

Two-part pricing contract and competition between two water supply chains: a theoretical and empirical analysis of the South-to-North Water Transfer Project in China

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ABSTRACT

Focusing on the established Eastern and Middle Routes of the South-to-North Water Transfer Project in China, this study investigates two water supply chains with each consisting of one water supplier and one water distributor. This research studies the performance of the water supply chain system and supply chain members under two-part pricing contracts and wholesale price contracts, with varying competition intensity and rainfall use efficiency levels. The results show the parameters of water supply chain members and the whole system decrease as the competition intensity increases. Water suppliers can change the expected profits of water supply system and members through changing the fixed costs in a certain range. When the quantity competition between the distributors is weak, the parameters of water supply chain decrease as the average rainfall increases. When the quantity competition is strong, the parameters also decrease as the average rainfall increases, but the decreasing range is much larger than that for the weak competition. Similarly, the range of fixed cost is much larger when the quantity competition is stronger than that for the weak competition.

Key words | Northern China, quantity competition, South-to-North Water Transfer Project, supply chain system, two-part pricing contract

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INTRODUCTION

Water scarcity is becoming acute along with economic development, population growth, and climate change (Kanakoudis *et al.* 2016, 2017; Wilson *et al.* 2017). In China, the average water availability is 2,259 m³ per capita, much less than the world average 8,036 m³ per capita (Berrittella *et al.* 2006). With the newly minted ‘two-child policy’, China’s population will likely increase at an annual rate of 10–20 million in future years, which will decrease the average water availability. In addition, uneven distribution of available water resources further intensifies water scarcity. In Northern China, less than 10% of the national water resources irrigates more than 30% of the irrigated croplands (Fan *et al.* 2014). In particular, in some populated areas, for instance, Beijing and Tianjin metropolitan areas, the average water availability is less than 400 m³ per capita (Berrittella

et al. 2006; Fan *et al.* 2018). Therefore, to solve water crisis in North China Plain, the Chinese Central Government launched the national South-to-North Water Transfer Project (SNWTP) to increase water supply in Northern China (Tian *et al.* 1989).

On October 30, 1952, the former China president Mao Zedong visited the South and stated, ‘There is more water in the South, while less in the North. If there is any means, we can transfer water from South to North’ (East Lake Hotel 2013). Later, under the leadership and supervision of the Central Government and the State Council, a scientific investigation team consisting of experts and researchers conducted many field investigations and on-site surveys. They initially proposed more than 50 planning options, and these were further compared and

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evaluated through feasibility analyses, cost–benefit analyses, environmental assessments, etc. Finally, the current SNWTP with Eastern, Middle, and Western Routes took its form (Liu et al. 1984). The Eastern Route withdraws water from Jiangdu Hydro-junction located in Sanjiangkou, Jiangsu province. Using existing waterways in Jiangsu, Shandong, and Hebei provinces, it lifts and pumps water all the way to Northern China. The Middle Route takes water from Danjiangkou Reservoir in Hubei province, goes north passing southwestern regions in Henan province, and finally reaches Beijing and Tianjin. The Eastern and Middle Routes are shown in Figure 1. With this national strategic project, emphasis is given to changing the situation ‘flood in the South and drought in the North’ and solve water scarcity in Northern China, thus achieving a balanced and sustainable development in both the south and north of China (Wilson et al. 2017).

Some research has been documented regarding the SNWTP. Theoretical support includes cooperation of

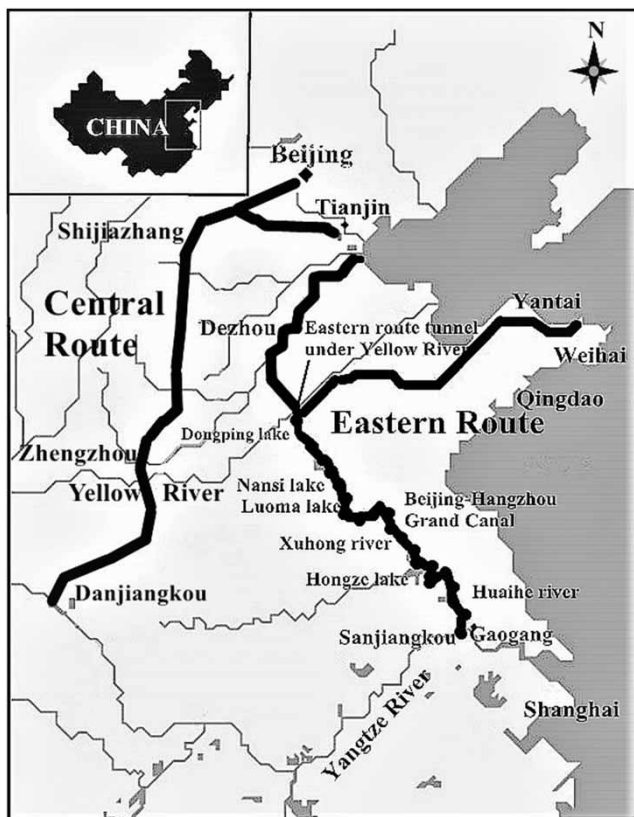


Figure 1 | The Eastern and Middle Routes of the South-to-North Water Transfer Project.

water users and their welfare changes based on game theory (Wei et al. 2010; Du et al. 2016), impacts of SNWTP on China's economy based on decision support systems (Feng et al. 2007), implementation of water demand management projects (He et al. 2010), risk assessment (Gu et al. 2012), environmental monitoring and pollution control (Wang et al. 2006; Zhang 2009). Using game theory, Wei et al. (2010) analyzed the water resources conflicts of SNWTP. However, engineering optimization (Chen & Wang 2012; Chen et al. 2013) and operation management (Liu & Zheng 2002; Ha et al. 2011) are still under-studied. To the best of the authors' knowledge, research has not reported the influence of rainfall on the performance of a water supply chain from the perspective of quantity competition, nor applied to the SNWTP (Lou 2014; Du et al. 2018, 2019). Therefore, this study tries to answer the following three fundamental questions relating to water supply chain management.

