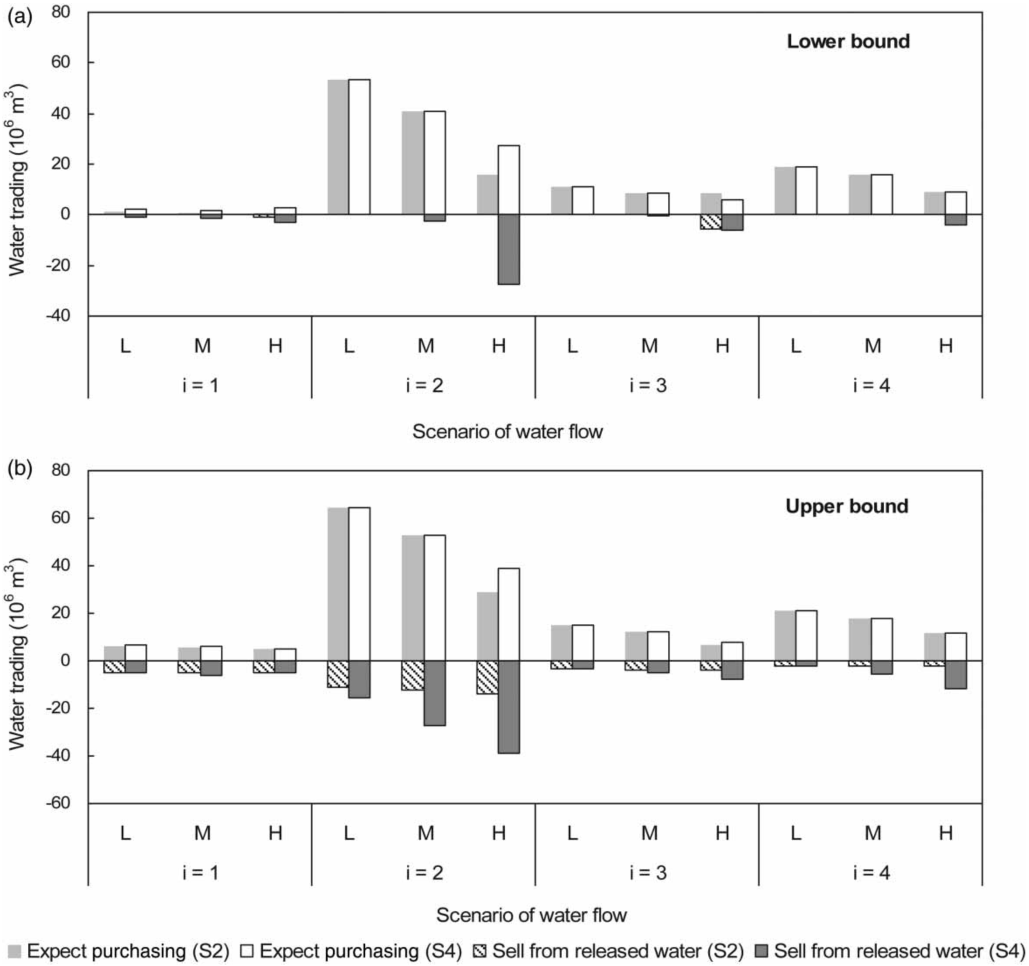

Figure 5 | Solutions for trading from released water in Kuerle county in scenarios 2 and 4.

benefit would be US$[0.31, 1.20] $\times 10^9$ under trading, which is lower than that under non-trading (i.e., the optimized system benefits would be US$[0.74, 1.88] $\times 10^9$ in S5). Owing to water allocation to each user by water permit proportionally under non-trading, the net system benefit cannot be influenced by decreasing of water permit, where net system benefit would be US$[0.74, 1.88] $\times 10^9$ under S1–S5. Meanwhile, net system benefit can be insensitive to water permit. Comparing net system benefit under trading and that under non-trading, the efficiency of trading and non-trading would be acquired. Moreover, due to trading from released water and other sources of water resources to remedy water deficiencies, water shortages with trading scheme are much smaller than with non-trading scheme in S2 as shown in Figure 7. For example, water shortages of industrial users in Hejing county ($j = 3$) with trading scheme would be [1.78, 5.74] $\times 10^6$ m^3 at medium level, while with non-trading scheme it would be [1.78, 8.05] $\times 10^6$ m^3 at medium level. Even some shortages would be resolved by trading, mostly such as municipal users in Heshuo county ($j = 4$). 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 regions.

