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Inter-basin water transfer supply chain coordination with the fairness concern under capacity constraint and random precipitation

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Abstract

Purpose – The purpose of this paper is to explore the impact of supply capacity constraint, water delivery loss and fairness concern on the operational decisions/efficiency of the IBWT supply chain under the random precipitation.

Design/methodology/approach – Two game-theoretic decision models for the IBWT supply chain coordination considering water delivery loss without/with fairness concern under the supply capacity constraint and random precipitation are developed, analyzed and compared. On this basis, the corresponding numerical analyses are conducted and compared to derive the corresponding management insights and policy implications.

Findings – The research results indicate that the two-part tariff contract could effectively coordinate the IBWT supply chain and achieve operational performance improvement; the binding supply capacity constraint makes the water capacity to be allocated among IBWT distributors in accordance with fair shortage allocation rule and reduces the profit (or utility) of the IBWT supply chain and its members; the existence of fairness concern reduces the utility of the IBWT supply chain and its members; a lower precipitation utilization factor in the case with non-binding capacity constraint is beneficial for improving the profit/utility of the IBWT supply chain while a higher precipitation utilization factor in the case with binding capacity constraint is beneficial for improving the profit/utility of the IBWT supply chain; and reducing the water delivery loss rate, the mainline transfer cost, the branch-line transfer cost, the holding cost and the shortage cost and setting a higher retail price are beneficial for improving the profit/utility of the IBWT supply chain.

Originality/value – Two innovative coordination decision models under random precipitation are developed, analyzed and compared through game-theoretic approaches to investigate the impact of supply capacity constraint, water delivery loss and fairness concern on the operational decisions/efficiency of the IBWT supply chain, which have enhanced the optimization decision theory for the operations management of IBWT projects and provided a better decision support for the IBWT stakeholders to make better operations strategies.

Keywords Supply chain coordination, Capacity constraint, Fairness concern, Inter-basin water transfer (IBWT), Random precipitation, Water delivery loss

Paper type Research paper

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1. Introduction

The inter-basin water transfer (IBWT) project is to use a large-scale artificial method to transfer a large amount of water from the water abundant basin to the water shortage basin, so as to promote the economic and social development and alleviate the contradiction of water shortage in the water-scarce region. Many large-scale IBWT projects have been built and operated in major river basins around the world, such as, the Central Valley Project in the USA (SWP, 2017; Yang, 2003) and the South-to-North Water Diversion (SNWD) Project in China (Wang *et al.*, 2009).

In the operations management of IBWT projects, several key factors have important impacts on the operational performance of projects. First, the terminal water market demand is affected by local precipitation: the more the regional precipitation is, the less the terminal water market demand is. Obviously, this random precipitation has an important impact on the operations decision and operational efficiency of the IBWT project. Second, owing to the existence of supply capacity constraint in the IBWT project, a situation that the total order quantity exceeds the supply capacity may occur. Thus, how to allocate scarce water resources to distributors fairly, to pursue economic benefit and social welfare, is still an urgent problem need to be solved in the IBWT projects. Third, there is generally a certain water loss in the water transfer process of the IBWT project. This water loss has an important impact on the operational decision making and operational efficiency of the IBWT project. Fourth, there are multiple operating entities in the IBWT project, including: local supplier, external supplier and multiple distributors. Thus, how to effectively coordinate multiple entities in the operations management of IBWT project to achieve operational performance improvement is also an urgent problem for IBWT projects. Finally, the operational entities of IBWT project usually have a certain fairness concern: inequity aversion, which is the preference for fairness and resistance to incidental inequalities. Apparently, this kind of fairness concern has an important impact on the operations decision and operational efficiency of the IBWT project.

Owing to the advantage of considering both the collective rationality and individual rationality simultaneously, supply chain management (SCM) theory has been applied in the operations management of IBWT project to investigate the interactions among the multiple stakeholders and develop cooperative/coordination operations mechanisms (Wang *et al.*, 2012). However, the interactions among the multiple stakeholders and operations management mechanisms in an IBWT supply chain considering fairness concern under the capacity constraint and the random precipitation are rarely investigated in the current literatures and practices.

Therefore, this paper will try to explore the issues of IBWT supply chain coordination without/with fairness concern under the supply capacity constraint and random precipitation. In the following sections, the corresponding literatures are reviewed first in Section 2; the theoretical modeling notation and overview for a generic IBWT supply chain are defined in Section 3; the IBWT supply chain coordination models considering water delivery loss without/with fairness concern under the supply capacity constraint and random precipitation are developed and analyzed in Sections 4.1 and 4.2; the corresponding numerical and sensitivity analysis for all models is conducted and the results and comparisons are summarized in Section 5; the management insights and policy implications are then discussed in Section 6; and, finally, the research contributions and foresights are summarized and concluded.

2. Literature review

Currently, game theory is applied to identify the interaction relationships among stakeholders in the operations management of IBWT projects are investigated through game theory, for example, game theory model for the water conflicts in the SNWD project (Wei *et al.*, 2010), game-theoretic model for the IBWT system considering both the quantity and quality

(Manshadi *et al.*, 2015), innovative option contract for allocating water in the IBWT projects (Rey *et al.*, 2016), and the incentive-compatible payments in the SNWD project (Sheng and Webber, 2017). Furthermore, cooperative game theory is applied to balance the individual rationality and the collective rationality in the operations management of IBWT projects; for example, optimal water allocation in the IBWT system using the crisp and fuzzy Shapley games (Sadegh *et al.*, 2010), water resources allocation considering the water quality in the IBWT system using cooperative game (Nikoo *et al.*, 2012), IBWT water resources allocation using least core game (Jafarzadegan *et al.*, 2013), IBWT water-resource allocation using a robust multi-objective bargaining methodology (Nasiri-Gheidari *et al.*, 2018).

Currently, the theories, methods and techniques of SCM have been applied to the study of the operations management of IBWT projects (especially the SNWD project in China), such as, Wang *et al.* (2012) studied the pricing and coordinating schemes of the eastern route of SNWD project and discussed the analytical results and their policy implications for the eastern route of SNWD water-resource supply chain. Chen and Wang (2012a) developed a decentralized decision model and a centralized decision model with strategic customer behavior using a floating pricing mechanism to construct a coordination mechanism via a revenue-sharing contract. Chen and Wang (2012b) further used several game-theoretical models such as Stackelberg game, asymmetric Nash bargaining *et al.* in studying the SNWD supply chain. A finite-horizon periodic-review inventory model with inflow forecasting updates following the Martingale Model of Forecast Evolution was developed to study two-echelon reservoirs in an IBWT project (Xu *et al.*, 2012). Chen *et al.* (2013) applied a two-tier pricing scheme to balance the water allocation by using a Stackelberg game model for the eastern route of SNWD project and they concluded that the two-tier pricing scheme is an effective way that can integrate the government control and market powers to ensure both the public interest and the economic benefit. Chen and Pei (2018) explored the interactions between multiple stakeholders of an IBWT green supply chain through the game-theoretic and coordination research approaches considering the government's subsidy to the water-green-level improvement under the social welfare maximization.

Nevertheless, these existing literatures regarding operations management of IBWT supply chain, neither explored the coordination strategies of IBWT supply chain under the supply capacity constraint and random precipitation, nor investigated the impact of supply capacity constraint, water delivery loss and fairness concern on the operational performance of IBWT supply chain. This paper intends to address the literature shortage issues and explore the coordination strategies for an IBWT supply chain without/with fairness concern under supply capacity constraint and random precipitation. A coordination decision model without fairness concern and a coordination decision model with fairness concern for the IBWT supply chain under capacity constraint and random precipitation are developed, solved and compared to explore the optimal operations strategies for the IBWT supply chain and the optimal pricing regulation policy for the government.

3. Theoretical modeling notations and overview

An IBWT distribution system is a typical "embedded" supply chain structure. In this supply chain system, a horizontal water supply system is embedded in a vertical water distribution system (see Figure 1). The horizontal water supply system is comprised of a local supplier and an external supplier and they serve as a joint IBWT supplier via an efficient cooperation mechanism, and the vertical water distribution system distributes water by the joint IBWT supplier through the multiple water distributors to many water consumers in the service region. Specifically, the water resources are transferred and supplied by the local supplier from the water source to the external supplier within the trunk channel and then distributed to water resources distributors of all water-intakes via river channels and artificial canal. Finally, the water resources are sold by each distributor to the water resources consumers in his service region. What needs to be noted is

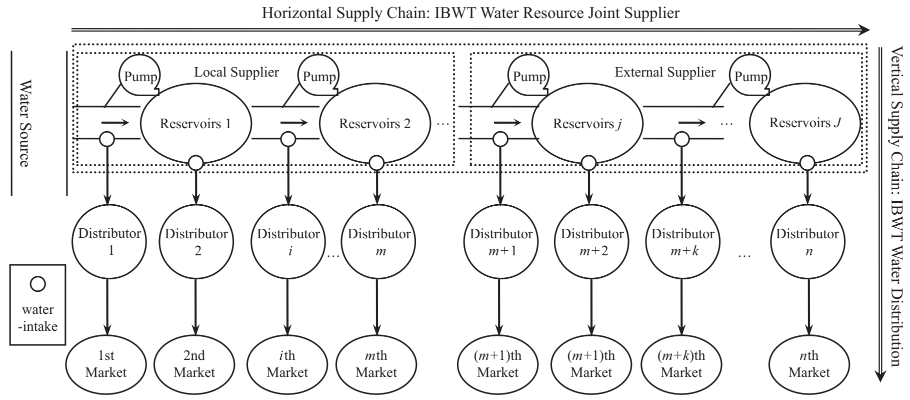


Figure 1.
A generic inter-basin water transfer supply chain system

that the water consumers can only buy water from their regional water distributors due to the fixed physical structure of the water transferring channel and the corresponding facilities and equipment. This feature determines that there is no competition among water distributors.

