

Article

Pricing Strategy for Residential Water in Drought Years. Application to the City of Tianjin, China

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Abstract: In drought years, most residents fail to improve water use efficiency due to residential water supply normally being prioritized in many regions, which makes other low-priority industrial water users suffer more from water shortage. This paper proposes a Pricing Strategy for Residential Water (PSRW), a water tariff that changes on annual time scale, based on the scarcity value of water resources, aiming to promote residential water conservation and reallocate water resources across the residential and industrial sectors during droughts. An optimization model to maximize the total benefit of residents and industrial sectors is introduced based on marginal benefit and price elasticity. The water shortage of industrial sectors is used to reflect the scarcity of water resources, and the lowest water supply standard for households and the maximum proportion of household water fee expenditure (HWFE) to household disposable income (HDI) are used to ensure the residents' acceptability to price raising. It shows an "S-type" relationship between the optimal price raising coefficient and industrial water shortage, and two turning points are found in the curve, which are the starting and stopping points of price raising. The appearance of starting point depends on the non-negative net benefit, and the stopping point is affected by the factors that represent the residents' acceptability to price raising. The application to Tianjin, a city in northern China with the rapid growth of population and economy but scarce water resources, shows PSRW is a potential means to improve water efficiency and optimize water resource allocation in water scarcity situations.

Keywords: scarcity pricing; pricing strategy in drought years; residential water; price elasticity



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1. Introduction

In recent years, with the influence of climate change and high-intensity human activities, extreme regional droughts happen frequently and severely, and water supply security in mega-cities becomes more and more prominent. For example, reservoirs ran below the dead water levels during the two drought events: California (USA) drought from 2012 to 2016 and Shandong (China) drought from 2010 to 2018. Under the condition of limited water resources, the change of residential water use behaviors is critical for water conservation. However, most residents fail to notice the shortage of water resources, and do not improve water use efficiency during droughts, due to residential water supply usually being prioritized in many regions [1]. The above phenomenon makes other low-priority users (e.g., industrial water users) suffer more from urban water shortage, leading to the simultaneous occurrence of water waste for high-priority users and water shortage for low-priority users.

To solve this problem, water administrative departments in many regions have begun to intervene in residential water use [2,3]. Usually, government intervention is embodied in two forms: prescriptive regulation and water pricing [4]. The most typical example

of prescriptive regulation is the “Hosepipe Ban” in England, which is implemented to restrict residential water use in gardens, car washes, and swimming pools during droughts. Although prescriptive regulation could change residential water use behaviors to some extent, water pricing policy is potentially a more effective means to foster urban water conservation, while maintaining equity in scarcity situations [5–9]. The shift of water policies to discontinuous pricing structures, such as increasing-block rates, is a typical instance of current attitudes toward water pricing [10]. However, the current increasing-block rates in most regions fail to be economically efficient in water conservation, since water prices are often underestimated [11–13].

The current water prices are only related to water consumption and not linked to water availability [14,15]. In other words, the scarcity value of water resources should be considered in the formulation of water prices. The scarcity value of water resources can be explained as the change in the marginal benefit of water use under different water availability and water demand levels [16]. Marginal benefit of water use is the benefit gained by increasing additional unit water to any user, whereby marginal resource opportunity cost (MROC) [17,18], which would be greater as the gap between water demand and water availability becomes larger. Due to the water supply priority rules adopted in most regions, it is possible that the marginal benefit of low-priority water users (e.g., industrial water users) who suffer more water shortage is greater than that of high-priority water users (e.g., residential water users) in drought years. Yet, in economic terms, the efficient management of water resources could be realized only when the marginal benefit of any water user is the same. Thus, it is necessary to establish a dynamic water pricing strategy based on the marginal benefit of water use so that more water could be saved and allocated to users with higher marginal benefits, thereby increasing water use efficiency and social benefits [19].

2. Literature Review

There have been studies paying attention to dynamic water pricing linked to the marginal benefit of water use. Rouge et al. [20] provided an economic engineering conceptual framework for smart meter-enabled dynamic pricing of residential water. They linked water tariff design, across a range of timescales, to potential benefits at the utility and river basin scale. In particular, tariffs that use sub-daily price variations were designed to yield benefits by reducing the cost of supply in distribution networks, whereas weekly or monthly variations were appropriate for scarcity pricing. However, the implementation of these dynamic water tariffs relies on smart water metering which can collect real-time water use information. Although previous researches [21–27] indicate that many regions have tried to use smart water meters, most of them only conducted pilot applications locally, which is not enough to support the formulation of dynamic water pricing policy for the entire region. Moreover, the implementation of smart water meters could be difficult for low-income consumers due to their expensive prices. Thus, water tariffs change at annual timescales are more realistic and feasible at this stage for most regions.

For urban water users, their annual water demands remain stable over a short term (less than 5 years), and the changes in the marginal benefit of water use depend mainly on annual water resource availability which fluctuates significantly. Therefore, water tariff that changes on annual time scale could match with the scale of urban water supply uncertainty, and the scarcity value of water resources could be reflected well. When the amount of annual water resource availability is much less than the amount of annual water demand, the marginal benefit of water use gets greater and the water price should be higher. Moreover, the annual water tariffs allow the establishment and publication of water prices at the beginning of every year, avoiding frequent changes in water prices and improving management efficiency. Relevant scholars have already carried out research on annual-scale dynamic water prices. Sahin et al. [28] simulated water pricing strategies with different annual tariff structures based on a system dynamics model. Its application in Australia’s populated southeast Queensland region demonstrated that introducing temporary drought pricing (i.e., progressive water prices set inverse with water availability) could reduce

the water use in scarcity periods. However, their water pricing strategies are not linked to the marginal benefit of water use. Macian-Sorribes et al. [29] proposed an efficient annual pricing policy based on the marginal benefit of water resources at the basin scale. Its application in Mijares River basin showed that this pricing policy could generate an incentive for water conservation during the scarcity periods and increase the economic benefit in the basin. However, the water price strategy they put forward is not for residential water. Lopez-Nicolas et al. [19] presented a framework for designing equitable, financially stable and economically efficient urban water tariffs. Rates were dynamic in the sense that they vary every year according to the estimated marginal value of water, which was linked to water scarcity and water demand. However, the above research did not analyze the acceptability of users for price increases, which is an important factor affecting the feasibility of water prices.