1. How are the profits of water distributors and suppliers affected by the competition intensity in different contracts?
2. How do the water distributors choose different contracts under different competition intensities and utilization rates of the regional rainfall?
3. What are the effective management strategies implemented by government to deal with the fixed costs caused by different suppliers?

Figure 2 presents research design, methods, and analysis in this study. Specifically, two water supply chains including two water suppliers and two distributors constitute the whole water supply chain system. The two distributors have deterministic demands in the water supply chain system, whereas the two water suppliers can change their supply using various contracts (Wang & Hu 2005; Du et al. 2019). Based on inter-chain competition and wholesale price contract, a Stackelberg game is built, and specific expressions of performance under varying contracts are derived. Sensitivity analysis is conducted to explore the performance of the water supply chain system and its components under two-part pricing contracts and with varying intensities of quantity competition. Fixed fees are determined under alternating contract options. Finally, the Eastern and Middle Routes of the SNWTP are considered as two water suppliers who provide water to two competing water distributors in

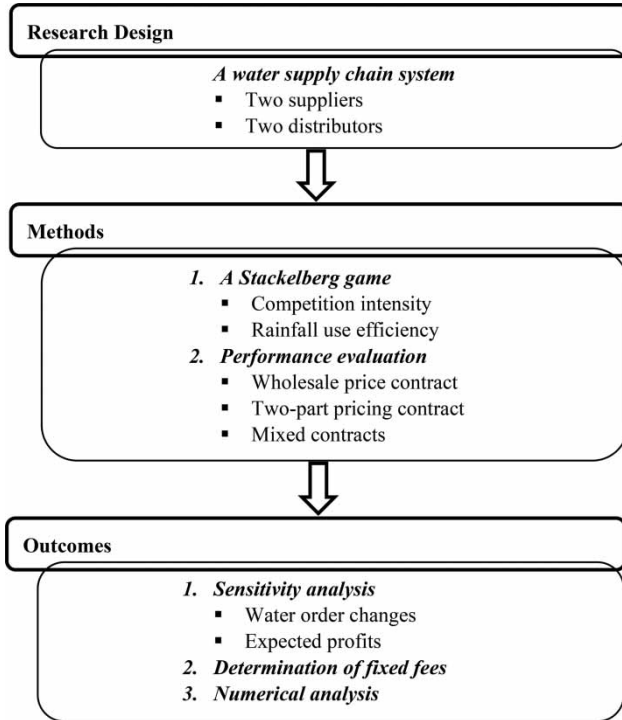


Figure 2 | A flow chart of the research design and analysis in this study.

Tianjin City. Thus, a numerical analysis is conducted with real values of water prices, water use, rainfall, etc.

MATERIALS AND METHODS

A conceptual model

A wholesale price contract sets a fixed unit price for any amount of water purchased by a water distributor from a supplier. While a two-part pricing contract consists of a lump-sum fee and a per-unit price (Chen et al. 2013). The lump-sum fee is used to secure the transaction and stabilize the purchase price, and the per-unit charge reflects the value of water (Du et al. 2018). Taking the wholesale price contract as a benchmark, the study looks at the performance of the two-part pricing contracts between two suppliers (M1 and M2) and two distributors (S1 and S2) with water quantity competition between the water supply chains of the Eastern and Middle Routes. The two-part pricing contract takes the form of (F_i, w_i) ($i = 1, 2$), where F_i is a fixed cost (lump-sum fee), and w_i is a wholesale price for the supplier (i.e., a per-unit charge). The fixed cost is assumed to be exogenous to

the supply chain, and it can be regulated and controlled by government at any time (Du et al. 2018). Assume that the suppliers can offer different wholesale prices to the two distributors regardless of the contract type. A Stackelberg game is played between the suppliers and distributors, with the suppliers as the leaders and distributors as the followers. The model is built as follows.

First, the two suppliers offer each distributor a wholesale price contract or a two-part pricing contract.

Second, the distributors independently choose the water quantity they want to order according to the contracts they accept.

Third, the suppliers meet the demand of water orders made by the distributors and the distributors meet the water demand of end-user market.

In this model, the two water suppliers and two water distributors form a horizontal water market with quantity competition. Water price paid by end users is affected by local rainfall. The heavier the rainfall, the more free water the local distributors can obtain and the less water they need to buy from the upstream water suppliers. For the distributors, water cost could be reduced if more rainfall is received and less water ordered from the suppliers. Consequently, the price of water users will be lower as well. Following Ha et al. (2011), the inverse demand function for water distributors can be represented by:

$$p_i = a - d_i - \beta d_j - \psi r \quad i = 1, 2 \quad j = 3 - i \quad (1)$$

where p is market water price, and it changes as the market demand (water consumption) d changes. The subscripts i, j indicate the two water distributors with quantity competition between them, i.e., i or $j = 1$ indicates the Eastern Route distributor, and i or $j = 2$ indicates the Middle Route distributor. In addition, a is water users' willingness to pay for each unit of water; β represents competition intensity, indicating water orders from one distributor are affected by the other's ($0 < \beta < 1$); r is average annual rainfall in the area where water is transferred to; and ψ is rainfall use efficiency ($0 < \psi < 1$), indicating the proportion of rainfall collected by water distributors and used for local consumption.

To ease the analysis and better evaluate the performance of water supply chain system under competition intensity

and local rainfall, other costs of the suppliers and distributors are assumed to be zero.

