Inter-basin water transfer green supply chain coordination with partial backlogging under random precipitation

Zhisong Chen and Huimin Wang

ABSTRACT

Water demand backlogging and delivery loss have important impacts on the operational decisions and efficiency of the inter-basin water transfer (IBWT) green supply chain. This paper formulates, analyzes, and compares three IBWT green supply chain coordination decision models considering water delivery loss with lost sales, fully backlogging and partial backlogging under random precipitation, conducts the corresponding numerical and sensitivity analyses, and summarizes the corresponding managerial insights and policy implications. The research results show that: first, a two-part tariff contract can effectively coordinate the IBWT green supply chain and improve operational performance; second, the fully/partial backlogging strategy can effectively improve the operational performance of the IBWT green supply chain; third, fully backlogging is the first-best strategy and partial backlogging is the second-best strategy for the IBWT green supply chain.

Key words | fully backlogging, green supply chain, inter-basin water transfer (IBWT), lost sales, partial backlogging, two-part tariff

Zhisong Chen (corresponding author)
Business School,
Nanjing Normal University,
No. 1 Wenyuan Road, Qixia District, Nanjing
  210023, Jiangsu,
China
E-mail: zhisongchen@gmail.com

Huimin Wang
College of Management and Economics,
Tianjin University,
No. 92 Weijin Road, Nankai District, Tianjin 300072,
China

INTRODUCTION

In the context of climate change, the spatial and temporal distribution of water resources is becoming increasingly uneven. With the development of social economy, the shortage of water resources is becoming more and more serious. Thus, many large-scale IBWT projects have been built and operated in major river basins around the world to alleviate the contradiction of water shortage in the water-scarce regions, such as the Central Valley Project in the United States (Yang 2003; SWP 2017) and the South-to-North Water Diversion (SNWD) Project in China (Wang et al. 2009).

Owing to the random precipitation, the water demand may exceed the order quantity, bringing about holding costs of extra water resources, or the water order quantity may exceed the water demand, resulting in shortage costs of unmet water demand. Thus, the backlogging of water demand is adopted to reduce the shortage cost in the operations management of the IBWT project. However, owing to the existence of supply capacity constraint in the IBWT project, these unmet water demands may be partially backlogged. Obviously, this partial backlogging behavior of water demand has an important impact on the operational decision and operational performance of IBWT projects. As well, water greenness issues (including inefficient use and waste of water resources, water environmental pollution, and unstable water quality) are urgent problems that need to be solved in the operations management of IBWT projects. Furthermore, there are multiple operating entities (including local supplier, external supplier, and multiple distributors) in the IBWT project, and how to effectively coordinate multiple entities to achieve operational performance improvement is also an urgent problem for IBWT projects. Finally, the water

delivery loss in the water transferring process has an important impact on the operational decisions and operational efficiency of the IBWT project, and should be considered in the operations management of the IBWT projects.

Due to the advantage of considering both the collective rationality and individual rationality simultaneously and considering the operational performance, resource efficiency, and environmental impact, the green supply chain management theory provides an appropriate perspective for solving the above problems and has been applied in the operations management of IBWT projects to investigate the interactions among the multiple stakeholders and develop cooperative/coordination operation mechanisms (Chen & Pei 2018). However, the interactions among the multiple stakeholders and operations management mechanisms in an IBWT green supply chain with partial backlogging under the random precipitation are rarely investigated in the current literature and practices.

Therefore, this paper will try to explore the issue of IBWT green supply chain coordination with partial backlogging under random precipitation. In the following sections, the corresponding literature is reviewed first; then, the theoretical modeling notation and assumptions for a generic IBWT green supply chain are defined; next, the IBWT green supply chain coordination models considering water delivery loss with lost sales, fully backlogging and partial backlogging under random precipitation are developed and analyzed; afterwards, the corresponding numerical and sensitivity analyses for all models are conducted and compared, and the managerial insights and policy implications are then discussed and summarized; and finally, the research contributions and foresights are summarized and concluded.

LITERATURE REVIEW

Currently, the interaction relationships among multiple stakeholders in the IBWT projects are investigated through game theory, such as water conflict game-theoretical model of the SNWD project (Wei et al. 2010), game-theoretical model of the IBWT project considering both the water quantity and water quality (Manshadi et al. 2015), water-allocation option contract for the IBWT projects (Rey et al. 2016), and incentive-compatible payments design for the SNWD project (Sheng & Webber 2017).

As well, cooperative game theory is applied to achieve Pareto improvement in IBWT projects, such as crisp and fuzzy Shapley game model for IBWT water allocation (Sadegh et al. 2010), cooperative game model for IBWT water allocation (Nikoo et al. 2012), IBWT water resources allocation using least core game (Jafarzadegan et al. 2013), and robust multi-objective bargaining game model for the IBWT water resource allocation (Nasiri-Gheidari et al. 2018).

Currently, theories and techniques of supply chain management (SCM) have been applied in IBWT projects to investigate the interactions among multiple stakeholders and develop equilibrium/coordination operational mechanisms, such as: stochastic decision and simulation of quantity and price for the IBWT supply chain (Ballestero 2004); optimal pricing and coordination schemes for the SNWD supply chain (Wang et al. 2012); coordination mechanism based on revenue-sharing contract for the SNWD supply chain with strategic customers (Chen & Wang 2012a); asymmetric Nash bargaining model for the SNWD supply chain (Chen & Wang 2012b); two-echelon water inventory model with inflow forecasting updates in an IBWT project (Xu et al. 2012); two-tier pricing and allocation schemes for the SNWD supply chain (Chen et al. 2013); competition intensity in the water supply chain under two contracts (Du et al. 2016); two-regime differential game model for two countries' cooperation in the water transfer project (Cabo & Tidball 2017); power structures for competitive water supply chains (Du et al. 2018); optimal pricing and ordering strategies for dual competing water supply chains under three contracts (Du et al. 2019); subsidy policies and operational strategies for the IBWT green supply chain under social welfare maximization (Chen & Pei 2018); and, subsidy policies and operational strategies for the IBWT supply chain under social welfare maximization (Chen et al. 2019).