In this paper, we develop a Pricing Strategy for Residential Water (PSRW) in drought years, which is a water tariff that changes on an annual time scale, clarifying the starting conditions for a price increase during droughts. The PSRW is used to stimulate residents to save water and reallocate the saved water to industrial users whose water supply is significantly reduced during droughts, thereby increasing the total benefits of residents and industrial users. The PSRW is determined by an optimization model based on the marginal benefit of water use, considering the constraints that reflects the acceptability of users for PSRW: the lowest water use standard for households and the maximum proportion of household water fee expenditure (HWFE) to household disposable income (HDI). The PSRW is applied to Tianjin, China, where water resources are scarce while population and gross domestic product (GDP) grow rapidly. The uncertainties of price elasticity of residential water and output elasticity of industrial water on PSRW are discussed.

3. Optimization Model of PSRW in Drought Years

In drought years, raising water price temporarily is an effective approach for residents to restrain water waste and promote water conservation, but not for industrial water users, whose water conservation depends on long-term process improvement and equipment remodeling. Therefore, this paper focuses on the PSRW in drought years, which is based on the current pricing strategy. The current water pricing strategy for residential water in China is an increasing-block water tariff, i.e., water price increases with water usage, and there are usually three blocks of water prices, from low to high, in most cities [30,31], as shown in Figure 1. An optimization model of PSRW is constructed to determine the price raising coefficients of each block under different industrial water shortage conditions, thereby obtaining the amount of residential water saving that could be reallocated to industrial water users. On the premise of ensuring residential basic water and the water fee expenditure within the scope of residents' acceptability, the PSRW aims to reduce industrial losses during droughts as much as possible.

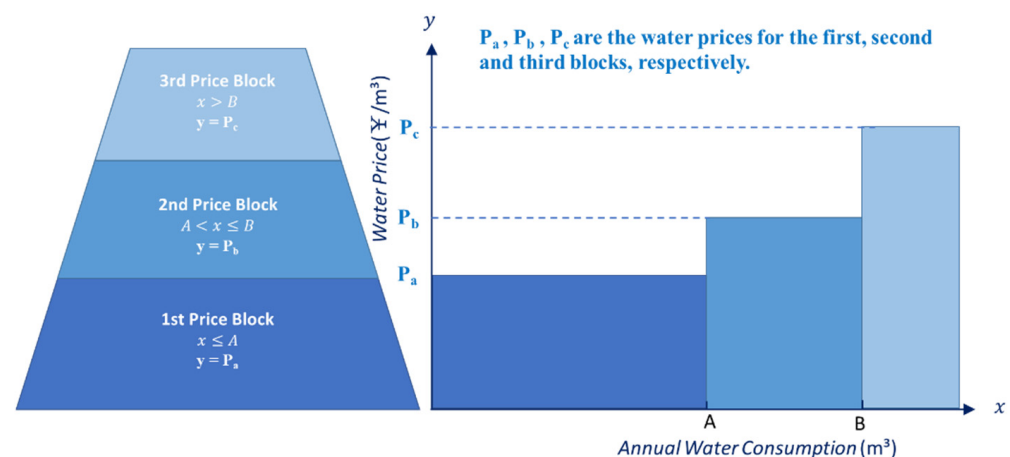


Figure 1. Increasing-block water rate for residential water use with three price blocks.

3.1. Objective Function

By raising the price of residential water in drought years, residential water consumption and its benefit of water use could be reduced. However, the residential water fee expenditure could be either decreased or increased under the combined influence of price raising and water conservation. The conserved residential water could be reallocated to industries, whose benefit of water use and water fee expenditure could be increased. With residential and industrial water use being taken as a whole, compared with the water use prior to price raising, the increased net benefit of the water use, i.e., total increased benefits minus total increased water fee, should be the larger the better.

An optimization model for PSRW is set up with objective function as follows:

$$\max NB = BIT_{res} + BIT_{ind} - FEE_{res} - FEE_{ind} \quad (1)$$

where NB is the increased net benefit of residential and industrial water uses after price raising; BIT_{res} and BIT_{ind} are the increased benefits of residential water use and industrial water use after price raising, respectively; FEE_{res} , and FEE_{ind} are the increased water fee expenditures of residential water use and industrial water use after price raising, respectively.

BIT_{res} is the decreased benefit with the water supply to residential use reduced from $\sum_{i=1}^M \sum_{j=1}^N Q_{ij0}^r$ to $\sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r)$ after price raising. $g(y)$ is the marginal benefit function of residential water use y , and should decrease as residential water use y increases in theory. BIT_{res} could be represented in the following form:

$$BIT_{res} = - \int_{\sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r)}^{\sum_{i=1}^M \sum_{j=1}^N Q_{ij0}^r} g(y) dy \quad (2)$$

BIT_{ind} is the increased benefit with the water supply to industrial use increased from S_{ind}^0 to $S_{ind}^0 + \sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r)$ after price raising. $f(x)$ is the marginal benefit functions of industrial water use x , and should decrease as industrial water use x increases in theory. BIT_{ind} could be represented in the following form:

$$BIT_{ind} = \int_{S_{ind}^0}^{S_{ind}^0 + \sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r)} f(x) dx \quad (3)$$

where S_{ind}^0 is the water supply to industrial use during the drought, which is less than the water demand of industrial sectors D^{in} , M is the number of price blocks, N is the number of residential water users in each price block, respectively, Q_{ij0}^r and Q_{ij}^r are the annual residential water supplies for the j th residential water user in the i th price block before and after price raising, respectively, $\sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r)$ is the conserved annual residential water or the increased annual industrial water after price raising.

FEE_{res} , the increased water fee expenditure of the residential water use after price raising, is described as:

$$FEE_{res} = \sum_{i=1}^M \sum_{j=1}^N (\alpha_i P_{i0}^r Q_{ij}^r - P_{i0}^r Q_{ij0}^r) \quad (4)$$

where P_{i0}^r and α_i are the original price and the price raising coefficient for residential water use in the i th price block, respectively. The price raising coefficients for residential water use in each price block are the variables that need to be optimized.

FEE_{ind} , the increased water fee expenditure of the industrial water use after price raising, is described as:

$$FEE_{ind} = P^{in} \sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r) \quad (5)$$

where P^{in} is the industrial water price in this year.