Three scenarios for performance evaluation

Performance under wholesale price contracts (w)

First, consider the situation when the Eastern and Middle Route water suppliers offer different wholesale price contracts to the two distributors in the same location. The two distributors have different wholesale prices, w_{iww} . The expected profits for the distributors and suppliers are:

$$ES_{iww}(d_{iww}) = (a - d_{iww} - \beta d_{jww} - \psi r - w_{iww}) d_{iww} \quad (2)$$

$$EM_{iww}(w_{iww}) = w_{iww} d_{iww} \quad (3)$$

For the Stackelberg game, the method of backward induction can be used to obtain the water demand of the two distributors after simple manipulations:

$$d_{iww} = 2(a - \psi r) / ((\beta + 2)(4 - \beta)) \quad (4)$$

As the suppliers determine the wholesale prices when maximizing their expected profits, the first-order condition can be taken to derive water price:

$$w_{iww} = (\beta - 2)(a - \psi r) / (\beta - 4) \quad (5)$$

Given the water price, the expected profits for water distributors, suppliers, and the whole supply chain system are, respectively:

$$ES_{iww} = 4(a - \psi r)^2 / ((\beta + 2)^2(\beta - 4)^2) \quad (6)$$

$$EM_{iww} = 2(2 - \beta)(a - \psi r)^2 / ((\beta + 2)(\beta - 4)^2) \quad (7)$$

$$\begin{aligned} ET_{iww} &= ES_{iww} + EM_{iww} \\ &= 2(6 - \beta^2)(a - \psi r)^2 / ((\beta + 2)^2(\beta - 4)^2) \end{aligned} \quad (8)$$

Performance under two-part pricing contracts (tt)

Similarly, the Eastern and Middle Route water suppliers can offer two-part pricing contracts to the two distributors in the same location. In this case, the two water suppliers have different fixed fees, F_i . Thus, the expected profits for the

distributors are:

$$ES_{itt}(d_{itt}) = (a - d_{itt} - \beta d_{jtt} - \psi r) d_{itt} - F_i - w_{itt} d_{itt} \quad (9)$$

Because the two water suppliers independently offer two-part pricing contracts, they can adjust their own profits through the fixed fees. Meanwhile, the suppliers can determine the wholesale prices through profit maximization in their supply chains. The expected profits for the supply chains are:

$$ET_{itt}(w_{itt}) = (a - d_{itt} - \beta d_{jtt} - \psi r) d_{itt} \quad (10)$$

In this Stackelberg game, the backward induction can be applied to obtain the optimal water demand and wholesale prices:

$$d_{itt} = 2(a - \psi r) / (\beta^2 - 2\beta - 4) \quad (11)$$

$$w_{itt} = \beta^2(-a + \psi r) / (\beta^2 - 2\beta - 4) \quad (12)$$

Thus, the expected profits for the distributors and the whole supply chain system are, respectively:

$$ES_{itt} = 4(a - \psi r)^2 / (\beta^2 - 2\beta - 4)^2 - F_i \quad (13)$$

$$ET_{itt} = 2(2 - \beta^2)(a - \psi r)^2 / (\beta^2 - 2\beta - 4)^2 \quad (14)$$

The expected profits for the suppliers can be calculated:

$$EM_{itt} = ET_{itt} - ES_{itt} = -2\beta^2(a - \psi r)^2 / (\beta - 2\beta - 4)^2 + F_i \quad (15)$$

Performance under a two-part pricing contract for the Eastern Route distributor and a wholesale price contract for the Middle Route distributor (tw)

The Eastern Route water supplier offers a two-part pricing contract to one distributor and the Middle Route water supplier offers a wholesale price contract to the other distributor. With different contracts, the two distributors pay different prices, w_{1tw} and w_{2tw} . The expected profits for the two distributors of the Eastern and Middle Route supply chains are, respectively:

$$ES_{1tw}(d_{1tw}) = (a - d_{1tw} - \beta d_{2tw} - \psi r) d_{1tw} - F_1 - w_{1tw} d_{1tw} \quad (16)$$

$$ES_{2tw}(d_{2tw}) = (a - d_{2tw} - \beta d_{1tw} - \psi r) d_{2tw} - w_{2tw} d_{2tw} \quad (17)$$

The expected profit for the Eastern Route supply chain system is:

$$ET_{1tw}(w_{1tw}) = (a - d_{1tw} - \beta d_{2tw} - \psi r) d_{1tw} \quad (18)$$

The expected profit for the supplier of the Middle Route supply chain system is:

$$EM_{2tw}(w_{2tw}) = w_{2tw} d_{2tw} \quad (19)$$

Using backward induction, the optimal water demand and wholesale prices for the two distributors can be obtained:

$$d_{1tw} = 2(4 + \beta)(2 - \beta)(a - \psi r) / (\beta^4 - 16\beta^2 + 32) \quad (20)$$

$$d_{2tw} = 2(4 - 2\beta - \beta^2)(a - \psi r) / (\beta^4 - 16\beta^2 + 32) \quad (21)$$

$$w_{1tw} = \beta^2(2 - \beta)(4 + \beta)(a - \psi r) / (\beta^4 - 16\beta^2 + 32) \quad (22)$$

$$w_{2tw} = (4 - \beta^2)(\beta^2 + 2\beta - 4)(a - \psi r) / (\beta^4 - 16\beta^2 + 32) \quad (23)$$

The expected profits for the two distributors are:

$$ES_{1tw} = 4(\beta - 2)^2(\beta + 4)^2(a - \psi r)^2 / (\beta^4 - 16\beta^2 + 32)^2 - F_1 \quad (24)$$

$$ES_{2tw} = 4(\beta^2 + 2\beta - 4)^2(a - \psi r)^2 / (\beta^4 - 16\beta^2 + 32)^2 \quad (25)$$

The expected profits for the Eastern Route supply chain system and Middle Route water supplier are:

$$ET_{1tw} = 2(2 - \beta^2)(\beta - 2)^2(\beta + 4)^2(a - \psi r)^2 / (\beta^4 - 16\beta^2 + 32)^2 - F_1 \quad (26)$$

$$EM_{2tw} = 2(4 - \beta^2)(\beta^2 + 2\beta - 4)^2(a - \psi r)^2 / (\beta^4 - 16\beta^2 + 32)^2 \quad (27)$$

Thus, the expected profits for the Eastern Route supplier and the Middle Route supply chain system can be calculated:

$$EM_{1tw} = ET_{1tw} - ES_{1tw} = -2\beta^2(\beta - 2)^2(\beta + 4)^2(a - \psi r)^2 / (\beta^4 - 16\beta^2 + 32)^2 + F_1 \quad (28)$$

$$ET_{2tw} = ES_{2tw} + EM_{2tw} = 2(6 - \beta^2)(\beta^2 + 2\beta - 4)^2(a - \psi r)^2 / (\beta^4 - 16\beta^2 + 32)^2 \quad (29)$$

RESULTS AND DISCUSSION

Sensitivity analysis

Proposition 1. In the case of $w\omega$, when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial w_{1tw} / \partial \beta < 0$, $\partial w_{1tw} / \partial r < 0$, $\partial d_{1tw} / \partial \beta < 0$, $\partial d_{1tw} / \partial r < 0$.