In Figure 1, the water distributors and the corresponding consumers are indexed by $i=1, 2, \ldots, n$. We assume there are m distributors supplied by the local supplier and $n-m$ distributors supplied by the external supplier. The branch-line water transfer cost from the ith water-intake to the ith distributor is c_{di}, the mainline water transfer cost from the $(k-1)$th water-intake to the kth water-intake within the horizontal green supply chain is c_k, and the water delivery loss from the $(k-1)$th water-intake to the kth water-intake within the horizontal green supply chain is δ_k, $k=1, 2, \ldots, n$. The order quantity of the ith water-intake is q_i, which is delivered from the water source with the original pumping quantity Q_i. Obviously, the relationship between the water demand of the ith water-intake q_i and the pumping quantity from the water source Q_i is $q_i = Q_i \prod_{k=1}^{i} (1-\delta_k)$, and the total transfer cost of the pumping quantity from the water source Q_i is $TC_i(Q_i) = Q_i \sum_{k=1}^{i}[c_k \prod_{j=0}^{k-1}(1-\delta_j)]$, hereinto, $\delta_0=0$. Therefore, the total transfer cost of the water demand (order quantity) of the ith water-intake is $TC_i(q_i) = \sum_{k=1}^{i}[c_k \prod_{j=0}^{k-1}(1-\delta_j)]/ \prod_{k=1}^{i} (1-\delta_k)q_i$. Define $C_i = \sum_{k=1}^{i}[c_k \prod_{j=0}^{k-1}(1-\delta_j)]/ \prod_{k=1}^{i} (1-\delta_k)$, then $TC_i(q_i)=C_i q_i$. It is assumed that the IBWT water supply capacity in the water source is $\overline{Q}$ and satisfies $\sum_{i=1}^{n} Q_i \leqslant \overline{Q}$. The fixed cost of water delivery for the ith water-intake of the IBWT supplier is c_{fi}, the fixed cost for the local supplier is c_{fl} and $c_{fl} = \sum_{i=1}^{m} c_{fi}$; the fixed cost for the external supplier is c_{fe} and $c_{fe} = \sum_{i=m+1}^{n} c_{fi}$; then the fixed cost for the IBWT supplier is $c_f = c_{fl}+c_{fe} = \sum_{i=1}^{n} c_{fi}$. The local supplier sells and transfers water resources to the external supplier with the wholesale price w (per m^3). The IBWT supplier sells water resources to the ith distributor with a two-part tariff system, i.e. an entry price (a lump-sum fee) w_{ei} and a usage price (charge per-use or per-unit) w_i. The ith distributor sells water resources to the consumers in his service region with a retail price p_i. The water demand for the ith water distributor is $d_i(x_i)=d_i-\vartheta x_i$, d_i is the basic water demand, ϑ is the precipitation utilization factor, x_i is the precipitation in the ith water distributor's service region defined in the range $[A,B]$ with $B>A\geqslant 0$, and x_i is a random variable with the cumulative distribution function $F_i(\cdot)$ and probability density function) $f_i(\cdot)$, and the mean value and standard deviation of x_i are μ_i and σ_i. The unit cost of holding water inventory for the ith distributor is h_i, while the shortage cost of unmet demand for the ith distributor is r_i. The benchmark profit of the IBWT supplier's ith water-intake are $\Pi_{S_i}^{b}$ in the case with non-binding capacity constraint (CNB) and $\overline{\Pi}_{S_i}^{b}$ in the case with binding capacity constraint (CB), the benchmark profit of the ith distributor are $\Pi_{D_i}^{b}$ in the CNB and $\overline{\Pi}_{D_i}^{b}$ in the CB.

Based on the foregoing parameters setting and model assumption, the profit function of the IBWT supply chain is as follows:

$$\Pi_{SC}(q_1,\ldots,q_i,\ldots,q_n)=\sum_{i=1}^{n}\left\{\begin{array}{l} p_iE\left[\min\{q_i,d_i(x_i)\}\right]-h_iE\left[q_i-d_i(x_i)\right]^+ \\ -r_iE\left[d_i(x_i)-q_i\right]^+-(C_i+c_{di})q_i-c_{fi}\end{array}\right\}.$$

In the IBWT vertical supply chain coordination model, the IBWT supplier offers the distributors a two-part tariff contract in which the IBWT supplier charges a usage price w_i from the ith distributor. The distributors either accept or reject the contract. If the distributors accept, they have to pay an entry price w_{ei}^c to the IBWT supplier, which are determined by the negotiation between the IBWT supplier and distributors. Under the two-part tariff contract, the profit functions of the ith water-intake of the IBWT supplier, the IBWT supplier and the ith distributor are as follows:

$$\prod\nolimits_{S_i}(w_i)=(w_i-C_i)q_i+w_{ei}-c_{fi},$$

$$\prod\nolimits_{S}(w_1,\ldots,w_i,\ldots,w_n)=\sum_{i=1}^{n}\prod\nolimits_{S_i}(w_i)=\sum_{i=1}^{n}\left[(w_i-C_i)q_i+w_{ei}-c_{fi}\right],$$

$$\prod\nolimits_{D_i}(q_i)=p_iE\left[\min\{q_i,d_i(x_i)\}\right]-h_iE\left[q_i-d_i(x_i)\right]^+-r_iE\left[d_i(x_i)-q_i\right]^+-(w_i+c_{di})q_i-w_{ei}.$$

On this basis, the profit functions of the local supplier and the external supplier are as follows:

$$\prod\nolimits_{LS}(w_1,\ldots,w_m,w)=\sum_{i=1}^{m}(w_i-C_i)q_i+\sum_{i=1}^{n}w_{ei}-c_{fl}+w\sum_{i=m+1}^{n}q_i,$$

$$\prod\nolimits_{ES}(w_{m+1},\ldots,w_n,w)=\sum_{i=m+1}^{n}(w_i-C_i)q_i+\sum_{i=m+1}^{n}w_{ei}-c_{fe}-w\sum_{i=m+1}^{n}q_i.$$

Due to the quasi-public-goods characteristics of the water resources and the quasi-public-welfare characteristics of the IBWT projects, the operations management of the IBWT projects should take both the economic benefit and the social welfare into account. However, the operations management of the IBWT project typically pursues only the economic benefit maximization, if the government does implement any regulation measures to pursue social welfare improvement. Therefore, the government's regulations (such as shortage allocation rule, etc.) are essential for guaranteeing social welfare in the operations management of IBWT project. Owing to the existence of supply capacity constraint, when the total order quantity exceeds the supply capacity, it is inevitable that the allocation of scarce water resources among IBWT distributors should be conducted. If the shortage allocation rule is made by the IBWT supplier, the water resources would be preferentially allocated to the high-value distributor (the distributor who can contribute more profit) by the IBWT supplier to pursue more profits without considering allocating fairness and social welfare. A fair shortage allocation rule is made by the government as follows: once the total order quantity exceeds the supply capacity, i.e. $\sum_{i=1}^{n}Q_i=\sum_{i=1}^{n}q_i/\prod_{k=1}^{i}(1-\delta_k)>\overline{Q}$, the ith distributor could be allocated with a certain ratio of initial order quantity, this ratio is set based on the overall order fulfillment ratio, i.e. $\lambda=\overline{Q}/\sum_{i=1}^{n}q_i/\prod_{k=1}^{i}(1-\delta_k)$.

4. IBWT supply chain coordination with fairness concern under capacity constraint and random precipitation

Based on modeling notations and assumptions in Section 3, the theoretical models of IBWT supply chain coordination without/with fairness concern under capacity constraint and random precipitation are developed, analyzed and compared in this section.