According to the price elasticity theory, water price is negatively related to water demand, i.e., E , the price elasticity coefficient, is negative generally. E could be estimated by analyzing the relationship between residential water demand, water price, household income and other influencing factors. Double logarithmic models are often used to fit the relationship curve [32]. After water price changing, water demand changes in the following form [33]:

$$\frac{Q}{Q_0} = \left(\frac{P}{P_0} \right)^E \quad (6)$$

where Q_0 and Q are water demand before and after price raising, respectively, P_0 and P are the original and raised price, respectively. Therefore, with the premise of the residential water use distribution in various price blocks, annual residential water use after price raising are obtained with the price elasticity theory:

$$Q_{ij}^r = Q_{ij0}^r \left(\frac{\alpha_i P_{i0}^r}{P_{i0}^r} \right)^{E_i} = \alpha_i^{E_i} Q_{ij0}^r \quad (7)$$

where E_i is the price elasticity coefficient in the i th price block for residential water use.

3.2. Constraints

3.2.1. Maximum and Minimum Water Supply

In drought years, basic residential water use should be met prior to other uses, i.e., the water supply for each residential water user could not be less than its basic water demand D_{min}^r , however, industrial water use would be reduced to some extent due to its lower priority in general, i.e., annual industrial water supply would be less than or equal to its annual demand D^{in} , as shown in following forms:

$$Q_{ij}^r \geq D_{min}^r \quad (8)$$

$$0 \leq S_{ind}^0 + \sum_{i=1}^M \sum_{j=1}^N (Q_{ij0}^r - Q_{ij}^r) \leq D^{in} \quad (9)$$

3.2.2. Residential Acceptability to Price Raising

The extent of resident acceptability to the increasing-block water price scheme should be considered, i.e., the proportion of HWFE to HDI should be in a reasonable range, as described in the following form:

$$\frac{\sum_{i=1}^M \sum_{j=1}^N \alpha_i P_{i0}^r Q_{ij}^r}{H \times U \times V} \leq \theta \quad (10)$$

where H is the number of households, U is average number of persons in each household, V is the per capita disposable income, and θ is the acceptable maximum proportion of HWFE to HDI. The research [32] indicates that: when the proportion of HWFE to HDI is in the range of 1 to 2%, residents can accept the water price and begin to be concerned with water consumption; when the proportion of HWFE to HDI is in the range of 2 to 2.5%, residents' lives are affected to some extent and residents begin to be concerned with water fee; when the proportion of HWFE to HDI is in the range of 2.5 to 3%, residents begin to pay attention to water conservation; when the proportion of HWFE to HDI reaches the range of 3 to 5%, residents are affected to a greater extent and begin to consider water reuse. However, since the water prices in most regions have been low, a sudden and large price increase will cause a series of social problems, so the value of θ should also refer to the actual situation in different regions.

3.2.3. Price Raising Coefficient

To promote residential water conservation effectively, the price raising coefficient for water users in higher price level should not be less than that in lower price level, and the price raising coefficient of each price level should not be less than 1:

$$\alpha_i \geq \alpha_{i-1} \geq 1 \quad (11)$$

4. Case Study

4.1. Study Area

Tianjin, the largest coastal city in North China, is chosen because it has high economy and population growth rates but limited local water resources. According to the Tianjin Statistical Yearbook [34] and Tianjin Water Resources Bulletin in 2015 [35], there were 3.5 million households and 2.8 persons in each household, the per capita residential water use was 80 L per day and annual residential water use was $2.9 \times 10^8 \text{ m}^3$. The industrial water use in Tianjin was $5.6 \times 10^8 \text{ m}^3$, and the gross industrial production was 6981×10^8 CNY (Chinese Yuan). However, Tianjin's per capita water resources are 160 m^3 , which is only 2% of the world per capita level.

In order to relieve water shortage, Tianjin has been diverting water from other river basins of abundant water resources, including Luan River and Hanjiang River (Mid-route of South-to-North Water Diversion Project, MSNWDP). Meanwhile, alternative water sources, such as desalinated seawater, have been exploited to a certain extent. The water supply system of Tianjin in 2015 is shown in Figure 2. There are 3 main types of water sources supplying for 11 regions of 4 plates, including water transferred through the MSNWDP, water transferred from Luan River, and desalinated seawater. The streamflow from Luan River comes into YuQiao (YQ) reservoir, providing water for Tianjin together with the natural inflow of YQ reservoir. The streamflow from MSNWDP comes into Tianjin from WangQingtuo (WQT) reservoir. The two types of inter-basin water sources are diverted to 19 water treatment works (WTW). Desalinated seawater is mainly provided to coastal regions where it is produced.

Even so, the crisis of water shortage still exists [36,37], this is because (a) the transferable water from the two water diversion projects is uncertain due to the seasonality in the source region; (b) the capacity of existing water conveyance projects is insufficient to deal with the uncertainties in transferred water and runoff; (c) alternative water sources are limited to certain regions and users, for example, seawater desalinization could be only supplied to industrial production in the coastal region. Therefore, it is necessary to implement PSRW to increase the efficiency and overall benefit of water use in Tianjin.

4.2. Scenario Construction

The planned annual water demands for the period 2015 to 2020 are used. According to Tianjin Water Resources Bulletin in 2015 [35], the residential water demand is $2.9 \times 10^8 \text{ m}^3$, and the industrial water demand is $5.6 \times 10^8 \text{ m}^3$. In the process of delivering these 3 types of water sources to 19 waterworks in 11 districts of Tianjin, the available water is restricted by the uncertainties of the inflows from multiple water sources, pipeline connectivity, the capacities of water pipelines, and the capacities of waterworks. Moreover, the costs of delivering different water sources to different waterworks are various, and the optimization of urban water supply cost also affects the allocation of multiple water sources. These engineering characteristics determine that the allocation of water resources in Tianjin is a particularly complex problem. Therefore, it is difficult to identify drought years only by the storage of reservoirs, like the research of Lopez-Nicolas et al. [19]. The uncertainties of the inflows from multiple water sources, the capacities of water pipelines and waterworks, and the cost of water supply all affect the identification of drought year.