The proofs of Proposition 1 and following propositions are provided in the Appendix, available with the online version of this paper. This proposition means that in the case of $w\omega$, both the wholesale prices and order quantities are monotonically decreasing functions of competition intensity and regional rainfall. The purchase decisions of water distributors are affected by competition intensity and rainfall. In regions with varying amounts of rainfall, a certain level of competition intensity can help control the water quantities ordered by the distributors and change the wholesale prices offered by the suppliers.

Proposition 2. In the case of $w\omega$, when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial ES_{1tw} / \partial \beta < 0$, $\partial ES_{1tw} / \partial r < 0$, $\partial EM_{1tw} / \partial \beta < 0$, $\partial EM_{1tw} / \partial r < 0$, $\partial ET_{1tw} / \partial \beta < 0$, $\partial ET_{1tw} / \partial r < 0$.

This proposition suggests that in the case of $w\omega$, the expected profits of the water suppliers, distributors and the whole supply chain system are monotonically decreasing functions of competition intensity and regional rainfall. Affected by the competition intensity and rainfall, the expected profits of all members and the whole system can be controlled at a certain level while given the competition intensity.

Proposition 3. In the case of tt , when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial w_{itt} / \partial \beta > 0$, $\partial w_{itt} / \partial r > 0$, $\partial d_{itt} / \partial \beta < 0$, $\partial d_{itt} / \partial r < 0$.

This proposition shows that in the case of tt , the wholesale prices are monotonically increasing functions of competition intensity and rainfall, while the water quantities are monotonically decreasing functions of competition intensity and rainfall. The stronger the competition between water distributors, the higher prices set by the upstream water suppliers, and the less water ordered by the distributors (Ha & Tong 2008). In this situation, more rainfall is favorable to the distributors, so that they can satisfy the increasing water demand by terminal users. Similarly, if there is more rain in the location, the upstream water supplier can set a higher price. With more rain, the local water distributors can

order less water from the suppliers, which indicates more rainfall benefits the distributors' decision-making.

Proposition 4. In the case of tt , when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial ES_{itt}/\partial\beta < 0$, $\partial ES_{itt}/\partial r < 0$, $\partial EM_{itt}/\partial\beta < 0$, $\partial EM_{itt}/\partial r < 0$, $\partial ET_{itt}/\partial\beta < 0$, $\partial ET_{itt}/\partial r < 0$.

This proposition shows that in the case of tt , the expected profits of the water suppliers, distributors and the whole supply chain system are monotonically decreasing functions of competition intensity and regional rainfall. This indicates the expected profits of the supply chain decrease as the competition becomes stronger (Ha & Tong 2008). Similarly, more regional rainfall decreases the expected profits of water suppliers and distributors, and the expected profit of the supply chain system also decreases. In the situation of SNWTP, with more rainfall in regions the routes go through, there is more water in the distributaries and canals belonging to the two routes, thus the costs of transferring water can be reduced (Chen & Wang 2012).

Proposition 5. In the case of tw , when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial w_{1tw}/\partial\beta > 0$, $\partial w_{1tw}/\partial r > 0$, $\partial w_{2tw}/\partial\beta < 0$, $\partial w_{2tw}/\partial r < 0$.

This proposition means that in the case of tw with different contracts, the price of the Eastern Route supply chain system under a two-part pricing contract is an increasing function of competition intensity and regional rainfall, while the price of the Middle Route supply chain system under a wholesale price contract is a decreasing function of competition intensity and rainfall. In this situation, for a given water quantity ordered by a distributor, a higher price set by the supplier will increase their expected profits.

Proposition 6. In the case of tw , (1) when $\psi \neq a/r$ and $0 < \beta \leq 0.3626$, then $\partial d_{1tw}/\partial\beta < 0$, $\partial d_{1tw}/\partial r < 0$, $\partial d_{2tw}/\partial\beta < 0$, $\partial d_{2tw}/\partial r < 0$; (2) when $\psi \neq a/r$ and $0.3626 < \beta < 1$, then $\partial d_{1tw}/\partial\beta > 0$, $\partial d_{1tw}/\partial r < 0$, $\partial d_{2tw}/\partial\beta < 0$, $\partial d_{2tw}/\partial r < 0$.

This proposition states two facts given two sets of competition intensity values in the case of tw . First, when the competition intensity is greater than 0 and equal to or smaller than 0.3626, the water quantity ordered by the downstream distributor under a two-part pricing contract decreases as the competition intensity increases. Second, when the competition intensity is between 0.3626 and 1, the water quantity under a two-part pricing contract increases as the competition intensity increases. For both contracts, the water quantities in the whole supply chain

are negatively correlated with the average rainfall, and thus the water price increases as more rainfall is received.