4.1 IBWT supply chain coordination without fairness concern under capacity constraint and random precipitation

4.1.1 IBWT supply chain centralized decision. Under the fair shortage allocation rule made by the government, the optimal problem for the centralized IBWT supply chain under capacity constraints can be formulated as follows:

$$\begin{cases} \max\limits_{q_1,\ldots,q_i,\ldots,q_n} & \prod_{SC}(q_1,\ldots,q_i,\ldots,q_n) \\ \text{s.t.} & \sum\limits_{i=1}^{n}\dfrac{q_i}{\prod_{k=1}^{i}(1-\delta_k)} \leqslant \overline{Q} \end{cases}.$$

Solving the first-order condition and the second-order derivative of the optimal problem w.r.t. the order quantity q_i, we can obtain the optimal order quantity of the water resources for the ith water-intake as follows:

$$q_i^c = \min\{q_i^*, \overline{q}_i^*\}, i = 1, 2, \ldots, n.$$

Hereinto:

$$q_i^* = d_i - \vartheta F_i^{-1}\left(\frac{C_i + c_{di} + h_i}{p_i + h_i + r_i}\right), \overline{q}_i^* = \lambda^* q_i^*, \lambda^* = \overline{Q}/\sum\nolimits_{i=1}^{n}\frac{q_i^*}{\prod_{k=1}^{i}(1-\delta_k)}.$$

Plugging the optimal order quantity of the water resources into the profit function of the IBWT supply chain, we can obtain the optimal profit of the IBWT supply chain as follows:

$$\Pi_{SC}^c = \begin{cases} \sum\limits_{i=1}^{n}\left\{[p_i - (C_i + c_{di})]d_i - \Lambda_i(q_i^*)\right\} - c_f, & \text{if} \quad \lambda^* \geqslant 1 \\ \sum\limits_{i=1}^{n}\left\{[p_i - (C_i + c_{di})]d_i - \Lambda_i(\overline{q}_i^*) - H_i(\overline{q}_i^*)\right\} - c_f, & \text{if} \quad \lambda^* < 1 \end{cases},$$

where:

$$\Lambda_i(z_i) = \vartheta(p_i + h_i)\int_A^B x_i f_i(x_i)dx_i - \vartheta(p_i + h_i + r_i)\int_A^{\frac{1}{\vartheta}(d_i - z_i)} x_i f_i(x_i)dx_i,$$

$$H_i(\overline{q}_i^*) = \left\{(p_i + h_i + r_i)F_i\left[\frac{1}{\vartheta}(d_i - \overline{q}_i^*)\right] - (C_i + c_{di} + h_i)\right\}(d_i - \overline{q}_i^*).$$

4.1.2 IBWT vertical supply chain coordination. In the IBWT vertical supply chain coordination model, the IBWT supplier offers the distributors a two-part tariff contract in which the IBWT supplier charges a usage price w_i from the ith distributor. The distributors either accept or reject the contract. If the distributors accept, they have to pay an entry price, w_{ei}^c in the CNB or $\lambda^* w_{ei}^c$ in the CB, to the IBWT supplier, which are determined by the negotiation between the IBWT supplier and distributors. Under the fair shortage allocation rule made by the government, the ith distributor's optimal problem under the two-part tariff contract is formulated as follows:

$$\begin{cases} \max\limits_{q_1} \ \Pi_{D_1}(q_1) \\ \vdots \\ \max\limits_{q_i} \ \Pi_{D_i}(q_i) \\ \vdots \\ \max\limits_{q_n} \ \Pi_{D_n}(q_n) \\ \text{s.t.} \ \sum\limits_{i=1}^{n} \frac{q_i}{\prod_{k=1}^{i}(1-\delta_k)} \leqslant \overline{Q} \end{cases}.$$

Solving the first-order condition and the second-order derivative of the optimal problem w.r.t. the order quantity q_i, respectively, and we can obtain the reaction function of the order quantity q_i w.r.t. the water usage price w_i under the two-part tariff contract as follows:

$$q_i^d(w_i) = \min\left\{q_i^{**}(w_i), \overline{q}_i^{**}(w_i)\right\}, i = 1, 2, \ldots, n.$$

Hereinto:

$$q_i^{**}(w_i) = d_i - \vartheta F_i^{-1}\left(\frac{w_i + c_{di} + h_i}{p_i + h_i + r_i}\right), \overline{q}_i^{**}(w_i) = \lambda^{**}(w_i) q_i^{**}(w_i), \lambda^{**}(w_i) = \overline{Q} / \sum\nolimits_{i=1}^{n} \frac{q_i^{**}(w_i)}{\prod_{k=1}^{i}(1-\delta_k)}.$$

Under the two-part tariff contract, to achieve the IBWT supply chain coordination, it is necessary to achieve the coordinated condition: $q_i^c = q_i^d(w_i)$. Then, we have the coordinated usage price for the ith water-intake of the IBWT supplier as follows:

$$w_i^c = C_i, i = 1, 2, \ldots, n.$$

Therefore, the coordinated profit of the distributors $\Pi_{D_i}^c$ and the IBWT supplier Π_S^c under the two-part tariff contract are shown below:

$$\Pi_{D_i}^c = \begin{cases} [p_i - (C_i + c_{di})] d_i - \Lambda_i(q_i^*) - w_{ei}^c, & \text{if } \lambda^* \geqslant 1 \\ [p_i - (C_i + c_{di})] d_i - \Lambda_i(\overline{q}_i^*) - H_i(\overline{q}_i^*) - \lambda^* w_{ei}^c, & \text{if } \lambda^* < 1 \end{cases}, i = 1, 2, \ldots, n,$$

$$\Pi_S^c = \sum_{i=1}^{n} \Pi_{S_i}^c = \begin{cases} \sum_{i=1}^{n} \left(w_{ei}^c - c_{fi}\right), & \text{if } \lambda^* \geqslant 1 \\ \sum_{i=1}^{n} \left(\lambda^* w_{ei}^c - c_{fi}\right), & \text{if } \lambda^* < 1 \end{cases}.$$

4.1.3 IBWT horizontal supply chain cooperation. Plugging w_i^c and q_i^c into the profit functions of the local supplier and the external supplier in the IBWT horizontal supply chain, we can get:

$$\Pi_{LS}^c(w) = \begin{cases} \sum_{i=1}^{m} \left(w_{ei}^c - c_{fi}\right) + w \sum_{i=m+1}^{n} q_i^*, & \text{if } \lambda^* \geqslant 1 \\ \sum_{i=1}^{m} \left(\lambda^* w_{ei}^c - c_{fi}\right) + w \sum_{i=m+1}^{n} \overline{q}_i^*, & \text{if } \lambda^* < 1 \end{cases},$$

$$\Pi_{ES}^c(w) = \begin{cases} \sum_{i=m+1}^{n} \left(w_{ei}^c - c_{fi}\right) - w \sum_{i=m+1}^{n}, \quad q_i^*, \text{if} \quad \lambda^* \geqslant 1 \\ \sum_{i=m+1}^{n} \left(\lambda^* w_{ei}^c - c_{fi}\right) - w \sum_{i=m+1}^{n} \overline{q}_i^*, & \text{if} \quad \lambda^* < 1 \end{cases}.$$

According to the Nash bargaining theory (Nash, 1950; Kalai and Smorodinsky, 1975; Binmore *et al.*, 1986; Muthoo, 1999), the asymmetric Nash bargaining problem for bargaining over the wholesale price w can be expressed as follows:

$$\max_{w} \quad \theta(w) = \left[\Pi_{LS}^c(w)\right]^{\tau} \left[\Pi_{ES}^c(w)\right]^{1-\tau}, \text{s.t.} \quad \Pi_{LS}^c(w) + \Pi_{ES}^c(w) = \Pi_S^c.$$

Hereinto, τ is the bargaining power of the local supplier.

Solving the first-order condition and the second-order derivative of the optimal problem w.r.t. the wholesale price w respectively, we can obtain the bargaining wholesale price w_c as follows:

$$w_c = \begin{cases} \frac{\tau\left(\sum_{i=1}^{n} w_{ei}^c - c_f\right) - \left(\sum_{i=1}^{m} w_{ei}^c - c_{fl}\right)}{\sum_{i=m+1}^{n} q_i^*}, & \text{if } \lambda^* \geqslant 1 \\ \frac{\tau\left(\sum_{i=1}^{n} \lambda^* w_{ei}^c - c_f\right) - \left(\sum_{i=1}^{m} \lambda^* w_{ei}^c - c_{fl}\right)}{\sum_{i=m+1}^{n} \overline{q}_i^*}, & \text{if } \lambda^* < 1 \end{cases}.$$

Hence, we can get the bargaining profit of the local supplier and the external supplier in the IBWT horizontal supply chain as follows:

$$\Pi_{LS}^c = \tau \Pi_S^c,$$

$$\Pi_{ES}^c = (1-\tau)\Pi_S^c.$$

Remark 1. Only when the following conditions hold: $\Pi_{S_i}^c \geqslant \Pi_{S_i}^b$, $\Pi_{D_i}^c \geqslant \Pi_{D_i}^b$, the IBWT supply chain members would have the economic motivation to coordinate, that is, the reasonable interval of the entry price is: $w_{ei}^c \in [\underline{w_{ei}^c}, \overline{w_{ei}^c}], i = 1, 2, ..., n$.

Hereinto:

$$\underline{w_{ei}^c} = \begin{cases} \Pi_{S_i}^b + c_{fi}, & \text{if} \quad \lambda^* \geqslant 1 \\ \frac{1}{\lambda^*}\left(\overline{\Pi}_{S_i}^b + c_{fi}\right), & \text{if} \quad \lambda^* < 1 \end{cases},$$

$$\overline{w_{ei}^c} = \begin{cases} \left[p_i - (C_i + c_{di})\right] d_i - \Lambda_i\left(q_i^*\right) - \Pi_{D_i}^b, \text{if} \quad \lambda^* \geqslant 1 \\ \frac{1}{\lambda^*}\left\{\left[p_i - (C_i + c_{di})\right] d_i - \Lambda_i\left(\overline{q}_i^*\right) - H_i\left(\overline{q}_i^*\right) - \overline{\Pi}_{D_i}^b\right\}, \text{if} \quad \lambda^* < 1 \end{cases}.$$

4.2 IBWT supply chain coordination with fairness concern under capacity constraint and random precipitation

Under the scenario with fairness concern, owing to the distributors' weak position in the IBWT supply chain, the IBWT supplier is fair neutral, the distributors have inequity aversion, the utility functions of the IBWT supplier and the distributors are defined as follows:

$$U_S = \Pi_S = \sum_{i=1}^{n} \Pi_{S_i},$$

$$U_{D_i} = \Pi_{D_i} - \kappa_i\left(\Pi_{S_i} - \Pi_{D_i}\right) = (1 + \kappa_i)\Pi_{D_i} - \kappa_i \Pi_{S_i}, i = 1, 2, \ldots, n,$$

where κ_i is the ith distributor's coefficient of fairness concern.