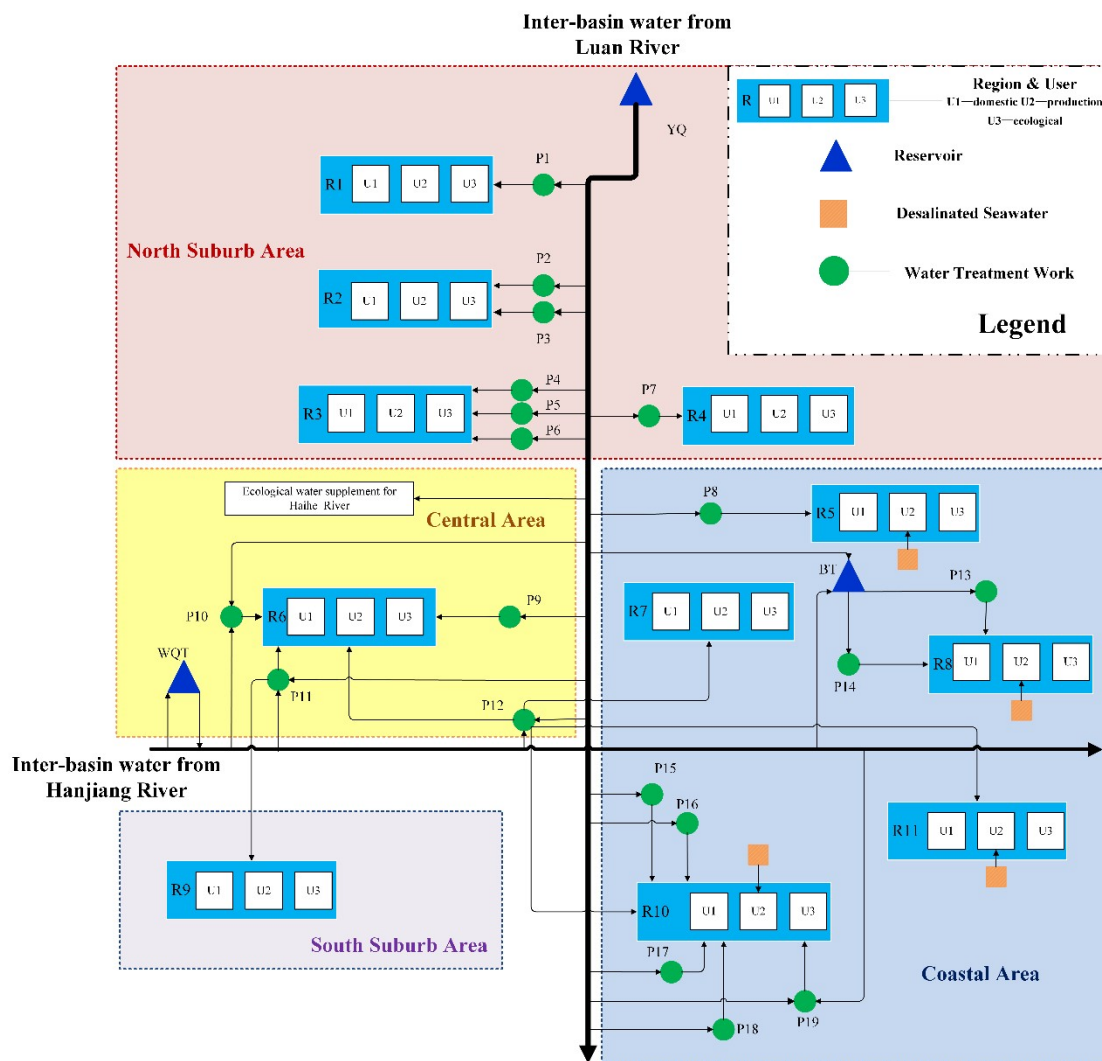


Figure 2. The topology network of the water supply system of Tianjin.

Considering that different available water will produce different water supply and water shortage, we convert the uncertainty of water availability into the uncertainty of water shortage, based on the multi-source optimal allocation model proposed in our previous studies [36,37]. The details of this model could be seen in Appendix A. This model considers the water delivery capacity of each link of “water source-waterworks-district user”, and could find higher performing solutions on the tradeoff between the urban water shortage and the urban water supply cost. It has been proven effective in optimizing the allocation of multiple water sources and evaluating the level of urban water shortage. On this basis, since the water supply priority of industrial users is lower than that of residential users in most regions, industrial users suffer more from urban water shortage, and their water shortage could be taken as the identification index for the extent of water scarce. In order to analyze the influence of different water scarce level on the price raising coefficient for residential water, 26 scenarios with different industrial water shortage levels, which starts from 0 to $5 \times 10^8 \text{ m}^3$, are constructed and applied as the input of the proposed optimization model of PSRW.

4.3. Residential Water Distribution

According to Tianjin Residential Water-use Quota [38], the range of the residential water-use quota in Tianjin municipality was between 70 and 120 L per person per day, i.e., the lowest water supply standard for meeting residential basic water demand was 70 L

per person per day. Residential water use data sample of 504 households from 108 typical communities in Tianjin surveyed by Shi et al. in 2015 [39] are used to fit the distribution of residential water through ranking the water consumption, as shown in Figure 3. The water use per person per day is 82 L and basically consistent with the data in the Tianjin Water Resources Bulletin in 2015. On this basis, the increasing-block water price scheme is carried out, where the critical values of annual water use for one household are 178 and 238 m³, and three increasing-block water prices are 4, 5.3, and 7.1 CNY, respectively. As shown in Figure 3, the proportion of households in the first price block is 95%, which is consistent with the original design guideline to guarantee that the 95% households could not be affected by the increasing-block water price scheme. Therefore, the surveyed samples are good representatives and could reflect the fundamental residential water use situation in Tianjin municipality practically. The residential water use distribution fitted by the sample is reliable and could be used to solve the optimization model of PSRW. Specific steps are as follows: first, use the optimization model of PSRW to determine the water savings of 504 households after the price increase; then, the per capita water saving of each block is determined according to the residential water use distribution; finally, combined with Tianjin's actual number of households and the per capita water saving of each block, the total water saving of each block is calculated, which is also the water transferred to industrial sectors. On this basis, the optimal price raising coefficient and the increased net benefit could be determined.