CONCLUSIONS

In this study, a two-stage interval-stochastic water trading (TIWT) model has been developed, based on techniques of

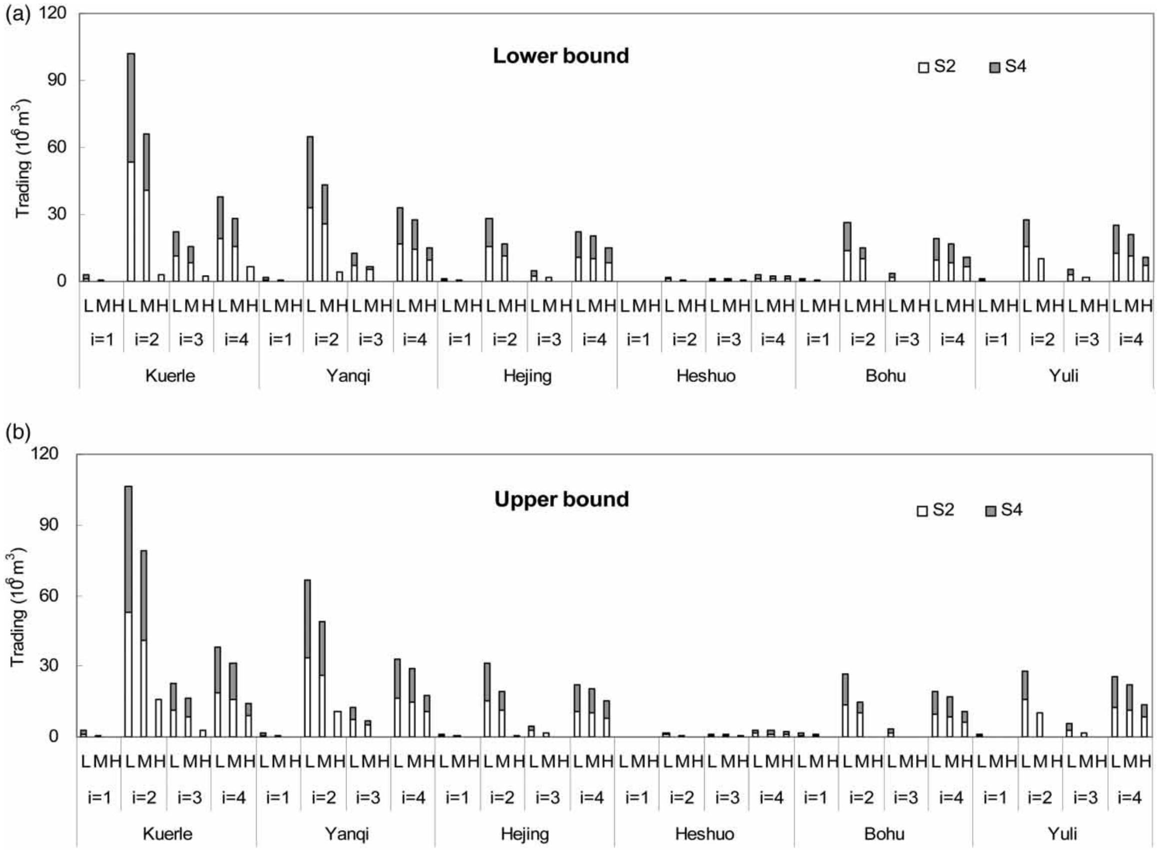

Figure 6 | Solutions for amounts of water trading in scenarios 2 and 4.

TSP and IPP. The TIWT model can incorporate uncertainties presented as intervals and probability distributions within its modeling framework. It can provide an effective linkage between water target and water shortage caused by incorrect policies due to uncertainties. Moreover, trading scheme makes water allocation more optimal in response to water moving from low value to high value. In the solution process, the TIWT model can be transformed into two deterministic submodels that correspond to the lower in two deterministic submodels that correspond to lower and upper bounds of the objective-function value. Solutions are combinations of deterministic, interval and distributional information, which can reflect different forms of uncertainties (i.e., stream flow, water demand, and trading permit) in the trading program.

The TIWT model was then applied to Kaidu-Kongque River in the northwestern China to identify an effective way to allocate water to multiple competitive users under severe water scarcity in such a typical arid region. Solutions have been generated, which can provide optimal water target, water shortage, and trading pattern. A number of scenarios were examined to help analyze different water resources allocations and trading efficiencies under different trading strategies. The results revealed that trading was sensitive to water permit, in which system benefit could vary with water permit; trading was more effective than non-trading under designated situations. Therefore, water permit should be considered the primary factor in a practical water resources system, where water permit should be adjusted based on regional development to remedy losses of water deficiency and improve the efficiency of water resources system by a market approach. Through demonstration in the case study, the methodology can help facilitate reducing the risks of establishing a water trading program, and the developed method will support the decision-maker to allocate or plan water resource effectively by TIWT.