Proposition 7. In the case of tw , (1) when $\psi \neq a/r$ and $0 < \beta \leq 0.3626$, then $\partial ES_{1tw}/\partial\beta < 0$; (2) when $\psi \neq a/r$ and $0.3626 < \beta < 1$, then $\partial ES_{1tw}/\partial\beta > 0$; (3) when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial ES_{2tw}/\partial\beta < 0$, $\partial EM_{1tw}/\partial\beta < 0$, $\partial EM_{2tw}/\partial\beta < 0$, $\partial ET_{1tw}/\partial\beta < 0$, $\partial ET_{2tw}/\partial\beta < 0$; (4) when $\psi \neq a/r$ and $0 < \beta < 1$, then $\partial ES_{1tw}/\partial r < 0$, $\partial ES_{2tw}/\partial r < 0$, $\partial EM_{1tw}/\partial r > 0$, $\partial EM_{2tw}/\partial r < 0$, $\partial ET_{1tw}/\partial r < 0$, $\partial ET_{2tw}/\partial r > 0$.

This proposition suggests different performances of water distributors in the supply chain in the case of tw . First, when the competition intensity is between 0 and 0.3626, the expected profit of the water distributor under a two-part pricing contract decreases as the competition intensity increases. Second, with strong competition, indicated by any value between 0.3626 and 1, the expected profit of the water distributor under a two-part pricing contract increases as the competition intensity increases. Third, in the case of tw , the expected profits of the distributors are negatively correlated with rainfall. In addition, in the case of $w\omega$ (Proposition 2), the expected profits of the distributors are negatively correlated with rainfall; in the case of tt (Proposition 4), the expected profits of the distributors are negatively correlated with rainfall as well. Furthermore, the expected profits of the distributors under two-part pricing contracts are negatively correlated with rainfall, while the expected profits of the distributors under wholesale price contracts are also negatively correlated with rainfall (Du et al. 2018).

Determination of fixed fees

Under two-part pricing contracts or wholesale price contracts

If $EM_{1tt} = EM_{1w\omega}$ and $ES_{1tt} = ES_{1w\omega}$, F_{11} and F_{12} represent the lower and upper bounds of the fixed fee:

$$F_{11} = -8(\beta^3 - 2\beta^2 - 4\beta - 8)(a - \psi r)^2 / ((\beta + 2)(\beta - 4)^2(\beta^2 - 2\beta - 4)^2) \quad (30)$$

$$F_{12} = -32(\beta^2 - 2\beta - 6)(a - \psi r)^2 / ((\beta + 2)^2(\beta - 4)^2(\beta^2 - 2\beta - 4)^2) \quad (31)$$

Suppose ψ_1 is a real solution of rainfall use efficiency ψ in F_{11} , and ψ_2 is a real solution of ψ in F_{12} . If $F_{11} = F_{12}$, then $\psi_1 = \psi_2 = a/r > 0$.

Lemma 1. (1) $\psi_1 = \psi_2 > 0$; (2) when $\psi \neq a/r$ and $0 < \beta \leq 0.5723$, then $F_{11} > 0$, $F_{12} > 0$, and $F_{11} < F_{12}$; (3) when $\psi \neq a/r$ and $0.5723 < \beta < 1$, then $F_{11} > 0$, $F_{12} > 0$, and $F_{11} > F_{12}$.

Proposition 8. (1) when $\psi \neq a/r$ and $0 < \beta \leq 0.5723$, $F_{11} < F_1 < F_{12}$, then $EM_{1tt} > EM_{1ww}$, $ES_{1tt} > ES_{1ww}$; (2) when $\psi \neq a/r$ and $0.5723 < \beta < 1$, $F_{11} > F_1 > F_{12}$, then $EM_{1tt} < EM_{1ww}$, $ES_{1tt} < ES_{1ww}$.

This proposition suggests the fixed fee of supply chain system, F_1 , can be adjusted within a certain range. When the competition intensity is relatively weak, that is, $0 < \beta \leq 0.5723$, the fixed fee can have a value in the range (F_{11}, F_{12}) with $F_{11} > 0$, $F_{12} > 0$ and $F_{11} < F_{12}$. The supply chain system offers two-part pricing contracts to realize Pareto improvement for the supplier and distributors at the same time. On the contrary, when competition intensity is relatively strong, i.e., $0.5723 < \beta < 1$, the fixed fee can be adjusted in the range (F_{12}, F_{11}) , $F_{11} > 0$, $F_{12} > 0$ and $F_{11} > F_{12}$. The supply chain system offers two-part pricing contracts to realize Pareto improvement for the suppliers and distributors at the same time.

Competition between distributors in two supply chains under wholesale price contracts

If $EM_{1tw} = EM_{1ww}$ and $ES_{1tw} = ES_{1ww}$, F_{13} and F_{14} are the lower and upper bounds of the fixed fee, respectively:

$$F_{13} = -8(\beta - 2)(\beta^6 - 16\beta^4 + 256)(a - \psi r)^2 / ((\beta + 2)(\beta - 4)^2(\beta^4 - 16\beta^2 + 32)^2) \quad (32)$$

$$F_{14} = -32(\beta^2 - 8)(\beta^4 - 18\beta^2 + 48)(a - \psi r)^2 / ((\beta + 2)(\beta - 4)^2(\beta^4 - 16\beta^2 + 32)^2) \quad (33)$$

Lemma 2. $0 < F_{13} < F_{14}$.

Proposition 9. When $F_{13} < F_1 < F_{14}$, then $EM_{1tw} = EM_{1ww}$, and $ES_{1tw} = ES_{1ww}$.

This proposition suggests that if the competing supply chain offers a wholesale price contract, the other supply chain can adjust the fixed fee within the range (F_{13}, F_{14}) . As the range highly depends on competition intensity and

regional rainfall use efficiency, Pareto improvement can be achieved in terms of the performance of both the suppliers and distributors.

Competition between distributors in two supply chains under two-part pricing contracts

If $EM_{2tt} = EM_{2tw}$ and $ES_{2tt} = ES_{2tw}$, F_{21} and F_{22} are the lower and upper bounds of the fixed fee under two-part pricing contracts, respectively.

$$F_{21} = -8(\beta^8 - 12\beta^6 - 16\beta^4 + 192\beta^2 - 256)(a - \psi r)^2 / ((\beta^2 - 2\beta - 4)^2(\beta^4 - 16\beta^2 + 32)^2) \quad (34)$$

$$F_{22} = -32(\beta^2 - 2)(\beta^2 - 4)(\beta^2 - 12)(a - \psi r)^2 / ((\beta^2 - 2\beta - 4)^2(\beta^4 - 16\beta^2 + 32)^2) \quad (35)$$

Lemma 3. $0 < F_{21} < F_{22}$.