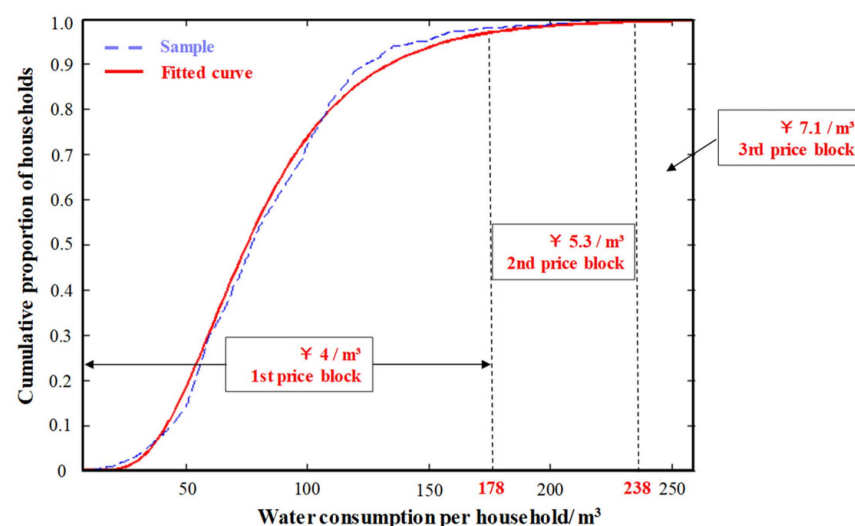


Figure 3. The distribution of residential water in Tianjin (sample).

4.4. Marginal Benefit of Industrial Water

The marginal benefit function of industrial water use $f(x)$ is described as the value of industrial output gained by increasing unit water based on the specific research on industrial water in Tianjin [40], expressed as follows:

$$f(x) = \frac{y\gamma}{1 - e^{-D^{in}}} e^{-x} \quad (12)$$

where y is annual value of industrial output, γ is the output elasticity of industrial water, i.e., the sensitivity of industrial output's variation response to the changes in water use when other factors of production are constant for industry, and D^{in} is the annual industrial water demand.

According to the Tianjin Statistical Yearbook [34] and Tianjin Water Resources Bulletin in 2015 [35], the industrial water demand in Tianjin municipality was 5.6×10^8 m³, the industrial water price was 6.65 CNY, and the gross industrial production was 6981×10^8 CNY. The output elasticity of industrial water, which was obtained by fitting the produce function including three producing elements, i.e., bankroll, labor force, and water resource,

based on [41], was 0.189 in 2015. The marginal benefits of different industrial water supplies can be computed with the above data, as shown in Figure 4, and it shows that with the increase in industrial water supply, the marginal benefit of water resource utilization decreased gradually.

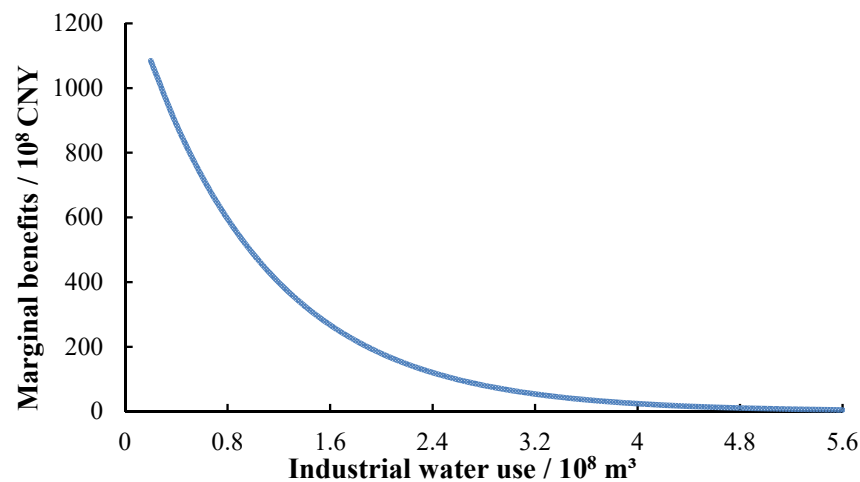


Figure 4. The marginal benefits of industrial water in Tianjin.

4.5. Other Parameters and Instructions

With regard to residential water, the marginal benefit of water use could decrease with the increase in water consumption. The marginal benefit of water use is very large when basic water demand is not met, however, the marginal benefit of water use is low when the water supply exceeds the basic water demand. Generally, with a higher priority level of water supply and larger planned water-use quota, the residential water use in drought years usually exceeds its basic demand. Therefore, the benefit of residential water use is slightly sacrificed, if only the portion of water above the basic residential water demand is saved and reallocated to industrial users. Since the amount of unsatisfied industrial water demand is usually large, the water conserved from the residential water supply may greatly benefit the industrial water supply. With price raising, compared with the increased benefit of industrial water use, the decreased benefit of residential water use is assumed to be negligible in this paper.

The price elasticity coefficient of residential water in Tianjin municipality is -0.12 , according to [42]. Generally, because households in different price blocks have different income levels and sensitivity to price increase, the price elasticity coefficients of households in different price blocks should also be different. However, the proportion of residential water users in the first price block of Tianjin has reached 95%, which means that the water consumption in the second and third price blocks accounts for a small proportion of the total residential water consumption, and the water saving potential of these two price blocks is limited. For the sake of simplicity, the price elasticity coefficients could be the same for the three price blocks, i.e., the value of E_i is -0.12 for all i in Equation (7).

In 2015, the proportion of HWFE to HDI in Tianjin municipality was 0.34% according to the Tianjin Statistical Yearbook [34,42]. In China, water prices are relatively low due to government compensation, and statistics indicate that the proportion of HWFE to HDI is lower than 1% in east-central-west regions of China [43]. Hence, the value of θ is given as 1% in Equation (10).

4.6. Solving Process

In the optimization model of PSRW, the price raising coefficients for residential water use in each price block are the variables that need to be optimized. The inputs of this model are as follows: (a) industrial water shortage obtained using a multi-source optimal allocation model (Industrial water supply S_{ind}^0 is equal to industrial water demand D^{in}

minus industrial water shortage); (b) the marginal benefit function related to the amount of industrial water supply S_{ind}^0 ; (c) industrial water price; (d) residential water distribution curve; (e) increasing-block water price for residential water. Under different industrial water shortage scenarios, Lingo software is used to solve the optimization model of PSRW and the price raising coefficients for residential water use in each block are determined. On this basis, total increased net benefit, conserved residential water, increased industrial water use benefit and increased residential water fee could be obtained using Equations (2)–(7) in Section 3.1. The solving process of the optimization model of PSRW could be seen in Figure 5.