Nevertheless, the existing literatures rarely touch upon the following critical factors in the operations management of IBWT projects from the perspective of green supply chain management: (1) the impact of partial backlogging behavior of water demand on the operational decisions and performance of IBWT projects; (2) the impact of water greenness (water green level) on the operational decisions and performance of IBWT projects; (3) the coordination strategies for the IBWT project with partial backlogging considering

water greenness; and, (4) the impact of water delivery loss on the operational decisions and performance of IBWT projects. In the face of these research shortcomings identified in the existing literatures, from the perspective of green supply chain management, coordination decision models under three scenarios (including lost sales/fully backlogging/partial backlogging) considering random precipitation and delivery loss will be developed, analyzed, and compared to explore the optimal operational strategies for the IBWT green supply chain and the optimal pricing regulation policy for the government.

THEORETICAL MODELING NOTATION AND ASSUMPTIONS

An IBWT supply chain system is a typical 'embedded' supply chain structure. In this system, a horizontal water supply system is embedded in a vertical water distribution system (see Figure 1).

The horizontal water supply system comprises a local supplier and an external supplier, and they serve as a joint IBWT supplier via an efficient cooperation mechanism. 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, 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 canals. Finally, water resources are sold by each distributor to water consumers in their service region. What needs to be noted is that 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. Furthermore, once the water demand outweighs its supply, the unfulfilled demand will be fully or partially backlogged. Backlogging is the water demand that cannot be fulfilled at the current time due to a lack of available supply, and the water may not be held in the IBWT system's available inventory but could still be transferring, or the IBWT supplier and distributors may need to still transfer more water. Fully backlogging means that all the unfulfilled water demand will be fully satisfied in the supplementary transferring period, and partial backlogging means that part of the unfilled water demand will be fulfilled in the supplementary transferring period.
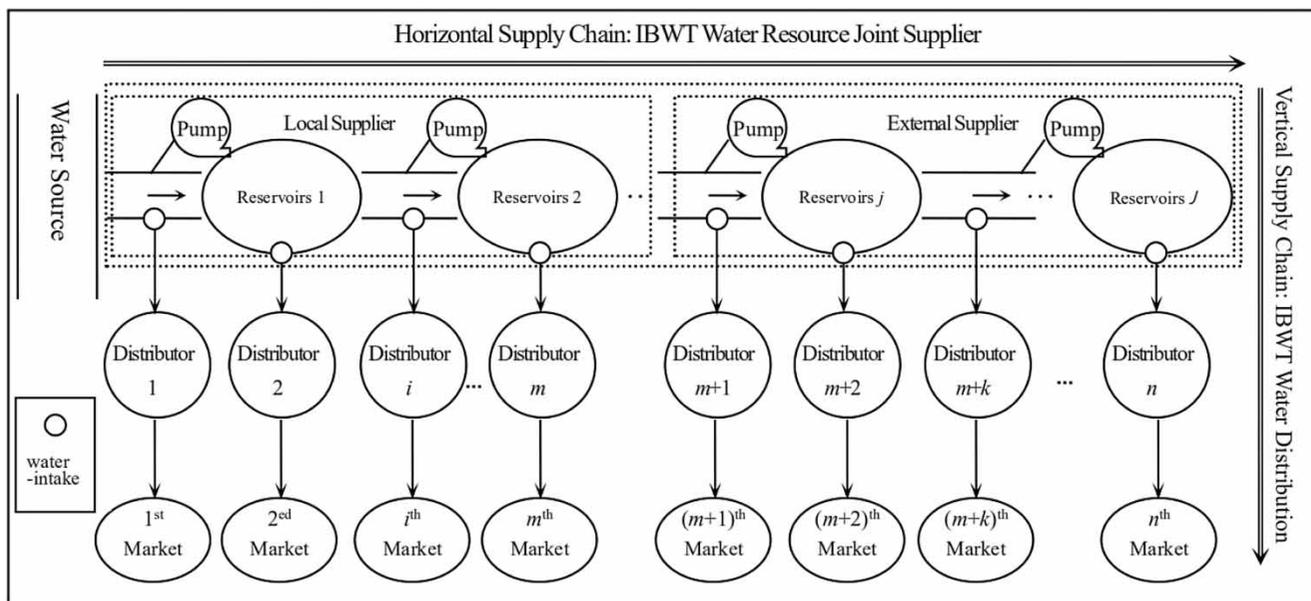

Figure 1 | A generic inter-basin water transfer supply chain system.

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 water transfer cost from the ith water-intake to the ith distributor is c_{di}, the water transfer cost from the $(k-1)^{\text{th}}$ water-intake to the kth water-intake within the horizontal green supply chain is c_k, and the water delivery loss from the $(k-1)^{\text{th}}$ water-intake to the kth water-intake within the horizontal green supply chain is δ_k, $k = 1, 2, \ldots, n$. The ordering quantity of the ith water-intake (the water demand for the ith water distributor) 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 original pumping quantity Q_i is $q_i = Q_i \prod_{k=1}^{i} (1 - \delta_k)$, and the total transfer cost of the original pumping quantity Q_i is $TC_i(Q_i) = Q_i \sum_{k=1}^{i} \left[c_k \prod_{j=0}^{k-1} (1 - \delta_j) \right]$, hereinto, $\delta_0 = 0$. Therefore, the total transfer cost of the water demand (ordering quantity) of the ith water-intake is $TC_i(q_i) = \dfrac{\sum_{k=1}^{i} \left[c_k \prod_{j=0}^{k-1} (1 - \delta_j) \right]}{\prod_{k=1}^{i} (1 - \delta_k)} q_i$. Define

$C_i = \dfrac{\sum_{k=1}^{i} \left[c_k \prod_{j=0}^{k-1} (1 - \delta_j) \right]}{\prod_{k=1}^{i} (1 - \delta_k)}$, then $TC_i(q_i) = C_i q_i$. The fixed cost for the local supplier is c_{fl}, and the fixed cost for the external supplier is c_{fe}, then the fixed cost for the IBWT supplier is $c_f = c_{fl} + c_{fe}$. 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 sell water resources to the consumers in his service region with a retail price p_i.