Proposition 10. When $F_{21} < F_2 < F_{22}$, then $EM_{2tt} > EM_{2tw}$, and $ES_{2tt} > ES_{2tw}$.

This proposition indicates that if the competing supply chain offers a two-part pricing contract, the other supply chain can adjust the fixed fee within the range (F_{21}, F_{22}) , which heavily depends on competition intensity and regional rainfall use efficiency. Using the two-part pricing contracts can realize Pareto improvement for the suppliers and distributor at the same time (Corbett & Karmarkar 2001; Du et al. 2016).

A numerical analysis

To better observe the effects of parameter changes on the supply chain system and the performance of individual members, this section presents a numerical analysis. Both the Eastern and Middle Routes transfer water to Northern China, in particular, both routes supply water for Tianjin City. The rainfall use efficiency is reported less than 5% in Tianjin (Liu et al. 2015). There are three water types according to which sectors the water is used, including (1) domestic, (2) industrial, municipal, and water for business purposes, and (3) water for special purposes. The domestic water use is charged based on a ladder-type water fee at 4.9/6.2/8.0 Yuan (1 USD = 6.80 Yuan)/m³; the industrial

water price is 7.9 Yuan/m³; the water price for special purposes is 22.3 Yuan/m³ (Tianjin 2015, 2017). Thus, the average water price is 12 Yuan/m³. For simplicity, assume the local rainfall use efficiency ψ is 0.03, and the water price a is 10 Yuan/m³. As the competition intensity shows differing effects when it is lower than 0.5723 and when higher, this section considers the performance of the supply chains separately. The study first presents results of the numerical analysis with varying competition intensity levels and constant regional rainfall and then presents the results of rainfall changes and constant competition intensity.

Results in Table 1 show under the three contract combinations, the parameters of water supply chain system change as the competition intensity changes, and some changes of the parameters are drastic. When both suppliers in the two competing water supply chains choose wholesale price contracts, there is no fixed fee in the supply chain system, thus the performance of the supply chain members and the entire system cannot be adjusted through changing the fixed fee. However, the parameters of all members and the system decrease as the competition intensity increases.

When mixed contracts are chosen (a wholesale price contract for one chain and a two-part pricing contract for the other chain), the supplier with the two-part pricing contract can change the expected profits through adjusting the fixed fee in a certain range given by government. In this case, the water supplier can maximize his profits. When the competition intensity equals 0.5723, the fixed fee F_1 can be determined by equaling the lower and upper bounds, i.e., $F_{11} = F_{12}$. This indicates when the competition is weak, the fixed fee is in a range, and this range gets smaller as the competition intensity increases, and when the competition is strong, the range for the fixed fee gets larger as the competition intensity increases. These changes further increase or decrease the expected profits of the suppliers and the entire supply chain system. When the suppliers choose two-part pricing contracts at the same time, both can make a difference in the expected profits of all members and the systems through changing their fixed fees.

Interestingly, the results under the three contract combinations show the fixed costs in both Middle and Eastern Routes are correlated with the expected profits of both suppliers and distributors, rather than the performance of the entire supply chain. With the wholesale price contracts

(ww), the performance of both Middle and Eastern Routes decreases as the competition intensity increases, but their expected profits are always equal. With one wholesale price contract and one two-part pricing contract (tw), the expected profit of the supply chain using the two-part pricing contract increases faster than that using the wholesale price contract. Thus, the total system profits are larger than that under the ww contracts. With the two-part pricing contracts (tt), the expected profit of each supply chain is greater than that under the ww contracts, and the total system profit is even greater than that under the tw contracts. In this case, both individual supply chains and the entire system achieve optimal performance, and the total system profit is greatest among the three contract combinations.

Table 2 shows the results of weak competition between water distributors under three different contract combinations. All parameters of the members and the entire system decrease as the average rainfall increases. In a similar vein, when the competition intensity is strong, as shown in Table 3, all parameters also decrease as the average rainfall increases. Table 3 shows with a strong competition intensity the range of decrease is much larger than that under a weak competition in Table 2. The range of fixed fee under a strong competition (Table 3) is much larger than that under a weak competition in Table 2. This suggests a stronger competition makes water suppliers adjust the fixed fee easier (Arshinder et al. 2008; Du et al. 2018), and the suppliers can have more flexibility as the regional rainfall increases (Chen et al. 2013; Du et al. 2016).

A comparison between Tables 2 and 3 shows the competition intensity presents varying effects on the supply chain members and the system under the three contract combinations. With wholesale price contracts (ww), the expected profits of the suppliers, distributors and each supply chain decrease as the competition intensity increases. A stronger competition intensity is not favorable for the performance of supply chains under the ww contracts, and it is a barrier for profit increase (Srdjevic et al. 2004). With a wholesale price contract and a two-part pricing contract (tw), a stronger competition intensity is favorable for the chain using the two-part pricing contract, while unfavorable for the other chain using the wholesale price contract (Corbett & Karmarkar 2001; Du et al. 2016). The profit of the total system, however,

Table 1 | Values of parameters in the water supply chain system with varying competition intensity levels, given $a = 10$, $\psi = 0.03$, and $r = 180$