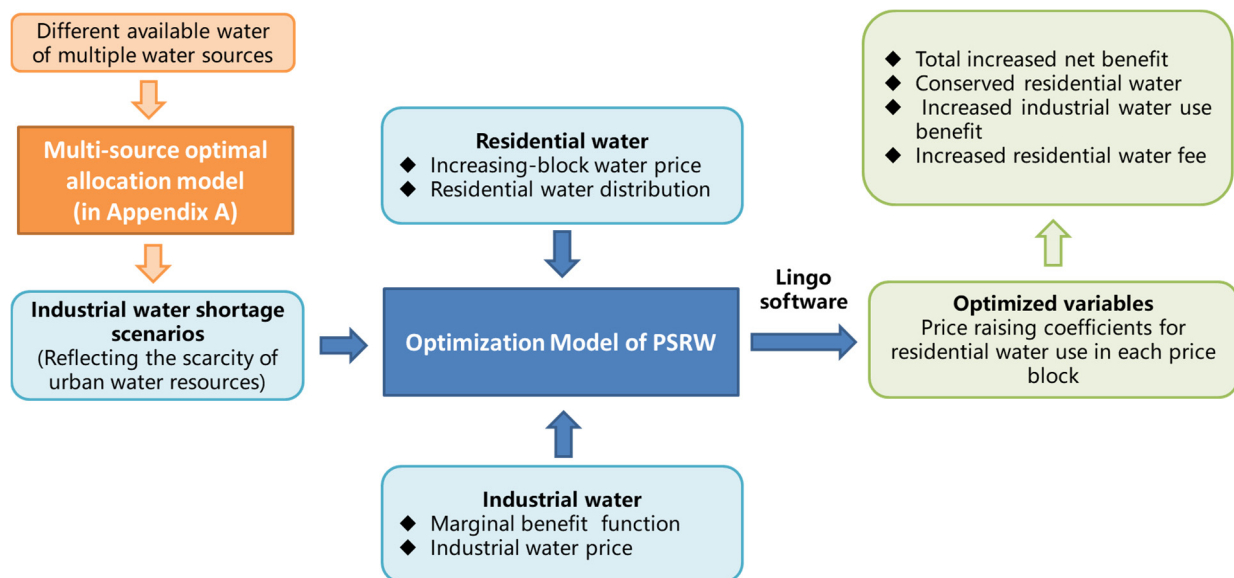


Figure 5. The solving process of the optimization model of PSRW.

5. Results

5.1. Pricing Strategy

The price raising coefficients of 26 industrial water shortage scenarios are determined through optimization. The results indicate that the net benefit of the water supply for residential and industrial water uses is largest when the price raising coefficients of each price block are equal, i.e., fair price increase strategy. This is because the price elasticity coefficients are the same for the three price blocks (See Section 4.5 for the reason). The optimal price raising coefficients and corresponding residential conserved water amounts under different industrial water shortage scenarios are shown in Figure 6a. It is observed that the two curves fit an S-type curve, in which two turning points exist. When the industrial water shortage is less than $2.0 \times 10^8 \text{ m}^3$, the optimal price raising coefficient is 1.0, i.e., price raising is not needed to promote residential water conservation. When the industrial water storage is between 2.0×10^8 and $3.4 \times 10^8 \text{ m}^3$, the optimal price raising coefficient and conserved residential water monotonically increase with the increase in industrial water shortage. When the industrial water storage is larger than $3.4 \times 10^8 \text{ m}^3$, the optimal price raising coefficient is 3.05, the maximum of conserved residential water is $0.36 \times 10^8 \text{ m}^3$, and then both the optimal price raising coefficient and the maximum of conserved residential water remain unchanged with the increase in industrial water storage.

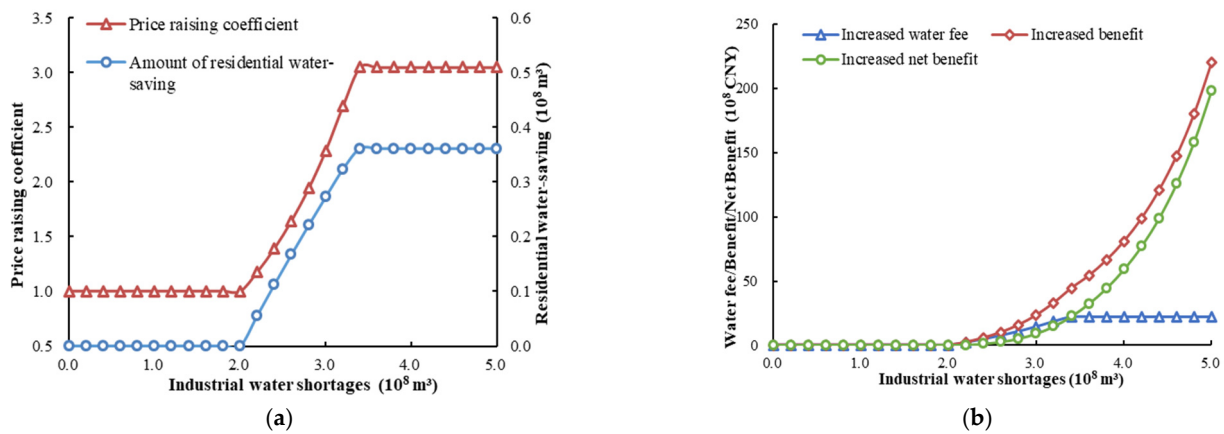


Figure 6. (a) The curves of the optimal price raising coefficient and residential water-saving with the change of industrial water shortages (b) The curves of increased water fee, increased benefit and increased net benefit with the change of industrial water shortages.

The curves of increased water fee, increased benefit and increased net benefit with the change of industrial water shortages are shown in Figure 6b. When the industrial water shortage is less than $2.0 \times 10^8 \text{ m}^3$, the increased benefit, water fee, and net benefit are all 0 because residential water prices for each block are not raised. When the industrial water shortage is between 2.0×10^8 and $3.4 \times 10^8 \text{ m}^3$, through price raising, the increased benefit is higher than the increased water fee expenditure, and the difference between the two increases with the water shortage getting larger. Therefore, the increased net benefit grows gradually and its growth rate becomes faster. When the industrial water shortage is larger than $3.4 \times 10^8 \text{ m}^3$, limited by the minimum residential water supply (70 L per person per day), the optimal price raising coefficient and conserved residential water reach the corresponding upper limits and remain unchanged. Meanwhile, the residential and industrial water fee expenditure also keep constant. However, with the increase in industrial water shortage, the marginal benefit of industrial water supply increases significantly, resulting in a greater increase in the benefit obtained by transferring the same amount of conserved residential water to the industrial sectors. Therefore, though the price raising coefficient and conserved water remain unchanged, the net benefit gets larger when the industrial water shortage is more severe.