According to the current literature regarding green supply chain, the definitions of eco-friendly (Liu *et al.* 2012), green level (Basiri & Heydari 2017), energy saving (Dai *et al.* 2017), and greenness index (Zhu & He 2017) are defined and decided within the framework of green supply chain management. Following their research thinking, we can define water green level (can be abbreviated to WGL) as the comprehensive green level of water quality, water

resources efficiency, and water environment impact in IBWT projects. The WGL improvement is g_i. The investment cost of WGL improvement for the IBWT supplier's i^{th} water-intake is $c_i(g_i)$, and $c_i(g_i) = \dfrac{1}{2} k g_i^2$, where k represents the investment cost factor related to WGL improvement for the IBWT supplier (Liu *et al.* 2012; Basiri & Heydari 2017; Dai *et al.* 2017). The water demand for the ith water distributor is $d_i(g_i, x_i) = a_i + \theta g_i - \vartheta x_i$, a_i is the basic water demand, θ is the WGL improvement coefficient of 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 $B > A \geq 0$, and x_i is a random variable with the CDF (cumulative distribution function) $F_i(\cdot)$ and PDF (probability density function) $f_i(\cdot)$, and the mean value and the 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 bargaining power of the local supplier is τ, and the bargaining power of the external supplier is $1 - \tau$, and $\tau \in (0, 1)$. The ratio of backlogging in unmet water demand for the ith distributor is κ_i, and $\kappa_i \in [0, 1]$. The benchmark profit of the IBWT supplier's i^{th} water-intake is $\bar{\Pi}_{S_i}^o$, $\bar{\Pi}_{S_i}^b$, $\bar{\Pi}_{S_i}^p$ under a scenario with lost sales, with fully backlogging, and with partial backlogging, respectively, while the benchmark profit of the ith distributor is $\bar{\Pi}_{D_i}^o$, $\bar{\Pi}_{D_i}^b$, $\bar{\Pi}_{D_i}^p$ under a scenario with lost sales, with fully backlogging, and with partial backlogging, respectively.

IBWT GREEN SUPPLY CHAIN COORDINATION DECISION MODELS WITH PARTIAL BACKLOGGING

Based on modeling notations and assumptions shown earlier, three game-theoretical coordination models of the IBWT green supply chain are developed, analyzed, and compared in this section. Specifically, sections present the IBWT green supply chain coordination decision model with partial backlogging, then the IBWT green supply chain coordination decision model with lost sales (i.e., without backlogging) or fully backlogging for comparison purpose.

It should be noted that the scenario with lost sales or fully backlogging are special cases of the scenario with partial backlogging. When the ratio of backlogging $\kappa_i \in (0, 1)$, it

is under the scenario with partial backlogging. When the ratio of backlogging $\kappa_i = 0$, it is under the scenario with lost sales. When the ratio of backlogging $\kappa_i = 1$, it is under the scenario with fully backlogging.

In the models to follow, note that the superscript or subscript c represents a centralized decision and coordination decision; the superscript or subscript d represents a decentralized decision; the superscript or subscript o represents the scenario with lost sales (i.e., without backlogging); the superscript or subscript b represents the scenario with fully backlogging; and, the superscript or subscript p represents the scenario with partial backlogging.

IBWT green supply chain coordination decision model with partial backlogging

Under the scenario with partial backlogging, the ratio of backlogging in unmet water demand for the ith distributor is κ_i, and $\kappa_i \in (0, 1)$. The detailed decision sequences are as follows: the local supplier and the external supplier will first bargain over the wholesale price w to achieve cooperative operations within IBWT horizontal supply chain; then, the IBWT supplier offers the distributors a two-part tariff contract: the IBWT supplier will make the water usage prices w_i at the actual transfer cost C_i and charge the ith water distributor an entry price w_{ei} in return, and the water distributors will make their retail prices p_i in accordance with the centralized pricing decision.

IBWT green supply chain centralized decision with partial backlogging

The optimal problem for the centralized IBWT green supply chain with partial backlogging can be formulated as follows:

$$\max_{q_i, g_i} \Pi_{SC}^p(q_i, g_i)$$

$$= \sum_{i=1}^n \left\{ \begin{array}{l} p_i E[\min\{q_i, d_i(g_i, x_i)\}] - h_i E[q_i - d_i(g_i, x_i)]^+ \\ + \{\kappa_i[p_i - (C_i + c_{di})] - r_i\}E[d_i(g_i, x_i) - q_i]^+ \\ - (C_i + c_{di})q_i - \frac{1}{2}kg_i^2 - c_{fi} \end{array} \right\} \tag{1}$$

Solving the first-order condition and the Hessian matrix of the optimal problem w.r.t. the order quantity of the water

resources q_i and WGL improvement g_i, we can obtain the optimal order quantity of the water resources and WGL improvement for the ith water-intake as follows:

$$q_i^{pc} = a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]$$
$$- \vartheta F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i}\right] \tag{2}$$

$$g_i^{pc} = \frac{\theta}{k}[p_i - (C_i + c_{di})] \tag{3}$$

Plugging the optimal order quantity of the water resources and WGL improvement into the profit function of the IBWT green supply chain, we can obtain the optimal profit of the IBWT green supply chain under partial backlogging as follows:

$$\Pi_{SC}^{pc} = \sum_{i=1}^n \left\{ [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 \right.$$
$$\left. - \Lambda_i^p\left\{F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i}\right]\right\} - c_{fi} \right\} \tag{4}$$

Here into,

$$\Lambda_i^p(z_i) = (p_i + h_i)\vartheta \int_A^B x_i f_i(x_i)dx_i$$
$$- [(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i]\vartheta \int_A^{z_i} x_i f_i(x_i)dx_i$$