		$\beta = 0.2$	$\beta = 0.4$	$\beta = 0.6$	$\beta = 0.8$
<i>ww</i>	w_1	2.1789	2.0444	1.8941	1.7250
	w_2	2.1789	2.0444	1.8941	1.7250
	d_1	1.1005	1.0648	1.0407	1.0268
	d_1	1.1005	1.0648	1.0407	1.0268
	ES_1	1.2111	1.1338	1.0831	1.0543
	ES_2	1.2111	1.1338	1.0831	1.0543
	EM_1	2.3979	2.177	1.9713	1.7712
	EM_2	2.3979	2.177	1.9713	1.7712
	ET_1	3.6089	3.3108	3.0544	2.8255
	ET_2	3.6089	3.3108	3.0544	2.8255
<i>tw</i>	F_{11}	2.4869	2.4915	2.6216	2.8721
	F_{12}	3.2414	2.7975	2.5300	2.3861
	F_{13}	129.1552	103.3772	85.4869	71.9116
	F_{14}	421.9957	357.8862	306.0187	260.6310
	F_{21}	2.2485	2.0443	1.9693	1.9971
	F_{22}	3.3619	3.0304	2.8885	2.907
	w_1	-0.0444	-0.1758	-0.4044	-0.7649
	w_2	2.0678	1.8224	1.5493	1.227
	d_1	2.2177	2.1981	2.2468	2.3903
	d_1	1.0443	0.9492	0.8513	0.7304
	ES_1	4.9184 - F1	4.8316 - F1	5.0482 - F1	5.7135 - F1
	ES_2	1.0906	0.9009	0.7247	0.5334
	EM_1	-0.0984 + F1	-0.3865 + F1	-0.9087 + F1	-1.8283 + F1
	EM_2	2.1595	1.7298	1.3189	0.8962
	ET_1	4.82	4.4451	4.1396	3.8852
	ET_2	3.2501	2.6307	2.0436	1.4296
<i>tt</i>	F_{11}	2.4869	2.4915	2.6216	2.8721
	F_{12}	3.2414	2.7975	2.5300	2.3861
	F_{13}	129.1552	103.3772	85.4869	71.9116
	F_{14}	421.9957	357.8862	306.0187	260.6310
	F_{21}	2.2485	2.0443	1.9693	1.9971
	F_{22}	3.3619	3.0304	2.8885	2.907
	w_1	-0.0422	-0.1586	-0.3421	-0.5935
	w_2	-0.0422	-0.1586	-0.3421	-0.5935
	d_1	2.1101	1.9828	1.9008	1.8548
	d_1	2.1101	1.9828	1.9008	1.8548
	ES_1	4.4525 - F1	3.9313 - F1	3.6131 - F1	3.4404 - F1
	ES_2	4.4525 - F2	3.9313 - F2	3.6131 - F2	3.4404 - F2
	EM_1	-0.089 + F1	-0.3145 + F1	-0.6504 + F1	-1.1009 + F1
	EM_2	-0.089 + F2	-0.3145 + F2	-0.6504 + F2	-1.1009 + F2
	ET_1	4.3634	3.6168	2.9628	2.3395
	ET_2	4.3634	3.6168	2.9628	2.3395

ww: wholesale price contracts for both supply chains; *tw*: a two-part pricing contract and a wholesale price contract; *tt*: two-part pricing contracts for both supply chains.

is still greater than that under the *ww* contracts. In this case, the competition intensity helps redistribute profit among supply chain members and increase the total system profit (Srdjevic et al. 2004; Wu 2013). With the two-part pricing contracts (*tt*), the expected profits of supply chain members are related to the fixed costs of each corresponding supply

chain, the total system profit is independent of the fixed costs (Cachon 2003; Chen & Wang 2012). Therefore, the competition intensity is unfavorable for the two supply chains and the entire system (Du et al. 2016).

In addition to the effect of competition intensity on the entire supply chain system mentioned above, comparisons

Table 2 | Values of parameters in the water supply chain system with changing average rainfall, given $a = 10$, $\psi = 0.03$, and $\beta = 0.2$

		$r = 100$	$r = 150$	$r = 200$	$r = 300$
<i>ww</i>	w_1	3.3158	2.6053	1.8947	0.4737
	w_2	3.3158	2.6053	1.8947	0.4737
	d_1	1.6746	1.3158	0.9569	0.2392
	d_1	1.6746	1.3158	0.9569	0.2392
	ES_1	2.8044	1.7313	0.9157	0.0572
	ES_2	2.8044	1.7313	0.9157	0.0572
	EM_1	5.5528	3.428	1.8131	0.1133
	EM_2	5.5528	3.428	1.8131	0.1133
	ET_1	8.3572	5.1593	2.7289	0.1706
ET_2	8.3572	5.1593	2.7289	0.1706	
<i>tw</i>	F_{11}	5.759	3.5553	1.8805	0.1175
	F_{12}	16.5135	10.1946	5.3922	0.337
	F_{13}	299.0834	184.6382	97.6599	6.1037
	F_{14}	977.2112	603.2783	319.0894	19.9431
	F_{21}	5.2068	3.2144	1.7002	0.1063
	F_{22}	7.785	4.8061	2.542	0.1589
	w_1	-0.0675	-0.0530	-0.0386	-0.0096
	w_2	3.1466	2.4723	1.7981	0.4495
	d_1	3.3748	2.6517	1.9285	0.4821
	d_1	1.5892	1.2487	0.9081	0.2270
	ES_1	11.3895 - F1	7.0312 - F1	3.719 - F1	0.2324 - F1
	ES_2	2.5256	1.5592	0.8247	0.0515
	EM_1	-0.2278 + F1	-0.1406 + F1	-0.0744 + F1	-0.0046 + F1
	EM_2	5.0006	3.0871	1.6329	0.1021
	ET_1	11.1617	6.8906	3.6446	0.2278
ET_2	7.5262	4.6463	2.4575	0.1536	
<i>tt</i>	F_{11}	5.759	3.5553	1.8805	0.1175
	F_{12}	16.5135	10.1946	5.3922	0.337
	F_{13}	299.0834	184.6382	97.6599	6.1037
	F_{14}	977.2112	603.2783	319.0894	19.9431
	F_{21}	5.2068	3.2144	1.7002	0.1063
	F_{22}	7.785	4.8061	2.542	0.1589
	w_1	-0.0642	-0.0505	-0.0367	-0.0092
	w_2	-0.0642	-0.0505	-0.0367	-0.0092
	d_1	3.211	2.5229	1.8349	0.4587
	d_1	3.211	2.5229	1.8349	0.4587
	ES_1	10.3106 - F1	6.3652 - F1	3.3667 - F1	0.2104 - F1
	ES_2	10.3106 - F2	6.3652 - F2	3.3667 - F2	0.2104 - F2
	EM_1	-0.2062 + F1	-0.1273 + F1	-0.0673 + F1	-0.0042 + F1
	EM_2	-0.2062 + F2	-0.1273 + F2	-0.0673 + F2	-0.0042 + F2
	ET_1	10.1044	6.2379	3.2994	0.2062
ET_2	10.1044	6.2379	3.2994	0.2062	

ww: wholesale price contracts for both supply chains; *tw*: a two-part pricing contract and a wholesale price contract; *tt*: two-part pricing contracts for both supply chains.