In order to better explain the reasons for the above changes, three scenarios from the three sections of the S-type curve are selected for analysis, as shown in Table 1. When the industrial water shortages are 1.6×10^8 , 2.6×10^8 , and $3.6 \times 10^8 \text{ m}^3$, the optimal price raising coefficients determined by optimization model of PSRW are 1, 1.6, and 3.05, respectively. Furthermore, the optimal conditions of the three scenarios are shown in Figure 7.

Table 1. Optimization results with three industrial water shortage scenarios.

IWS 10^8 m^3	Price Raising Coefficient			CRW 10^8 m^3	CRW/RW	INB 10^8 CNY	IWB 10^8 CNY	IRWF 10^8 CNY	HWFE/HDI
	First Block	Second Block	Third Block						
1.6	1	1	1	0	0	0	0	0	0.32%
2.6	1.6	1.6	1.6	0.16	5.49%	2.58	9.64	6.00	0.48%
3.6	3.05	3.05	3.05	0.36	12.4%	32.21	53.69	19.11	0.85%

Note: IWS—Industrial water shortage; INB—Total increased net benefit; CRW—Conserved residential water; RW—Residential water; IWB—Increased industrial water use benefit; IRWF—Increased residential water fee.

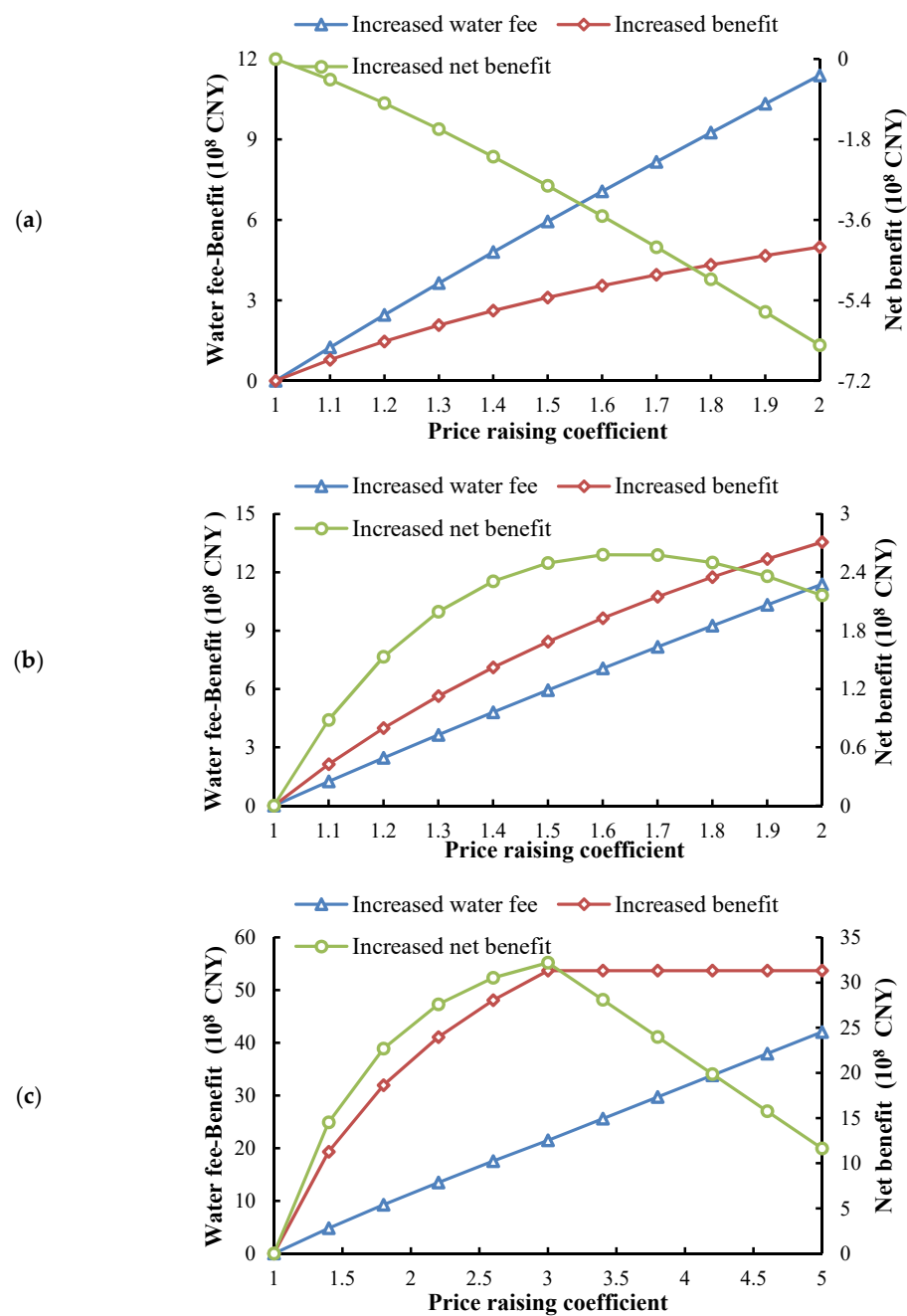


Figure 7. The curves of increased benefit, water fee and net benefit with the change of price raising coefficient: (a) industrial water shortage: $1.6 \times 10^8 \text{ m}^3$; (b) industrial water shortage: $2.6 \times 10^8 \text{ m}^3$; (c) industrial water shortage: $3.6 \times 10^8 \text{ m}^3$.

When the industrial water shortage is $1.6 \times 10^8 \text{ m}^3$, the price raising coefficients for three price blocks are all 1.0, i.e., the total increased net benefit is maximum when the price is not raised, as shown in Figure 7a. With the increase in the price raising coefficient, the total increased benefit of residential and industrial water use is always less than their increased water fee expenditure, and the total increased net benefit is negative or zero. Therefore, the total increased net benefit is greatest when the prices for three price blocks are not raised. This scenario is representative of the first section of the S-type curve. As shown in Figure 6a, when the industrial water shortage is less than $2.0 \times 10^8 \text{ m}^3$, the price is not needed to raise.