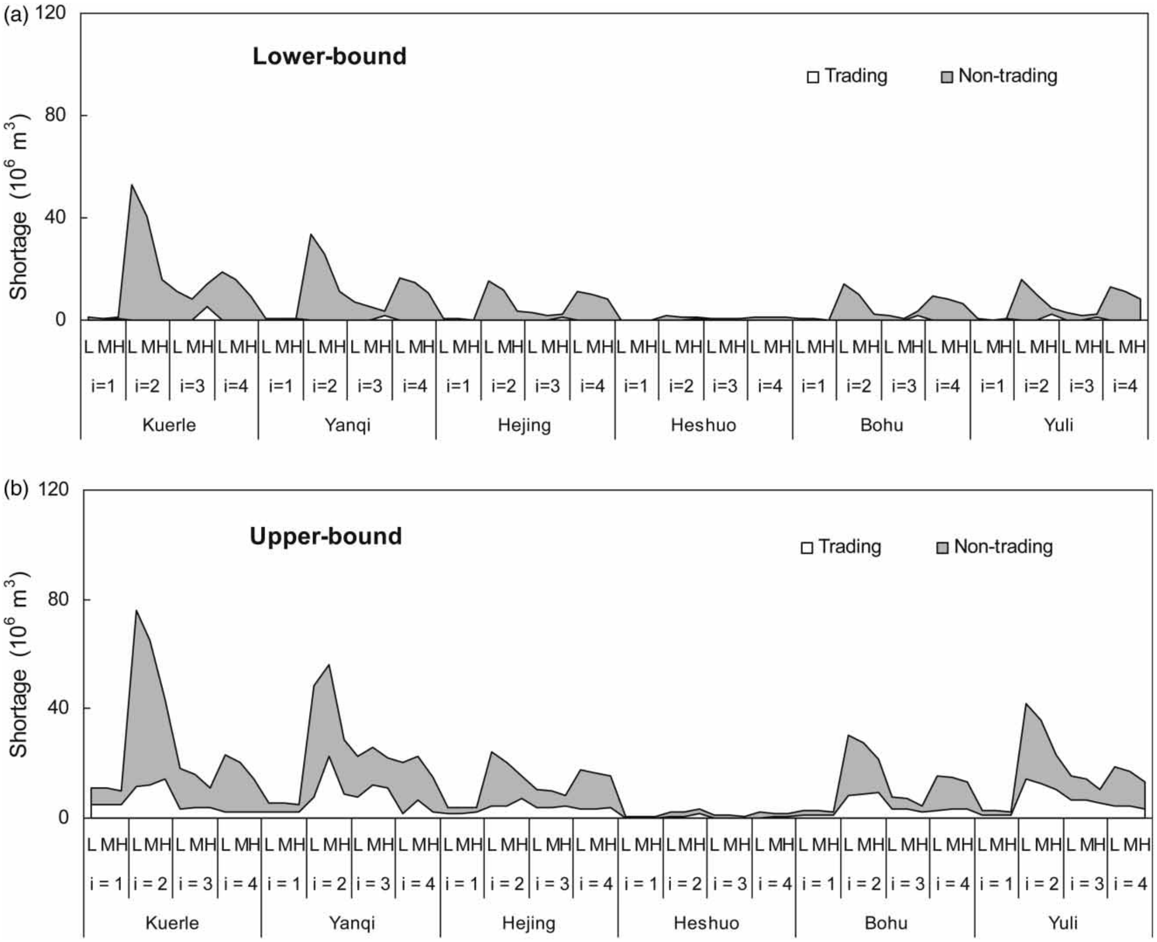

Figure 7 | Shortages with trading and non-trading schemes (scenario 2).

Although the TIWT model can effectively deal with uncertainties existing in water trading planning problems, there are also several limitations of the proposed method that are subject to further improvement. For example, in the practical trading programs, multiple uncertainties (e.g., trading policy, imprecise economic data, and opportunity cost) could affect efficiency of water-allocation and -trading patterns. The TIWT model would be integrated with more robust optimization techniques to enhance its capacities in tackling uncertainties presented in multiple formats. As well, in a trading program, many impact factors (e.g., trading ratio, trading efficiency, and trading quota) should be considered. Trading ratio is often influenced by stochastic events, which are not measured with certainty but in fact represented as a probability distribution around the actual water policy. The developed TIWT model could be further enhanced through studying more system components, introducing more advanced method, and considering more uncertainties into the optimal framework for water resources systems planning.

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