IBWT vertical green supply chain coordination decision with partial backlogging

In the IBWT vertical green 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}^{pc} to the IBWT supplier, which is determined by the negotiation between the IBWT supplier and distributors. Under the two-part tariff contract, the profit functions of the ith distributor, the IBWT supplier, the local supplier, and the external supplier are formulated as follows:

$$\Pi_{D_i}^p(q_i) = p_i E[\min\{q_i, d_i(g_i, x_i)\}] - h_i E[q_i - d_i(g_i, x_i)]^+$$
$$+ \{\kappa_i[p_i - (w_i + c_{di})] - r_i\}E[d_i(g_i, x_i) - q_i]^+ - (w_i + c_{di})q_i - w_{ei}^{pc} \tag{5}$$

$$\Pi_S^p(w_i, g_i) = \sum_{i=1}^n \Pi_{S_i}^p(w_i, g_i) = \sum_{i=1}^n$$

$$\left\{ (w_i - C_i)q_i + \kappa_i(w_i - C_i)E[d_i(g_i, x_i) - q_i]^+ - \frac{1}{2}kg_i^2 + w_{ei}^{pc} - c_{fi} \right\} \tag{6}$$

$$\Pi_{LS}^p(w) = \sum_{i=1}^m \left\{ (w_i - C_i)q_i + \kappa_i(w_i - C_i)E[d_i(g_i, x_i) - q_i]^+ \right.$$
$$\left. - \frac{1}{2}kg_i^2 + w_{ei}^{pc} - c_{fi} \right\} + w\sum_{i=m+1}^n q_i \tag{7}$$

$$\Pi_{ES}^p(w) = \sum_{i=m+1}^n \left\{ (w_i - C_i)q_i + \kappa_i(w_i - C_i)E[d_i(g_i, x_i) - q_i]^+ \right.$$
$$\left. - \frac{1}{2}kg_i^2 + w_{ei}^{pc} - c_{fi} \right\} - w\sum_{i=m+1}^n q_i \tag{8}$$

Solving the first-order condition and the second-order derivative of the ith distributor's optimal problem w.r.t. the order quantity q_i, respectively, we can obtain the reaction function of the order quantity q_i w.r.t. the water usage price w_i and WGL improvement g_i under the two-part tariff contract as follows:

$$q_i^{pd}(g_i, w_i) = a_i + \theta g_i$$
$$- \vartheta F_i^{-1}\left[\frac{w_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(w_i + c_{di}) + r_i + h_i} \right] \tag{9}$$

Plugging $g_i^{pc} = \frac{\theta}{k}[p_i - (C_i + c_{di})]$ into $q_i^{pd}(g_i, w_i)$, then we can get

$$q_i^{pd}(w_i) = a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]$$
$$- \vartheta F_i^{-1}\left[\frac{w_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(w_i + c_{di}) + r_i + h_i} \right] \tag{10}$$

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

$$w_i^{pc} = C_i \tag{11}$$

Plugging w_i^{pc} into the profit functions of the IBWT supplier and the ith distributor, we can get $\Pi_S^{pc}(w_{e1}, \ldots, w_{en})$

$$= \sum_{i=1}^n \Pi_{S_i}^{pc}(w_{ei}) = \sum_{i=1}^n \left\{ w_{ei} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\}$$

and $\quad \Pi_{D_i}^{pc}(w_{ei}) = [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]^2$

$$- \Lambda_i^p\left\{ F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i} \right] \right\} - w_{ei}.$$

Remark 1: Only when the following conditions hold: $\Pi_{S_i}^{pc}(w_{ei}) \geq \bar{\Pi}_{S_i}^p$, $\Pi_{D_i}^{pc}(w_{ei}) \geq \bar{\Pi}_{D_i}^p$, the IBWT green supply chain members would have the economic motivation to coordinate; that is, the reasonable interval of the entry price is: $w_{ei}^{pc} \in [\underline{w_{ei}^{pc}}, \overline{w_{ei}^{pc}}]$, $i = 1, 2, \ldots, n$.

Hereinto, $\quad \underline{w_{ei}^{pc}} = \bar{\Pi}_{S_i}^p + \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 + c_{fi},$

$$\overline{w_{ei}^{pc}} = [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]^2$$
$$- \Lambda_i^p\left\{ F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i} \right] \right\} - \bar{\Pi}_{D_i}^p.$$

IBWT horizontal green supply chain cooperation decision with partial backlogging

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

$$\Pi_{LS}^{pc}(w) = \sum_{i=1}^m \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\}$$
$$+ w\sum_{i=m+1}^n q_i^{pc} \tag{12}$$

$$\Pi_{ES}^{pc}(w) = \sum_{i=m+1}^n \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\}$$
$$- w\sum_{i=m+1}^n q_i^{pc} \tag{13}$$

According to the Nash bargaining theory (Nash 1950; Kalai & 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:

$$\max_w \quad \theta(w) = [\Pi_{LS}^{pc}(w)]^\tau [\Pi_{ES}^{pc}(w)]^{1-\tau}$$
$$s.t. \quad \Pi_{LS}^{pc}(w) + \Pi_{ES}^{pc}(w) = \Pi_S^{pc} \tag{14}$$

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_{pc} as follows:

$$w_{pc} = \frac{1}{\sum_{i=m+1}^{n} q_i^{pc}} \left\{ \tau \sum_{i=1}^{n} \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\} - \sum_{i=1}^{m} \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\} \right\} \quad (15)$$

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

$$\Pi_{D_i}^{pc} = [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^p \left\{ F_i^{-1} \left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i} \right] \right\} - w_{ei}^{pc} \quad (16)$$

$$\Pi_S^{pc} = \sum_{i=1}^{n} \Pi_{S_i}^{pc} = \sum_{i=1}^{n} \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\} \quad (17)$$

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

$$\Pi_{LS}^{pc} = \tau \Pi_S^{pc} \quad (18)$$

$$\Pi_{ES}^{pc} = (1 - \tau)\Pi_S^{pc} \quad (19)$$

The analytical modeling results of the section 'IBWT green supply chain coordination decision model with partial backlogging' are summarized in Table 1.