Thus, the utility function of the IBWT supply chain is as follows:

$$U_{SC} = U_S + \sum_{i=1}^{n} U_{D_i} = \Pi_{SC} - \sum_{i=1}^{n} \kappa_i\left(\Pi_{S_i} - \Pi_{D_i}\right).$$

Likewise, the benchmark utility of the IBWT supplier's ith water-intake are $U_{S_i}^{fb} = \Pi_{S_i}^b$ in the CNB and $\overline{U}_{S_i}^{fb} = \overline{\Pi}_{S_i}^b$ in the CB, and the benchmark utility of the ith distributor are $U_{D_i}^{fb} = (1 + \kappa_i)\Pi_{D_i}^b - \kappa_i \Pi_{S_i}^b$ in the CNB and $\overline{U}_{D_i}^{fb} = (1 + \kappa_i)\overline{\Pi}_{D_i}^b - \kappa_i \overline{\Pi}_{S_i}^b$ in the CB.

4.2.1 IBWT supply chain centralized decision. Under the fair shortage allocation rule made by the government, the optimal problem for the centralized IBWT supply chain under capacity constraints can be formulated as follows:

$$\begin{cases} \max\limits_{q_1,\ldots,q_i,\ldots,q_n} U_{SC}(q_1, \ldots, q_i, \ldots, q_n) \\ \text{s.t.} \quad \sum\limits_{i=1}^{n} \dfrac{q_i}{\prod_{k=1}^{i}(1 - \delta_k)} \leqslant \overline{Q} \end{cases}.$$

Solving the first-order condition and the second-order derivative of the optimal problem w.r.t. the order quantity q_i, we can obtain the optimal order quantity function of the water resources q_i w.r.t. the usage price w_i as follows:

$$q_i^{fc}(w_i) = \min\left\{q_i^{f*}(w_i), \overline{q}_i^{f*}(w_i)\right\}, i = 1, 2, \ldots, n.$$

Hereinto:

$$q_i^{f*}(w_i) = d_i - \vartheta F_i^{-1}\left[\frac{(1+\kappa_i)(C_i+c_{di}+h)+2\kappa_i(w_i-C_i)}{(1+\kappa_i)(p_i+h_i+r_i)}\right], \overline{q}_i^{f*}(w_i) = \lambda_f^*(w_i) q_i^{f*}(w_i), \lambda_f^*(w_i) = \overline{Q}/\sum_{i=1}^{n}\frac{q_i^{f*}(w_i)}{\prod_{k=1}^{i}(1-\delta_k)}.$$

4.2.2 IBWT vertical supply chain coordination. In the IBWT vertical supply chain coordination model, the IBWT supplier offers the distributors a two-part tariff contract in which the IBWT supplier charges a usage price w_i from the ith distributor. The distributors either accept or reject the contract. If the distributors accept, they have to pay an entry price, w_{ei}^{fc} in the CNB or $\lambda_f^* w_{ei}^{fc}$ in the CB, to the IBWT supplier, which are determined by the negotiation between the IBWT supplier and distributors. Under the fair shortage allocation rule made by the government, the ith distributor's optimal problem under the two-part tariff contract is formulated as follows:

$$\begin{cases} \max\limits_{q_1} \; U_{D_1}(q_1) \\ \vdots \\ \max\limits_{q_i} \; U_{D_i}(q_i) \\ \vdots \\ \max\limits_{q_n} \; U_{D_n}(q_n) \\ \text{s.t.} \; \sum\limits_{i=1}^{n}\frac{q_i}{\prod_{k=1}^{i}(1-\delta_k)} \leqslant \overline{Q} \end{cases}.$$

Solving the first-order condition and the second-order derivative of the optimal problem w.r.t. the order quantity q_i, respectively, and we can obtain the reaction function of the order quantity q_i w.r.t. the water usage price w_i under the two-part tariff contract as follows:

$$q_i^{fd}(w_i) = \min\left\{q_i^{f**}(w_i), \overline{q}_i^{f**}(w_i)\right\}, i = 1,2,\ldots,n.$$

Hereinto:

$$q_i^{f**}(w_i) = d_i - \vartheta F_i^{-1}\left[\frac{(1+\kappa_i)(w_i+c_{di}+h_i)+\kappa_i(w_i-C_i)}{(1+\kappa_i)((p_i+h_i+r_i))}\right],$$

$$\overline{q}_i^{f**}(w_i) = \lambda_f^{**}(w_i) q_i^{f**}(w_i), \lambda_f^{**}(w_i) = \overline{Q}/\sum_{i=1}^{n}\frac{q_i^{f**}(w_i)}{\prod_{k=1}^{i}(1-\delta_k)}.$$

Under the two-part tariff contract, to achieve the IBWT supply chain coordination, it is necessary to achieve the coordinated condition: $q_i^{fc}(w_i) = q_i^{fd}(w_i)$. Then, we have the coordinated usage price for the ith water-intake of the IBWT supplier as follows:

$$w_i^{fc} = C_i, i = 1,2,\ldots,n.$$

Thus, we can obtain the optimal order quantity of the water resources for the ith water-intake as follows:

$$q_i^{fc} = \min\left\{q_i^{f*}, \overline{q}_i^{f*}\right\}, i = 1, 2, \ldots, n.$$

Hereinto:

$$q_i^{f*} = d_i - \vartheta F_i^{-1}\left(\frac{C_i + c_{di} + h_i}{p_i + r_i + h_i}\right), \overline{q}_i^{f*} = \lambda_f^* q_i^{f*}, \lambda_f^* = \overline{Q} / \sum_{i=1}^{n} \frac{q_i^{f*}}{\prod_{k=1}^{i}(1-\delta_k)}.$$

Therefore, the optimal utility of the IBWT supply chain U_{SC}^{fc}, the coordinated utility of the IBWT supplier U_S^{fc} and the distributors $U_{D_i}^{fc}$ under the two-part tariff contract are shown below:

$$U_{SC}^{fc} = \begin{cases} \sum_{i=1}^{n}\left\{(1+\kappa_i)\{[p_i-(C_i+c_{di})]d_i - \Lambda_i(q_i^*)\} + \kappa_i c_{fi} - 2\kappa_i w_{ei}^{fc}\right\} - c_f, & \text{if} \quad \lambda_f^* \geqslant 1 \\ \sum_{i=1}^{n}\left\{(1+\kappa_i)\{[p_i-(C_i+c_{di})]d_i - \Lambda_i(\overline{q}_i^*) - H_i(\overline{q}_i^*)\} + \kappa_i c_{fi} - 2\kappa_i \lambda_f^* w_{ei}^{fc}\right\} - c_f, & \text{if} \quad \lambda_f^* < 1 \end{cases},$$

$$U_{D_i}^{fc} = \begin{cases} (1+\kappa_i)\{[p_i-(C_i+c_{di})]d_i - \Lambda_i(q_i^*)\} + \kappa_i c_{fi} - (1+2\kappa_i) w_{ei}^{fc}, & \text{if} \quad \lambda_f^* \geqslant 1 \\ (1+\kappa_i)\{[p_i-(C_i+c_{di})]d_i - \Lambda_i(\overline{q}_i^*) - H_i(\overline{q}_i^*)\} + \kappa_i c_{fi} - (1+2\kappa_i)\lambda_f^* w_{ei}^{fc}, & \text{if} \quad \lambda_f^* < 1 \end{cases},$$

$$U_S^{fc} = \Pi_S^{fc} = \sum_{i=1}^{n} \Pi_{S_i}^{fc} = \begin{cases} \sum_{i=1}^{n}\left(w_{ei}^{fc} - c_{fi}\right), & \text{if} \quad \lambda_f^* \geqslant 1 \\ \sum_{i=1}^{n}\left(\lambda_f^* w_{ei}^{fc} - c_{fi}\right), & \text{if} \quad \lambda_f^* < 1 \end{cases}.$$

4.2.3 IBWT horizontal supply chain cooperation. Plugging w_i^{fc} and q_i^{fc} into the profit functions of the local supplier and the external supplier in the IBWT horizontal supply chain, we can get:

$$U_{LS}^{fc}(w) = \begin{cases} \sum_{i=1}^{m}\left(w_{ei}^{fc} - c_{fi}\right) + w \sum_{i=m+1}^{n} q_i^{f*}, & \text{if} \quad \lambda_f^* \geqslant 1 \\ \sum_{i=1}^{m}\left(\lambda^* w_{ei}^{fc} - c_{fi}\right) + w \sum_{i=m+1}^{n} \overline{q}_i^{f*}, & \text{if} \quad \lambda_f^* < 1 \end{cases},$$

$$U_{ES}^{fc}(w) = \begin{cases} \sum_{i=m+1}^{n}\left(w_{ei}^{fc} - c_{fi}\right) - w \sum_{i=m+1}^{n} q_i^{f*}, & \text{if} \quad \lambda_f^* \geqslant 1 \\ \sum_{i=m+1}^{n}\left(\lambda^* w_{ei}^{fc} - c_{fi}\right) - w \sum_{i=m+1}^{n} \overline{q}_i^{f*}, & \text{if} \quad \lambda_f^* < 1 \end{cases}.$$

The asymmetric Nash bargaining problem for bargaining over the wholesale price w can be expressed as follows:

$$\max_{w} \quad \theta(w) = \left[U_{LS}^{fc}(w)\right]^{\tau}\left[U_{ES}^{fc}(w)\right]^{1-\tau} \quad \text{s.t.} \quad U_{LS}^{fc}(w) + U_{ES}^{fc}(w) = U_S^{fc},$$

where τ is the bargaining power of the local supplier.