between *tw* and *tt* in Tables 1–3 indicate government can adjust the fixed costs to balance the profits of the supply chains (Du et al. 2018). The investments are more controllable by the government, and more effective as well to change the performance of local suppliers and distributors (Ai et al. 2012; Chen & Wang 2012; Wu 2013).

CONCLUSIONS

In this research, the Eastern and Middle Routes of SNWTP are considered competing water supply chains. Each supply chain consists of a risk-neutral supplier and a risk-neutral distributor. Taking regional rainfall into

Table 3 | Values of parameters in the water supply chain system with changing average rainfall, given $a = 10$, $\psi = 0.03$, and $\beta = 0.8$

		$r = 100$	$r = 150$	$r = 200$	$r = 300$
<i>ww</i>	w_1	2.625	2.0625	1.5	0.375
	w_2	2.625	2.0625	1.5	0.375
	d_1	1.5625	1.2277	0.8929	0.2232
	d_1	1.5625	1.2277	0.8929	0.2232
	ES_1	2.4414	1.5072	0.7972	0.0498
	ES_2	2.4414	1.5072	0.7972	0.0498
	EM_1	4.1016	4.0393	1.3393	0.0837
	EM_2	4.1016	4.0393	1.3393	0.0837
	ET_1	6.543	2.5321	2.1365	0.1335
	ET_2	6.543	2.5321	2.1365	0.1335
<i>tw</i>	F_{11}	6.651	4.106	2.1718	0.1357
	F_{12}	15.4716	9.5513	5.0519	0.3157
	F_{13}	166.525	102.8037	54.3755	3.3985
	F_{14}	603.5406	372.5939	197.0745	12.3172
	F_{21}	4.6247	2.855	1.5101	0.0944
	F_{22}	6.7317	4.1558	2.1981	0.1374
	w_1	-1.1640	-0.9145	-0.6651	-0.1663
	w_2	1.8672	1.4671	1.067	0.2667
	d_1	3.6374	2.8580	2.0785	0.5196
	d_1	1.1114	0.8733	0.6351	0.1588
	ES_1	13.2308 - F1	8.168 - F1	4.3203 - F1	0.27 - F1
	ES_2	1.2353	0.7626	0.4024	0.0252
	EM_1	-4.2338 + F1	-2.6138 + F1	-1.3825 + F1	-0.0864 + F1
	EM_2	2.0753	1.2812	0.6776	0.0424
ET_1	8.9969	5.5542	2.9378	0.1836	
ET_2	3.3106	2.0438	1.081	0.0676	
<i>tt</i>	F_{11}	6.651	4.106	2.1718	0.1357
	F_{12}	15.4716	9.5513	5.0519	0.3157
	F_{13}	166.525	102.8037	54.3755	3.3985
	F_{14}	603.5406	372.5939	197.0745	12.3172
	F_{21}	4.6247	2.855	1.5101	0.0944
	F_{22}	6.7317	4.1558	2.1981	0.1374
	w_1	-0.9032	-0.7097	-0.5161	-0.129
	w_2	-0.9032	-0.7097	-0.5161	-0.129
	d_1	2.8226	2.2177	1.6129	0.4032
	d_1	2.8226	2.2177	1.6129	0.4032
	ES_1	7.967 - F1	4.9184 - F1	2.6015 - F1	0.1626 - F1
	ES_2	7.967 - F2	4.9184 - F1	2.6015 - F1	0.1626 - F1
	EM_1	-2.5494 + F1	-1.5739 + F1	-0.8325 + F1	-0.0520 + F1
	EM_2	-2.5494 + F2	-1.5739 + F1	-0.8325 + F1	-0.0520 + F1
ET_1	5.4175	3.3445	1.769	0.1106	
ET_2	5.4175	3.3445	1.769	0.1106	

ww: wholesale price contracts for both supply chains; *tw*: a two-part pricing contract and a wholesale price contract; *tt*: two-part pricing contracts for both supply chains.

consideration, this study investigates the performance improvement under two-part pricing contracts compared to wholesale price contracts. Furthermore, this study analyzes the effects of competition intensity and rainfall use efficiency on contract choosing behaviors. The

theoretical and empirical analyses show some main findings.

1. Under different contracts, the parameters of the supply chain members and the entire system decrease as the

competition intensity increases. However, the suppliers can affect the expected profits of all members and the system through adjusting the range of the fixed fees.

- Under different contracts, when the competition is weak, all parameters of the supply chains decrease as the average rainfall increases. While when the competition is strong, all parameters also show a decrease, but the decreasing trend is much larger than the range under a weak competition. Similarly, the adjusting range for the fixed fees under a strong competition is larger than that under a weak competition.

The limitation of our research is from the assumption of risk-neutral supply chain members and each supply chain consisting of one supplier and one distributor. One important extension of this work in the near future is to include stochastic demand, supply costs, and environmental costs (Wu 2013; Kanakoudis & Papadopoulou 2014; Kanakoudis 2015; Li 2017). Another future research can examine the structural models with multiple supply chains incorporating risk-averse water suppliers and distributors (Chen et al. 2015; Du et al. 2018).

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