Table 1 │ Analytical results of IBWT supply chain coordination with partial backlogging

Scenarios	Partial backlogging
w_i^*	$w_i^{pc} = C_i$
q_i^*	$q_i^{pc} = a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})] - \vartheta F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i}\right]$
g_i^*	$g_i^{pc} = \frac{\theta}{k}[p_i - (C_i + c_{di})]$
$w*$	$w_{pc} = \frac{1}{\sum_{i=m+1}^{n} q_i^{pc}} \left\{ \tau \sum_{i=1}^{n} \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\} - \sum_{i=1}^{m} \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\} \right\}$
Π_S^*	$\Pi_S^{pc} = \sum_{i=1}^{n} \Pi_{S_i}^{pc} = \sum_{i=1}^{n} \left\{ w_{ei}^{pc} - \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi} \right\}$
Π_{LS}^*	$\Pi_{LS}^{pc} = \tau \Pi_S^{pc}$
Π_{ES}^*	$\Pi_{ES}^{pc} = (1 - \tau)\Pi_S^{pc}$
$\Pi_{D_i}^*$	$\Pi_{D_i}^{pc} = [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^p\left\{F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i}\right]\right\} - w_{ei}^{pc}$
Π_{SC}^*	$\Pi_{SC}^{pc} = \sum_{i=1}^{n} \left\{ [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^p\left\{F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i}\right]\right\} - c_{fi} \right\}$
Range of w_{ei}^*	$w_{ei}^{pc} \in [\underline{w_{ei}^{pc}}, \overline{w_{ei}^{pc}}]$
	$\underline{w_{ei}^{pc}} = \bar{\Pi}_{S_i}^p + \frac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 + c_{fi}$
Note	$\overline{w_{ei}^{pc}} = [p_i - (C_i + c_{di})]a_i + \frac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^p\left\{F_i^{-1}\left[\frac{C_i + c_{di} + h_i}{(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i}\right]\right\} - \bar{\Pi}_{D_i}^p$
	$\Lambda_i^p(z_i) = (p_i + h_i)\vartheta \int_A^B x_i f_i(x_i)dx_i - [(1 - \kappa_i)p_i + \kappa_i(C_i + c_{di}) + r_i + h_i]\vartheta \int_A^{z_i} x_i f_i(x_i)dx_i$

IBWT green supply chain coordination decision model with non-partial backlogging

In this section, the IBWT green supply chain with lost sales ($\kappa_i = 0$) or fully backlogging ($\kappa_i = 1$) will be modeled and analyzed by the same game-theoretical modeling approach used in the section 'IBWT green supply chain coordination decision model with partial backlogging'. The analytical results are summarized in Tables 2 and 3 to compare with those derived in the same section.

Comparisons and discussion of analytical results

Based on the analytical results found in the sections 'IBWT green supply chain coordination decision model with partial backlogging' and 'IBWT green supply chain coordination

decision model with non-partial backlogging', the analytical results under three scenarios are compared and discussed as follows:

1. the optimal usage price of each water-intake is identical under three scenarios;
2. the optimal WGL improvement of each water-intake is identical under three scenarios;
3. the optimal order quantity of each water-intake under the scenario with partial backlogging is higher than that under the scenario with fully backlogging, and is lower than that under the scenario with lost sales;
4. the optimal profits of the IBWT green supply chain and its members under the scenario with partial backlogging are higher than those under the scenario with lost sales, and is lower than those under the scenario with fully backlogging.

Table 2 | Analytical results of IBWT supply chain coordination with lost sales

Scenarios	Lost sales
w_i^*	$w_i^{oc} = C_i$
q_i^*	$q_i^{oc} = a_i + \dfrac{\theta^2}{k}[p_i - (C_i + c_{di})] - \vartheta F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{p_i + r_i + h_i}\right)$
g_i^*	$g_i^{oc} = \dfrac{\theta}{k}[p_i - (C_i + c_{di})]$
$w*$	$w_{oc} = \dfrac{1}{\sum_{i=m+1}^{n} q_i^{oc}}\left\{\tau \sum_{i=1}^{n}\left\{w_{ei}^{oc} - \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi}\right\} - \sum_{i=1}^{m}\left\{w_{ei}^{oc} - \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi}\right\}\right\}$
Π_S^*	$\Pi_S^{oc} = \sum_{i=1}^{n} \Pi_{S_i}^{oc} = \sum_{i=1}^{n}\left\{w_{ei}^{oc} - \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi}\right\}$
Π_{LS}^*	$\Pi_{LS}^{oc} = \tau \Pi_S^{oc}$
Π_{ES}^*	$\Pi_{ES}^{oc} = (1 - \tau)\Pi_S^{oc}$
$\Pi_{D_i}^*$	$\Pi_{D_i}^{oc} = [p_i - (C_i + c_{di})]a_i + \dfrac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^o\left[F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{p_i + r_i + h_i}\right)\right] - w_{ei}^{oc}$
Π_{SC}^*	$\Pi_{SC}^{oc} = \sum_{i=1}^{n}\left\{[p_i - (C_i + c_{di})]a_i + \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^o\left[F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{p_i + r_i + h_i}\right)\right] - c_{fi}\right\}$
Range of w_{ei}^*	$w_{ei}^{oc} \in [\underline{w_{ei}^{oc}}, \overline{w_{ei}^{oc}}]$
	$\underline{w_{ei}^{oc}} = \bar{\Pi}_{S_i}^o + \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 + c_{fi}$
Note	$\overline{w_{ei}^{oc}} = [p_i - (C_i + c_{di})]a_i + \dfrac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i\left[F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{p_i + r_i + h_i}\right)\right] - \bar{\Pi}_{D_i}^o$
	$\Lambda_i^o(z_i) = \vartheta(p_i + h_i)\int_A^B x_i f_i(x_i)dx_i - \vartheta(p_i + r_i + h_i)\int_A^{z_i} x_i f_i(x_i)dx_i$

Table 3 | Analytical results of IBWT supply chain coordination with fully backlogging