Solving the first-order condition and the second-order derivative of the optimal problem w.r.t. the wholesale price w, respectively, we can obtain the bargaining wholesale price w_c^f as follows:

$$w_c^f = \begin{cases} \dfrac{\tau\left(\sum_{i=1}^{n} w_{ei}^{fc} - c_f\right) - \left(\sum_{i=1}^{m} w_{ei}^{fc} - c_{fl}\right)}{\sum_{i=m+1}^{n} q_i^{f*}}, & \text{if} \quad \lambda_f^* \geqslant 1 \\ \dfrac{\tau\left(\sum_{i=1}^{n} \lambda_f^* w_{ei}^{fc} - c_f\right) - \left(\sum_{i=1}^{m} \lambda_f^* w_{ei}^{fc} - c_{fl}\right)}{\sum_{i=m+1}^{n} \overline{q}_i^{f*}}, & \text{if} \quad \lambda_f^* < 1 \end{cases}.$$

Hence, we can get the bargaining profit of the local supplier and the external supplier in the IBWT horizontal supply chain as follows:

$$U_{LS}^{fc} = \tau U_S^{fc},$$

$$U_{ES}^{fc} = (1-\tau) U_S^{fc}.$$

Remark 2. Only when the following conditions hold: $U_{S_i}^{fc} \geqslant U_{S_i}^{fb}$, $U_{D_i}^{fc} \geqslant U_{D_i}^{fb}$, the IBWT supply chain members would have the economic motivation to coordinate, that is, the reasonable interval of the entry price is: $w_{ei}^{fc} \in [\underline{w_{ei}^{fc}}, \overline{w_{ei}^{fc}}]$, $i = 1, 2, ..., n$.

Hereinto:

$$\underline{w_{ei}^{fc}} = \begin{cases} U_{S_i}^{b} + c_{fi}, & \text{if} \quad \lambda_f^* \geqslant 1 \\ \frac{1}{\lambda_f^*}\left(\overline{U}_{S_i}^{b} + c_{fi}\right), & \text{if} \quad \lambda_f^* < 1 \end{cases},$$

$$\overline{w_{ei}^{fc}} = \begin{cases} \frac{1}{1+2\kappa_i}\left\{(1+\kappa_i)\left\{\left[p_i - (C_i + c_{di})\right] d_i - \Lambda_i\left(q_i^*\right)\right\} + \kappa_i c_{fi} - U_{D_i}^{fb}\right\}, & \text{if} \quad \lambda_f^* \geqslant 1 \\ \frac{1}{(1+2\kappa_i)\lambda_f^*}\left\{(1+\kappa_i)\left\{\left[p_i - (C_i + c_{di})\right] d_i - \Lambda_i\left(\overline{q}_i^*\right) - H_i\left(\overline{q}_i^*\right)\right\} + \kappa_i c_{fi} - \overline{U}_{D_i}^{fb}\right\}, & \text{if} \quad \lambda_f^* < 1 \end{cases}.$$

5. Numerical and sensitivity analysis

Based on the real characteristics of IBWT project, an IBWT supply chain with one IBWT supplier and six water distributors is developed for the numerical analysis of the IBWT supply chain models developed and analyzed in Section 4. Since there are six water-intakes and six water distributors in the IBWT supply chain, i.e. $n = 6$. We assume that three water distributors are supplied by the local supplier (i.e. $m = 3$) and three water distributors are supplied by the external supplier (i.e. n–$m = 3$). The random precipitation x_i obeys normal distribution, i.e. $x_i \sim N(\mu_i, \sigma_i^2)$. A is set at 0 and B is set at 1.0E + 10. The local supplier's bargaining power τ is 0.6. The precipitation utilization factor ϑ is 0.01. The water delivery loss from the (i–1)th water-intake to the ith water-intake within the horizontal green supply chain δ_i is 5 percent. The fixed cost of water delivery for the ith water-intake of the IBWT supplier c_{fi} is 20,000. The ith distributor's coefficient of fairness concern κ_i is 0.8. To simplify the analysis, the supply capacity $\overline{Q}$ is set as 1,500,000,000 and 1,200,000,000. Table I lists the parameters mainly relating to the IBWT supply chain and their values for the numerical analysis.

5.1 Numerical analysis

The numerical analysis assesses and compares the quantity decisions and the resulting profits for the IBWT supply chain coordination models under capacity constraint and random precipitation considering fairness concern or not. The numerical analysis results of IBWT supply chain coordination without fairness concern are shown in Table II (CNB) and Table III (CB), and the numerical analysis results of IBWT supply chain coordination with

Table I. Parameters in the IBWT supply chain for the numerical analysis

Water intake i	Mainline water transfer cost c_i	Actual water transfer cost C_i	Branch-line water transfer cost c_{di}	Retail price p_i	Holding cost h_i	Shortage cost r_i	Basic water demand d_i
1	0.25	0.26	0.05	0.94	0.05	0.42	50,000,000
2	0.30	0.59	0.06	1.96	0.12	0.95	100,000,000
3	0.35	0.99	0.07	3.19	0.20	1.59	150,000,000
4	0.40	1.47	0.08	4.64	0.29	2.35	200,000,000
5	0.45	2.02	0.09	6.32	0.40	3.23	250,000,000
6	0.50	2.65	0.10	8.25	0.53	4.24	300,000,000
Water intake i	Mean value of precipitation μ_i	Standard deviationD of precipitation σ_i		Benchmark profit $\Pi_{S_i}^b$	Benchmark profit $\Pi_{D_i}^b$	Benchmark profit $\overline{\Pi}_{S_i}^b$	Benchmark profit $\overline{\Pi}_{D_i}^b$
1	3.00E + 08	1.00E + 07		12,000,000	9,000,000	10,800,000	8,100,000
2	2.50E + 08	8.00E + 06		60,000,000	40,000,000	54,000,000	36,000,000
3	2.00E + 08	6.00E + 06		150,000,000	100,000,000	135,000,000	90,000,000
4	1.50E + 08	4.00E + 06		300,000,000	200,000,000	270,000,000	180,000,000
5	1.00E + 08	2.00E + 06		400,000,000	300,000,000	360,000,000	270,000,000
6	5.00E + 07	1.00E + 06		600,000,000	500,000,000	540,000,000	450,000,000

Table II. Numerical analysis results of IBWT supply chain coordination without fairness concern (CNB)

i	w_{ei}^c	Range of w_{ei}^c	w_i^c	q_i^c	$\Pi_{D_i}^c$	Π_S^c
1	15,000,000	[12,020,000, 20,420,988]	0.26	47,064,721	14,420,988	1,939,880,000
2	65,000,000	[60,020,000, 87,372,701]	0.59	97,552,751	62,372,701	Π_{LS}^c
3	160,000,000	[150,020,000, 214,785,202]	0.99	148,039,834	154,785,202	1,163,928,000
4	320,000,000	[300,020,000, 414,130,097]	1.47	198,526,647	294,130,097	Π_{ES}^c
5	530,000,000	[400,020,000, 749,093,822]	2.02	249,013,348	519,093,822	775,952,000
6	850,000,000	[600,020,000, 1,147,514,348]	2.65	299,506,686	797,514,348	Π_{SC}^c
Note	–	$wc = 1.24$	Total	1,039,703,988	1,842,317,157	3,782,197,157

Table III. Numerical analysis results of IBWT supply chain coordination without fairness concern (CB)

i	$\lambda^* w_{ei}^c$	Range of $\lambda^* w_{ei}^c$	w_i^c	q_i^c	$\Pi_{D_i}^c$	Π_S^c
1	13,811,165	[11,751,362, 19,028,779]	0.26	43,334,574	11,809,475	1,786,123,953
2	59,848,380	[58,669,926, 80,512,238]	0.59	89,821,140	50,282,805	Π_{LS}^c
3	147,319,089	[146,642,232, 197,054,274]	0.99	136,306,834	124,117,512	1,071,674,372
4	294,638,178	[293,262,742, 378,798,823]	1.47	182,792,280	234,138,681	Π_{ES}^c
5	487,994,482	[391,009,749, 686,858,439]	2.02	229,277,623	414,426,515	714,449,581
6	782,632,660	[586,503,763, 1,049,619,324]	2.65	275,769,076	633,798,356	Π_{SC}^c
Note	–	$wc = 1.24$	Total	957,301,526	1,468,573,345	3,254,697,297

fairness concern are shown in Table IV (CNB) and Table V (CB). The findings from the numerical analysis results are summarized below:

(1) Comparing the numerical analysis results between the CNB (Table II) and the CB (Table III) under the scenario without fairness concern: the coordinated usage prices are the same between the CNB and the CB; the entry prices in the CNB are higher than those in the CB; the actual received quantities of water resources in the CNB are higher than those in the CB; and the profits of the IBWT supply chain and its members in the CNB are higher than those in the CB.