Scenarios	Fully backlogging
w_i^*	$w_i^{bc} = C_i$
q_i^*	$q_i^{bc} = a_i + \dfrac{\theta^2}{k}[p_i - (C_i + c_{di})] - \vartheta F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{C_i + c_{di} + r_i + h_i}\right)$
g_i^*	$g_i^{bc} = \dfrac{\theta}{k}[p_i - (C_i + c_{di})]$
$w*$	$w_{bc} = \dfrac{1}{\sum_{i=m+1}^{n} q_i^{bc}}\left\{\tau\sum_{i=1}^{n}\left\{w_{ei}^{bc} - \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi}\right\} - \sum_{i=1}^{m}\left\{w_{ei}^{bc} - \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi}\right\}\right\}$
Π_S^*	$\Pi_S^{bc} = \sum_{i=1}^{n}\Pi_{S_i}^{bc} = \sum_{i=1}^{n}\left\{w_{ei}^{bc} - \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - c_{fi}\right\}$
Π_{LS}^*	$\Pi_{LS}^{bc} = \tau\Pi_S^{bc}$
Π_{ES}^*	$\Pi_{ES}^{bc} = (1 - \tau)\Pi_S^{bc}$
$\Pi_{D_i}^*$	$\Pi_{D_i}^{bc} = [p_i - (C_i + c_{di})]a_i + \dfrac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^b\left[F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{C_i + c_{di} + r_i + h_i}\right)\right] - w_{ei}^{bc}$
Π_{SC}^*	$\Pi_{SC}^{bc} = \sum_{i=1}^{n}\left\{[p_i - (C_i + c_{di})]a_i + \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^b\left[F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{C_i + c_{di} + r_i + h_i}\right)\right] - c_{fi}\right\}$
Range of w_{ei}^*	$w_{ei}^{bc} \in [\underline{w_{ei}^{bc}}, \overline{w_{ei}^{bc}}]$
	$\underline{w_{ei}^{bc}} = \bar{\Pi}_{S_i}^b + \dfrac{\theta^2}{2k}[p_i - (C_i + c_{di})]^2 + c_{fi}$
Note	$\overline{w_{ei}^{bc}} = [p_i - (C_i + c_{di})]a_i + \dfrac{\theta^2}{k}[p_i - (C_i + c_{di})]^2 - \Lambda_i^b\left[F_i^{-1}\left(\dfrac{C_i + c_{di} + h_i}{C_i + c_{di} + r_i + h_i}\right)\right] - \bar{\Pi}_{D_i}^b$
	$\Lambda_i^b(z_i) = \vartheta(p_i + h_i)\int_A^B x_i f_i(x_i)dx_i - \vartheta[(C_i + c_{di}) + r_i + h_i]\int_A^{z_i} x_i f_i(x_i)dx_i$

NUMERICAL AND SENSITIVITY ANALYSES

As this study focuses on exploring the coordination strategies for a generic IBWT green supply chain with partial backlogging considering water delivery loss, the corresponding numerical and sensitivity analyses are conducted to validate and supplement the foregoing modeling analysis results and derive the general coordination strategies and pricing policies for a generic IBWT green supply chain with partial backlogging. Thus, based on the real characteristics of IBWT projects, e.g., the SNWD project in China (Wang et al. 2009), the supply chain structure, the relationships among stakeholders (including the local supplier, external supplier, and distributors), and the values of the parameters and their relationships in the IBWT green supply chain are set to mimic the real-world case. Without any loss of generality, an IBWT green supply chain with one local supplier, one external supplier, and six water distributors is developed for numerical analysis. Since there are six water-intakes and six water distributors in the IBWT green 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., $n - m = 3$).

Table 4 lists the parameters mainly relating to the IBWT green supply chain and their values for the numerical analysis. Table 5 lists the benchmark profits in the IBWT green supply chain for the numerical analysis. Generally, the transferring cost increases as the water diversion cascade increases. Thus, the water transferring cost from the $(i - 1)^{th}$ water-intake to the ith water-intake and the water transferring cost from the ith water-intake to i^{th} water distributor are roughly set as Table 4, based on the water price of eastern and middle routes of the SNWD project (Wang et al.

Table 4 | Parameters' settings

Water-intake i	Mainline 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 a_i	Mean value of precipitation μ_i	Standard deviation of precipitation σ_i
1	0.25	0.05	0.94	0.05	0.42	50,000,000	3×10^8	1×10^7
2	0.30	0.06	1.96	0.12	0.95	100,000,000	2.5×10^8	8×10^6
3	0.35	0.07	3.19	0.20	1.59	150,000,000	2×10^8	6×10^6
4	0.40	0.08	4.64	0.29	2.35	200,000,000	1.5×10^8	4×10^6
5	0.45	0.09	6.32	0.40	3.23	250,000,000	1×10^8	2×10^6
6	0.50	0.10	8.25	0.53	4.24	300,000,000	5×10^7	1×10^6

Table 5 | Benchmark profits' settings

Water-intake i	Benchmark profit $\bar{\Pi}^o_{S_i}$	Benchmark profit $\bar{\Pi}^o_{D_i}$	Benchmark profit $\bar{\Pi}^b_{S_i}$	Benchmark profit $\bar{\Pi}^b_{D_i}$	Benchmark profit $\bar{\Pi}^p_{S_i}$	Benchmark profit $\bar{\Pi}^p_{D_i}$
1	12,000,000	9,000,000	12,600,000	9,450,000	12,300,000	9,225,000
2	60,000,000	40,000,000	63,000,000	42,000,000	61,500,000	41,000,000
3	150,000,000	100,000,000	157,500,000	105,000,000	153,750,000	102,500,000
4	300,000,000	200,000,000	315,000,000	210,000,000	307,500,000	205,000,000
5	400,000,000	300,000,000	420,000,000	315,000,000	410,000,000	307,500,000
6	600,000,000	500,000,000	630,000,000	525,000,000	615,000,000	512,500,000

2009). Likewise, the holding cost, shortage cost, and retail price are roughly set as Table 4. Besides, the farther away from the water source, the greater the water shortage and the greater the water demand. Thus, the basic water demand quantities are set as Table 4. Without a loss of generality, 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 set at 5%; the fixed cost of water delivery for the ith water-intake of the IBWT supplier c_{fi} is set at 20,000; the investment cost factor related to WGL improvement for the IBWT supplier k is set at 2; the WGL improvement coefficient of water demand θ is set at 1,000; the precipitation utilization factor ϑ is set at 0.01; and, the ratio of backlogging in unmet water demand for the ith distributor κ_i is set at 0.8. Due to the local supplier's strong market power within the IBWT horizontal supply chain, the local supplier's bargaining power is set at 0.6. Without loss of generality, the random precipitation x_i obeys normal distribution, i.e., $x_i \sim N(\mu_i, \sigma_i^2)$, parameter A is set at 0.01 and B is set at 1×10^{10}, and the mean value and standard deviation of precipitation are set as Table 4.

Numerical analysis

The numerical analysis assesses and compares the quantity decisions and the resulting profits for the IBWT green supply chain coordination models with lost sales, fully backlogging, and partial backlogging under random precipitation. The numerical analysis results of IBWT green supply chain coordination with lost sales (i.e., without backlogging), fully backlogging, and partial backlogging are shown in Tables 6–8, respectively. The findings from the numerical analysis results are summarized below:

1. Comparing the numerical analysis results between the scenario with lost sales (Table 6) and fully backlogging (Table 7) under random precipitation: (i) the coordinated usage prices are the same between the scenario with lost sales and the scenario with fully backlogging; (ii) the entry prices in the scenario with fully backlogging are higher than those in the scenario with lost sales; (iii) the ordering quantities of water resources in the scenario with fully backlogging are lower than those in the

Table 6 | Numerical analysis results of IBWT green supply chain coordination with lost sales

i	w_{ei}^c	Range of w_{ei}^c	w_i^c	g_i^c	q_i^c	$\Pi_{D_i}^c$	Π_S^c
1	15,000,000	[12,118,233, 20,612,304]	0.26	313.42	47,378,142	14,612,304	1,923,825,617
2	65,000,000	[60,447,194, 88,228,872]	0.59	653.60	98,206,352	63,228,872	Π_{LS}^c
3	160,000,000	[151,151,651, 217,049,773]	0.99	1,063.79	149,103,624	157,049,773	1,154,295,370
4	320,000,000	[302,413,667, 418,912,075]	1.47	1,547.15	200,073,795	298,912,075	Π_{ES}^c
5	530,000,000	[404,458,331, 757,967,047]	2.02	2,106.73	251,120,083	527,967,047	769,530,247
6	850,000,000	[607,585,307, 1,162,644,750]	2.65	2,750.51	302,257,197	812,644,750	Π_{SC}^c
Note	–	$w_c = 1.22$	Total		1,048,139,193	1,874,414,822	3,798,240,439

Table 7 | Numerical analysis results of IBWT green supply chain coordination with fully backlogging

i	w_{ei}^c	Range of w_{ei}^c	w_i^c	g_i^c	q_i^c	$\Pi_{D_i}^c$	Π_S^c
1	15,100,000	[12,718,233, 21,026,090]	0.26	313.42	47,322,235	15,376,090	1,924,425,617
2	65,100,000	[63,447,194, 87,676,525]	0.59	653.60	98,163,956	64,576,525	Π_{LS}^c
3	160,100,000	[158,651,651, 213,910,837]	0.99	1,063.79	149,072,452	158,810,837	1,154,655,370
4	320,100,000	[317,413,667, 410,930,204]	1.47	1,547.15	200,053,238	300,830,204	Π_{ES}^c
5	530,100,000	[424,458,331, 744,795,720]	2.02	2,106.73	251,109,879	529,695,720	769,770,247
6	850,100,000	[637,585,307, 1,138,834,711]	2.65	2,750.51	302,252,117	813,734,711	Π_{SC}^c
Note	–	$w_c = 1.22$	Total		1,047,973,876	1,883,024,086	3,807,449,703

Table 8 | Numerical analysis results of IBWT green supply chain coordination with partial backlogging

i	w_{ei}^c	Range of w_{ei}^c	w_i^c	g_i^c	q_i^c	$\Pi_{D_i}^c$	Π_S^c
1	15,050,000	[12,418,233, 20,981,654]	0.26	313.42	47,338,499	15,156,654	1,924,125,617
2	65,050,000	[61,947,194, 88,231,588]	0.59	653.60	98,176,088	64,181,588	Π_{LS}^c
3	160,050,000	[154,901,651, 215,842,093]	0.99	1,063.79	149,081,319	158,292,093	1,154,475,370
4	320,050,000	[309,913,667, 415,315,650]	1.47	1,547.15	200,059,066	300,265,650	Π_{ES}^c
5	530,050,000	[414,458,331, 751,740,654]	2.02	2,106.73	251,112,766	529,190,654	769,650,247
6	850,050,000	[622,585,307, 1,150,973,918]	2.65	2,750.51	302,253,552	813,423,918	Π_{SC}^c
Note	–	$w_c = 1.22$	Total		1,048,021,290	1,880,510,556	3,804,636,173

scenario with lost sales; (iv) the WGL improvement is the same between the scenario with lost sales and the scenario with fully backlogging; and, (v) the profits of the IBWT supply chain and its members in the scenario with fully backlogging are higher than those in the scenario with lost sales.

2. Comparing the numerical analysis results between the scenario with lost sales (Table 6) and partial backlogging (Table 8) under random precipitation: (i) the coordinated usage prices are the same between the scenario with lost sales and the scenario with partial backlogging; (ii) the entry prices in the scenario with partial backlogging are higher than those in the scenario with lost sales; (iii) the ordering quantities of water resources in the scenario with partial backlogging are lower than those in the scenario with lost sales; (iv) the WGL improvement is the same between the scenario with lost sales and the scenario with partial backlogging; and, (v) the profits of the

IBWT supply chain and its members in the scenario with partial backlogging are higher than those in the scenario with lost sales.