(2) Comparing the numerical analysis results between the CNB (Table IV) and the CB (Table V) under the scenario with fairness concern: the coordinated usage prices are the same between the CNB and the CB; the entry prices in the CNB are higher than those in the CB; the actual received quantities of water resources in the CNB are higher than those in the CB; and the utilities of the IBWT supply chain and its members in the CNB are higher than those in the CB.

(3) Comparing the numerical analysis results between the scenario with fairness concern (Table IV) and the scenario without fairness concern (Table II) in the CNB: the coordinated usage prices are the same between the scenario with fairness concern and the scenario without fairness concern; the entry prices are set the same between the scenario with fairness concern and the scenario without fairness concern; the actual received quantities of water resources are the same between the scenario with fairness concern and the scenario without fairness concern; and the utilities of the IBWT supply chain and its members under the scenario with fairness concern are no more than those under the scenario without fairness concern.

(4) Comparing the numerical analysis results between the scenario with fairness concern (Table V) and the scenario without fairness concern (Table III) in the CB: the coordinated usage prices are the same between the scenario with fairness concern and the scenario without fairness concern; the entry prices are set the same between

Table IV. Numerical analysis results of IBWT Supply chain coordination with fairness concern (CNB)

i	w_{ei}^{fc}	Range of w_{ei}^{fc}	w_i^{fc}	q_i^{fc}	$U_{D_i}^{fc}$	U_S^{fc}
1	15,000,000	[12,020,000, 17,836,068]	0.26	47,064,721	13,973,778	1,939,880,000
2	65,000,000	[60,020,000, 78,956,485]	0.59	97,552,751	60,286,861	U_{LS}^{fc}
3	160,000,000	[150,020,000, 194,857,447]	0.99	148,039,834	150,629,363	1,163,928,000
4	320,000,000	[300,020,000, 379,019,298]	1.47	198,526,647	273,450,175	U_{ES}^{fc}
5	530,000,000	[400,020,000, 641,686,492]	2.02	249,013,348	510,384,880	775,952,000
6	850,000,000	[600,020,000, 979,054,548]	2.65	299,506,686	755,541,826	U_{SC}^{fc}
Note	–	$w_c^f = 1.24$	Total	1,039,703,988	1,764,266,882	3,704,146,882

Table V. Numerical analysis results of IBWT supply chain coordination with fairness concern (CB)

i	$\lambda_f^* w_{ei}^{fc}$	Range of $\lambda_f^* w_{ei}^{fc}$	w_i^{fc}	q_i^{fc}	$U_{D_i}^{fc}$	U_S^{fc}
1	13,811,165	[11,751,362, 16,789,574]	0.26	43,334,574	10,224,124	1,786,123,953
2	59,848,380	[58,669,926, 73,791,526]	0.59	89,821,140	42,646,345	U_{LS}^{fc}
3	147,319,089	[146,642,232, 181,542,877]	0.99	136,306,834	105,572,251	1,071,674,372
4	294,638,178	[293,262,742, 352,480,029]	1.47	182,792,280	185,755,084	U_{ES}^{fc}
5	487,994,482	[391,009,749, 595,828,073]	2.02	229,277,623	355,588,141	714,449,581
6	782,632,660	[586,503,763, 907,122,229]	2.65	275,769,076	514,746,913	U_{SC}^{fc}
Note	–	$w_c^f = 1.24$	Total	957,301,526	1,214,532,858	3,000,656,811

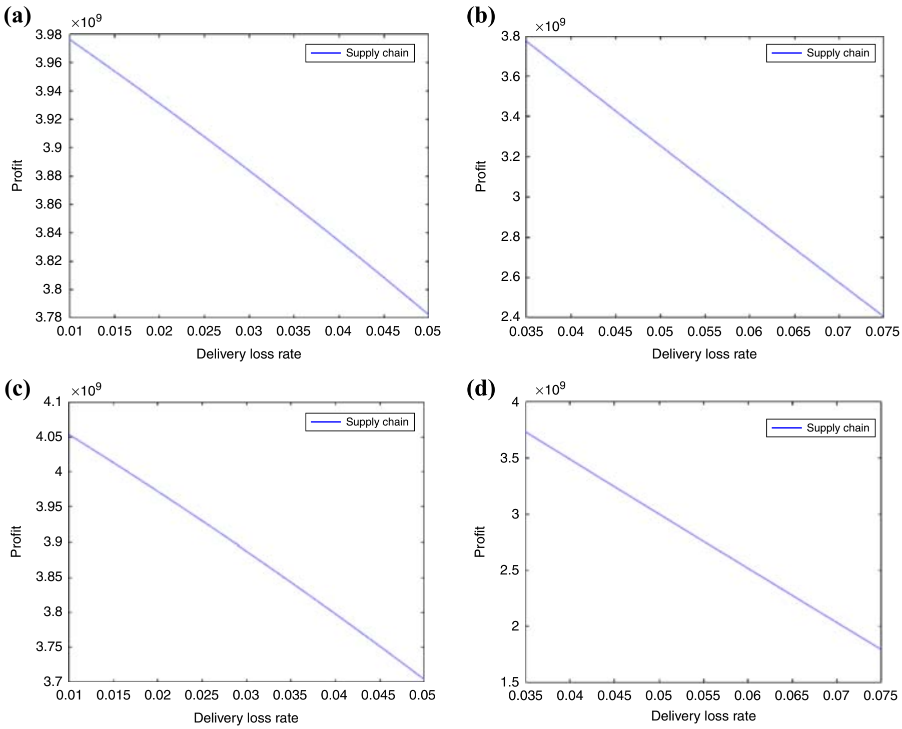
the scenario with fairness concern and the scenario without fairness concern; the actual received quantities of water resources are the same between the scenario with fairness concern and the scenario without fairness concern; and the utilities of the IBWT supply chain and its members under the scenario with fairness concern are no more than those under the scenario without fairness concern.

5.2 Sensitivity analysis

The sensitivity analysis assesses and compares the impacts of the changes of the water delivery loss rate, precipitation utilization factor, retail price, mainline transfer cost, branch-line transfer cost, holding cost, shortage cost and coefficient of fairness concern for the IBWT supply chain coordination models under the capacity constraints considering fairness concern or not.

To capture the impact of the change of key parameters, we only select the parameters from the 1st distributor and the 1st water intake to conduct sensitivity analysis, including: the retail price, the mainline transfer cost, the branch-line transfer cost, the holding cost and the shortage cost. The findings from the sensitivity analysis results are summarized below:

(1) The sensitivity analysis results of the water delivery loss rate for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 2. The results show that: no matter under the scenario without fairness concern or under the scenario with fairness concern, no



Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

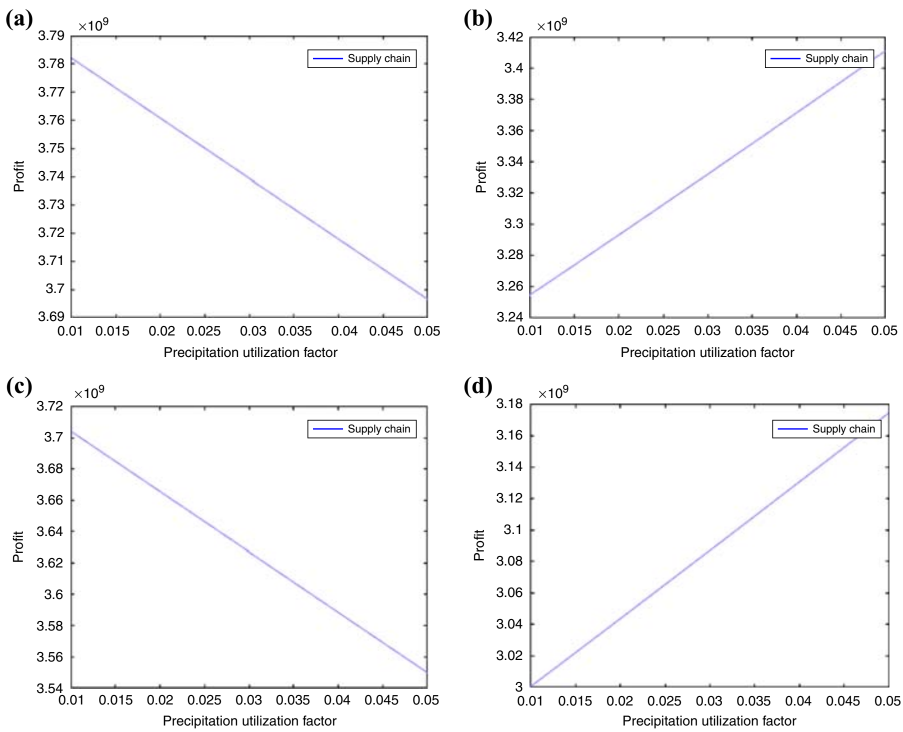
Figure 2.
The impact of water delivery loss rate change on the profit of IBWT supply chain without/with fairness concern (FC)

matter in the CNB or in the CB, the profit (or utility) of IBWT supply chain decreases as the water delivery loss rate increases.