3. Comparing the numerical analysis results between the scenario with fully backlogging (Table 7) and partial backlogging (Table 8) under random precipitation: (i) the coordinated usage prices are the same between the scenario with fully backlogging and the scenario with partial backlogging; (ii) the entry prices in the scenario with partial backlogging are lower than those in the scenario with fully backlogging; (iii) the ordering quantities of water resources in the scenario with partial backlogging are higher than those in the scenario with fully backlogging; (iv) the WGL improvement is the same between the scenario with fully backlogging and the scenario with partial backlogging; and, (v) the profits of the IBWT supply chain and its members in the scenario with partial backlogging are lower than those in the scenario with fully backlogging.

Sensitivity analysis

The sensitivity analysis assesses and compares the impacts of the changes of the backlogging ratio, water delivery loss rate, precipitation utilization factor, retail price, mainline transfer cost, branch-line transfer cost, holding cost, and shortage cost for the IBWT green supply chain coordination models with partial backlogging under random precipitation (see Figure A1 in the Appendix).

To capture the impact of the change of key parameters, we only select the parameters from the first distributor and the first 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 here: (1) the profit of the IBWT green supply chain increases as the backlogging ratio increases; (2) the profit of the IBWT green supply chain decreases as the water delivery loss rate increases; (3) the profit of the IBWT green supply chain increases as the WGL improvement coefficient increases; (4) the profit of the IBWT green supply chain decreases as the WGL investment cost coefficient increases; (5) the profit of the IBWT green

supply chain decreases as the precipitation utilization factor increases; (6) the profit of the IBWT green supply chain increases as the retail price increases; (7) the profit of the IBWT green supply chain decreases as the mainline transfer cost increases; (8) the profit of the IBWT green supply chain decreases as the branch-line transfer cost increases; (9) the profit of the IBWT green supply chain decreases as the holding cost increases; and, (10) the profit of the IBWT green supply chain decreases as the shortage cost increases.

MANAGERIAL INSIGHTS AND POLICY IMPLICATIONS

Based on the comparisons and discussions of the aforementioned analytical and numerical results, the corresponding managerial insights and policy implications can be summarized as follows:

1. No matter under the scenario with lost sales, or under the scenario with fully backlogging, or under the scenario with partial backlogging, the two-part tariff contract can effectively coordinate the IBWT green supply chain and achieve operational performance improvement.

2. The IBWT green supply chain and its members would order less water resources under the scenario with fully/partial backlogging than those under the scenario with lost sales, and can gain more profits under the scenario with fully/partial backlogging than those under the scenario with lost sales. Hence, fully/partial backlogging of water demands are beneficial for improving the operational performance of the IBWT green supply chain.

3. The IBWT green supply chain and its members would order less water resources under the scenario with fully backlogging than under the scenario with partial backlogging, and can gain more profits under the scenario with fully backlogging than those under the scenario with partial backlogging. Hence, fully backlogging of water demand outperforms partial backlogging of water demand, and is the first-best strategy for improving the operational performance of the IBWT green supply chain.

4. In the actual operations of the IBWT project, owing to the existence of water supply capacity, fully backlogging of water demand is usually not feasible for the IBWT green supply chain. In this context, partial backlogging can effectively improve the profit of the IBWT green supply chain, compared with the scenario with lost sales. Hence, partial backlogging is the second-best strategy for improving the operational performance of the IBWT green supply chain.

5. Under the scenario with partial backlogging, reducing the WGL investment cost, 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 operational performance of the IBWT green supply chain. As well, setting a higher retail price and increasing backlogging ratio are beneficial for improving the operational performance of the IBWT green supply chain. Furthermore, a higher WGL improvement coefficient of water demand and a lower precipitation utilization factor are beneficial for improving the operational performance of the IBWT green supply chain.

In summary, the government should set suitable retail prices of water resources to promote consumer's water saving and guarantee a certain profit of the IBWT supply chain, encourage improving the precipitation utilization to reduce unnecessary water transfer and waste, and encourage implementing WGL improvement to improve operational performance and achieve water ecological environment improvement for the IBWT project. The decision-maker of the IBWT green supply chain should make a great effort to increase the backlogging ratio and WGL improvement coefficient of water demand, and reduce the WGL investment cost, the water delivery loss rate, the mainline and branch-line transfer cost, holding cost and shortage cost to improve the operational performance. Finally, the two-part tariff contract is recommended to coordinate the IBWT green supply chain and improve the operational performance under random precipitation.

CONCLUSION

In the context of global climate change and sustainable development, the water demand backlogging and water delivery loss have important impacts on the green operational decisions and efficiency of the inter-basin water transfer (IBWT) project. From the perspective of green supply chain management, this paper tries to explore the coordination issue in the green operations management of the IBWT project considering the water delivery loss with partial backlogging under random precipitation. Three IBWT green supply chain coordination decision models considering water delivery loss with lost sales, fully backlogging, and partial backlogging under random precipitation are developed, analyzed, and compared through the game-theoretical modeling approach, and the corresponding numerical and sensitivity analyses for all models are conducted and compared; finally, the corresponding managerial insights and policy implications are discussed and summarized in this paper. The research results indicate that: (1) the two-part tariff contract can effectively coordinate the IBWT green supply chain and improve the operational performance; (2) the fully/partial backlogging strategy can effectively improve the operational performance of the IBWT green supply chain; (3) the fully backlogging strategy is the first-best strategy and partial backlogging strategy is the second-best strategy for improving the operational performance of the IBWT green supply chain; (4) reducing the WGL investment cost coefficient, 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 operational performance of the IBWT green supply chain; (5) setting a higher retail price and increasing backlogging ratio are beneficial for improving the operational performance of the IBWT green supply chain; (6) a higher WGL improvement coefficient of water demand and a lower precipitation utilization factor are beneficial for improving the operational performance of the IBWT green supply chain.

In terms of theoretical contribution, based on the theories and methods of the Nash bargaining game and two-part tariff contract, the IBWT green supply chain coordination decision models considering water delivery loss with fully/partial backlogging under the random precipitation are developed, analyzed, and compared respectively, which have enhanced the optimization decision theory for the green operations management of IBWT projects. With respect to the practical contribution, the comparisons and

discussion of the modeling and numerical analysis results provide better decision support to governments to produce appropriate pricing policies, and the IBWT stakeholders to create better operations' strategies.

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SUPPLEMENTARY MATERIAL

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