(2) The sensitivity analysis results of the precipitation utilization factor for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 3. The results show that: in the CNB, no matter under the scenario without fairness concern or under the scenario with fairness concern, the profit (or utility) of IBWT supply chain decreases as the precipitation utilization factor increases; in the CB, no matter under the scenario without fairness concern or under the scenario with fairness concern, the profit (or utility) of IBWT supply chain increases as the precipitation utilization factor increases.

(3) The sensitivity analysis results of the retail price for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 4. The results show that: no matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB or in the CB, the profit (or utility) of IBWT supply chain increases as the retail price increases.

(4) The sensitivity analysis results of the mainline transfer cost for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 5. The results show that: no matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB or in the CB, the profit (or utility) of IBWT supply chain decreases as the mainline transfer cost increases.



Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

Figure 3. The impact of precipitation utilization factor change on the profit of IBWT supply chain without/with fairness concern (FC)

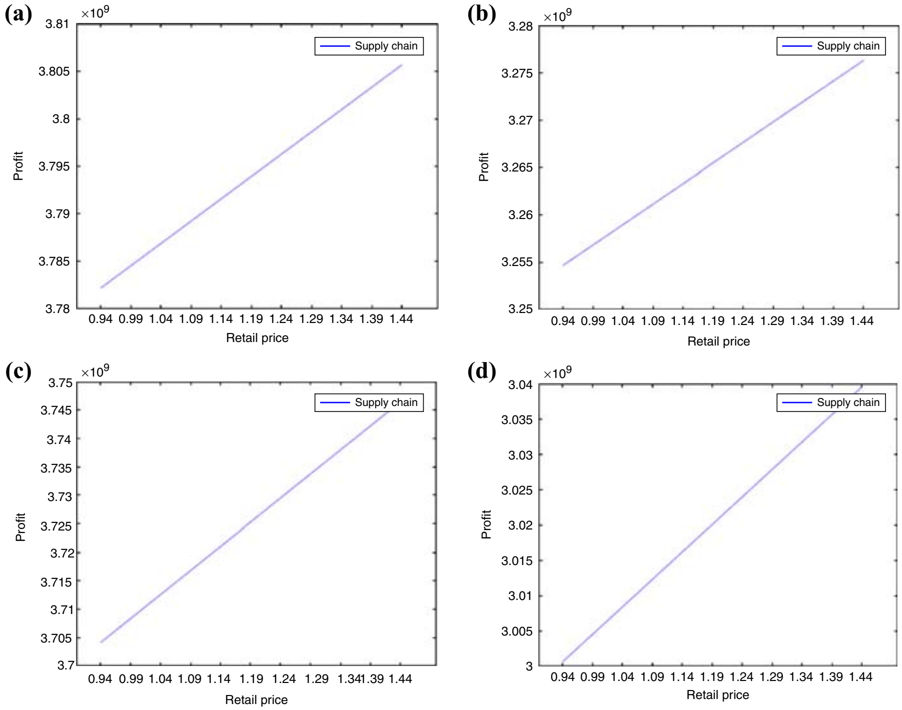


Figure 4.
The impact of retail price change on the profit of IBWT supply chain without/with fairness concern (FC)

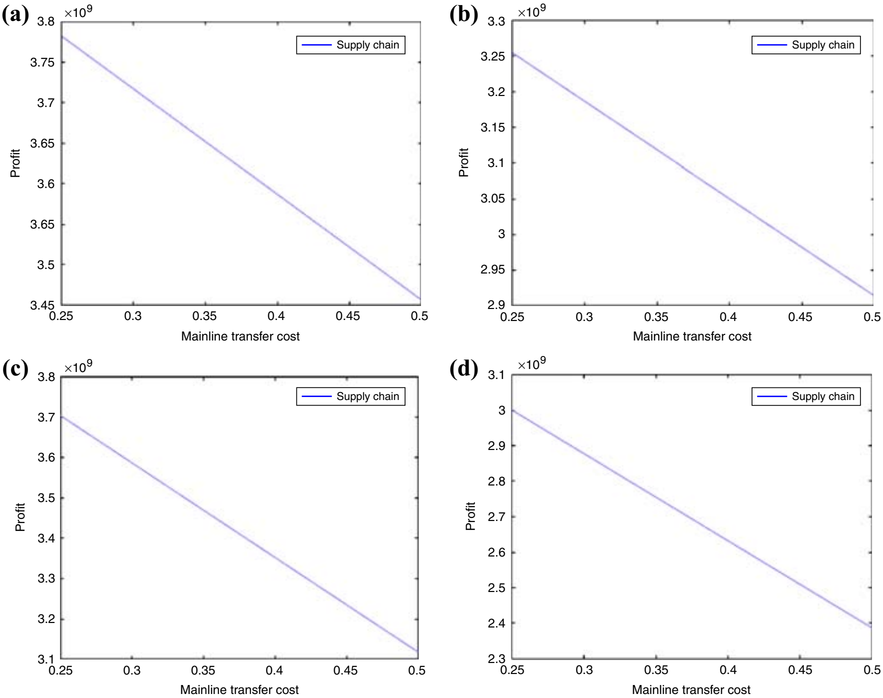
Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

(5) The sensitivity analysis results of the branch-line transfer cost for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 6. The results show that: no matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB,or in the CB, the profit (or utility) of IBWT supply chain decreases as the branch-line transfer cost increases.

(6) The sensitivity analysis results of the holding cost for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 7. The results show that: no matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB or in the CB, the profit (or utility) of IBWT supply chain decreases as the holding cost increases.

(7) The sensitivity analysis results of the shortage cost for the IBWT supply chain coordination decision under the supply capacity constraints without/with fairness concern are shown in Figure 8. The results show that: no matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB or in the CB, the profit (or utility) of IBWT supply chain decreases as the shortage cost increases.

(8) The sensitivity analysis results of the coefficient of fairness concern for the IBWT supply chain coordination decision under the supply capacity constraints with



Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

Figure 5.
The impact of mainline transfer cost change on the profit of IBWT supply chain without/with fairness concern (FC)

fairness concern are shown in Figure 9. The results show that: no matter in the CNB or in the CB, the utility of IBWT supply chain decreases as the coefficient of fairness concern increases.

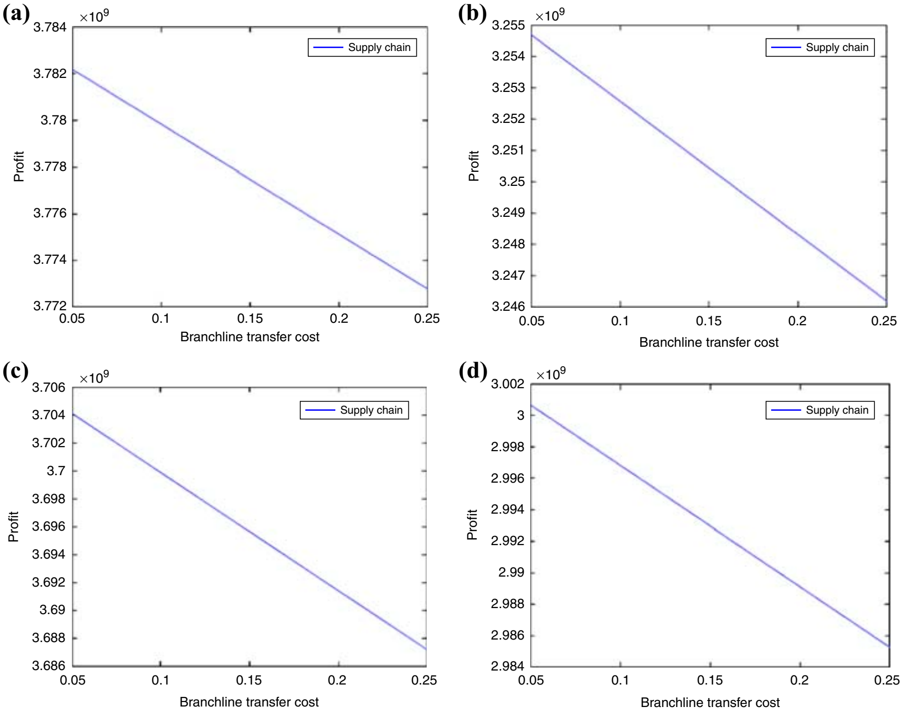
6. Managerial insights and policy implications

Based on the modeling and numerical analytical results of Sections 4 and 5, the corresponding management insights and policy implications can be summarized as follows:

(1) No matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB (case with non-binding capacity constraint) or in the CB (case with binding capacity constraint), the two-part tariff contract could effectively coordinate the IBWT supply chain and achieve operational performance improvement.

(2) No matter under the scenario without fairness concern or under the scenario with fairness concern, the actual received quantity in the CB is lower than CNB, and so do the profits of the IBWT supply chain and its members. Thus, once the total order quantity touch upon the supply capacity constraint, the received quantities are allocated by the IBWT supplier according to the overall order fulfillment ratio, and the profits of all the stakeholders are also restricted.

(3) No matter in the CNB or in the CB, owing to the existence of inequity aversion, the IBWT distributors suffer from negative utilities of inequity aversion, the IBWT



Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

Figure 6.
The impact of branch-line transfer cost change on the profit of IBWT supply chain without/with fairness concern (FC)

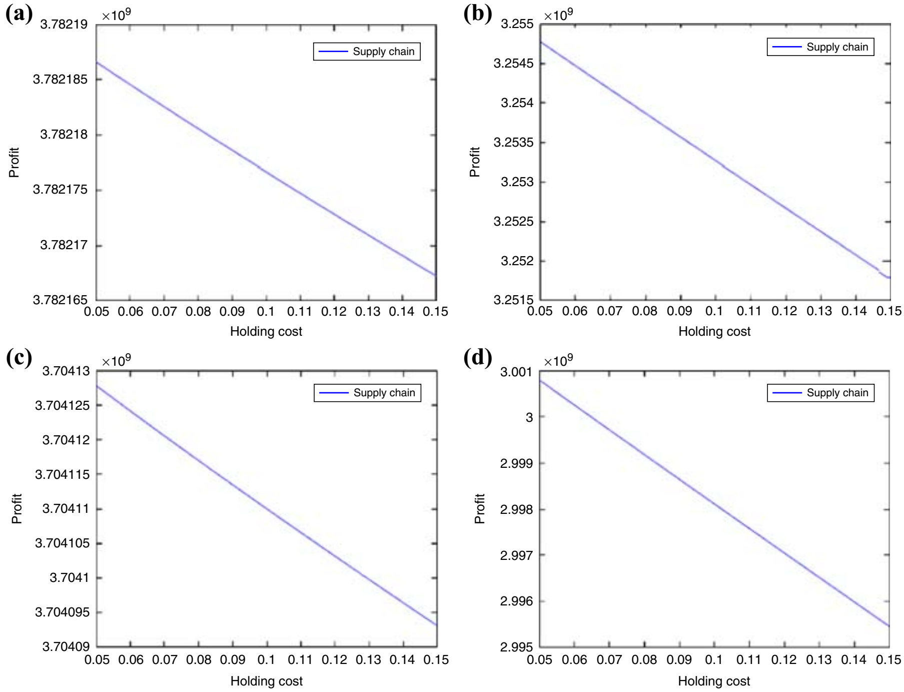
supply chain and its members could gain less utilities under the scenario with fairness concern than those under the scenario without fairness concern.

(4) No matter under the scenario without fairness concern or under the scenario with fairness concern, no matter in the CNB or in the CB, reducing the water delivery loss rate, the mainline transfer cost, the branch-line transfer cost, the holding cost and the shortage cost are beneficial for improving the profit/utility of the IBWT supply chain. Setting a higher retail price is beneficial for improving the profit/utility of the IBWT supply chain.

(5) No matter under the scenario without fairness concern or under the scenario with fairness concern, a lower precipitation utilization factor in the CNB is beneficial for improving the profit/utility of the IBWT supply chain while a higher precipitation utilization factor in the CB is beneficial for improving the profit/utility of the IBWT supply chain.

(6) No matter in the CNB or in the CB, a lower coefficient of fairness concern (inequity aversion) is beneficial for improving the utility of the IBWT supply chain under the scenario with fairness concern.

In sum, the government should make fair shortage allocation rule for the IBWT supply chain, set suitable retail prices of water resources to promote consumer's water saving and guarantee a certain profit of IBWT supply chain and encourage improving the precipitation utilization to reduce unnecessary water transfer and waste. The decision maker of the IBWT supply chain should design a suitable water supply capacity to avoid the shortage of



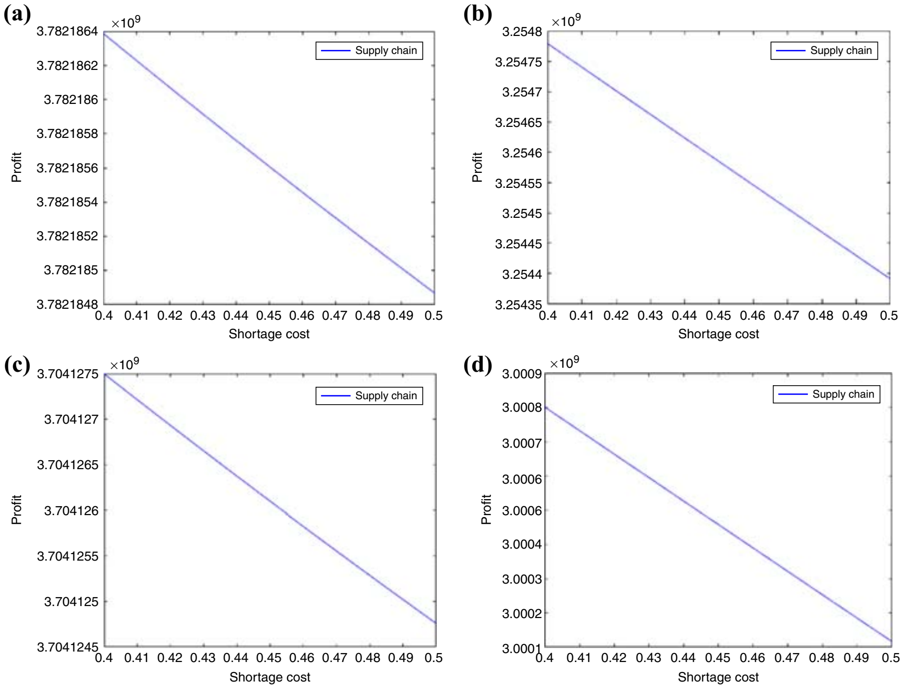
Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

Figure 7. The impact of holding cost change on the profit of IBWT supply chain without/with fairness concern (FC)

necessary water demand to reduce total water shortage cost and improve the operational performance. Besides, the IBWT supply chain should make a lot effort to reduce the water delivery loss rate, the mainline and branch-line transfer cost, holding cost and shortage cost and inequity aversion to improve the operational performance. Finally, two-part tariff contract is recommended to coordinate the IBWT supply chain and improve the operational performance under the capacity constraint.

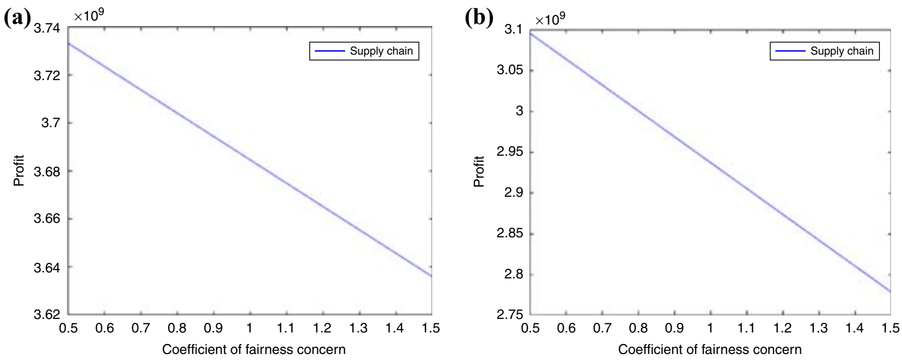
7. Conclusion

In the operations management of IBWT project, the supply capacity constraint, the water delivery loss and the fairness concern have important impacts on the operations decision and operational efficiency of the IBWT project under the random precipitation. From a supply chain perspective, this paper tries to explore the issues of the operations management mechanism of IBWT project considering the water delivery loss without/with fairness concern under the supply capacity constraint and random precipitation. The IBWT distribution system is defined as an IBWT supply chain system first; and then a fair shortage allocation rule is made by the government; on this basis, the IBWT supply chain coordination models considering water delivery loss without/with fairness concern under the supply capacity constraint and random precipitation are developed, analyzed and compared through the game-theoretic and coordination research approaches, and the corresponding numerical and sensitivity analysis for all models is conducted and compared; finally, the corresponding management insights and policy implications are summarized in this paper. The research results indicate that: the two-part tariff contract could effectively coordinate the IBWT supply chain and achieve operational performance improvement;



Notes: (a) CNB without FC; (b) CB without FC; (c) CNB with FC; (d) CB with FC

Figure 8.
The impact of shortage cost change on the profit of IBWT supply chain without/with fairness concern (FC)



Notes: (a) CNB with FC; (b) CB with FC

Figure 9.
The impact of coefficient of fairness concern change on the profit of IBWT supply chain with fairness concern (FC)

the binding supply capacity constraint makes the water capacity to be allocated among IBWT distributors in accordance with fair shortage allocation rule and reduces the profit (or utility) of the IBWT supply chain and its members; the existence of fairness concern reduces the utility of the IBWT supply chain and its members; a lower precipitation utilization factor in CNB is beneficial for improving the profit/utility of the IBWT supply chain while a higher precipitation utilization factor in CB is beneficial for improving the profit/utility of the IBWT supply chain; and reducing the water delivery loss rate, the mainline transfer cost, the branch-line transfer cost, the holding cost and the shortage cost and setting a higher retail price are beneficial for improving the profit/utility of the IBWT supply chain.

In the theoretical modeling, based on the theories and methods of Nash bargaining game and two-part tariff contract, the coordination decision models considering water delivery loss without/with fairness concern under the capacity constraint and random precipitation are developed, analyzed and compared for the IBWT supply chain, respectively, which have enhanced the optimization decision theory for the operations management of IBWT projects. In practice, the modeling and corresponding numerical analysis results provide a better decision support to the governments to make appropriate shortage allocation regulations and the IBWT stakeholders to make better operations strategies.

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