When the industrial water shortage is $2.6 \times 10^8 \text{ m}^3$, the increased net benefit curve climbs up and then declines, and the price raising coefficient corresponding to the highest

point in this curve is the optimal price raising coefficient, as shown in Figure 7b. Influenced by PSRW, the conserved residential water increases and then is transferred to industrial sectors. With the increase in industrial water, the benefit increases nonlinearly and shows a convex curve due to the decreased industrial marginal benefit. However, the residential and industrial water fees increase linearly with the increase in the price raising coefficient. Therefore, the difference between benefit and water fee climbs up and then declines, and the maximum of increased net benefit is 2.58×10^8 CNY with the optimal price raising coefficient of 1.6. This scenario is representative of the second section of the S-type curve. As shown in Figure 6a, when the industrial water shortage is between 2.0×10^8 and 3.4×10^8 m³, through price raising, the increased benefit is always higher than the increased water fee expenditure, and the difference between the two increases with the increase in water shortage. Therefore, to achieve the objective of maximum net benefit, the optimal price raising coefficient keeps increasing so that more conserved residential water could be transferred to industrial sectors.

When the industrial water shortage is 3.6×10^8 m³, the increased net benefit curve still has a turning point where the corresponding price raising coefficient is optimal. However, unlike the second scenario (with a water shortage of 2.6×10^8 m³), the increased net benefit decreased linearly after the turning point, as shown in Figure 7c. This variation is because that when the price raising coefficient increases to 3.05, with a restriction of the minimum residential water use (70 L per person per day), the conserved residential water reaches the maximum and no longer increases. After that, with the increase in price raising coefficient, the increased benefit remains unchanged, but the increased water fee continues to rise, resulting in a linear decline in the increased net benefit. Therefore, 3.05 is not only the optimal price raising coefficient in this scenario but also the maximum price raising coefficient of the S-type curve. This scenario is representative of the third section of the S-type curve. As shown in Figure 6a, when the industrial water shortage is larger than 3.4×10^8 m³, the optimal price raising coefficient and conserved residential water reach the corresponding upper limits and remain unchanged, and the total water fee expenditure of residential and industrial water use also remain unchanged. However, with the increase in industrial water shortage, the marginal benefit of industrial water supply increases significantly. This makes the increased benefit, which is obtained through transferring the same amount of conserved residential water to industrial sectors, more significant. In other words, though the price raising coefficient and conserved water remain unchanged, the net benefit gets larger in drier years.

In conclusion, two turning points in the S-type curve indicate the start and stop conditions of price raising in drought years. Under current water supply–demand relationship in Tianjin municipality, residential water price raising should start when industrial water shortage is larger than 2.0×10^8 m³, and it should cease when industrial water shortage is larger than 3.4×10^8 m³. The maximum residential water price raising coefficient is 3.05. With the increase in residential water price raising coefficient, the corresponding residential conserved water increases from 0 to 0.36×10^8 m³, and the highest proportion of conserved water to total residential water could reach 12.5%. The proportion of HWFE to HDI increases from 0.34 to 0.84%, and the highest net benefit reaches 198×10^8 CNY. According to the actual industrial water shortage and residents' acceptability to price raising, decision-makers could adopt the reasonable increasing-block water price raising scheme in drought years based on the curves of optimal price raising coefficient and net benefit.

5.2. Rationality Analysis of Pricing Strategy

With the increase in the optimal price raising coefficient, the proportion of HWFE to HDI increases linearly, as shown in Figure 8.

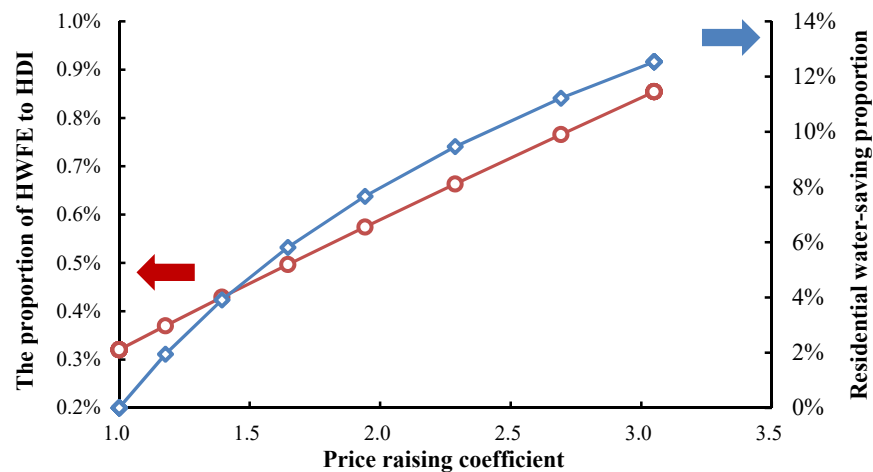


Figure 8. The curves of the residential conserved water proportion and the proportion of HWFE to HDI with the change of price raising coefficient.

For the residential water in Tianjin municipality, its price elasticity is relatively low, which means that increasing an additional unit water price will not save much water. Moreover, the conserved water is limited to the portion of water above the basic residential water demand. Hence, in order to achieve the objective of maximizing net benefit, the price raising coefficient increases rapidly, so that more residential water could be saved and reallocated to industrial sectors. Meanwhile, the rapid increase in water price plays a critical role to the increase in HWFE. Based on Tianjin Statistical Yearbook in 2015, the proportion of HWFE to HDI under the original price is 0.34%. When the price raising coefficient increases to 3.05, the proportion of HWFE to HDI reaches 0.84%, and the annual increased HWFE is 513 CNY. According to the data provided by the relevant water administration department of Tianjin, HDI and the proportion of HWFE to HDI during the period from 2003 to 2015 in Tianjin are shown in Figure 9. It is observed that the proportion of HWFE to HDI is larger and 1% at largest due to the lower HDI before 2008; it is about 0.40% from 2008 to 2012, and then declines gradually with the increase in HDI since 2012. With the PSRW in drought years applied, the threshold values of the proportion of HWFE to HDI are within its historical range, and it means that the range of threshold values is acceptable. Above all, PSRW could be implemented in Tianjin municipality.

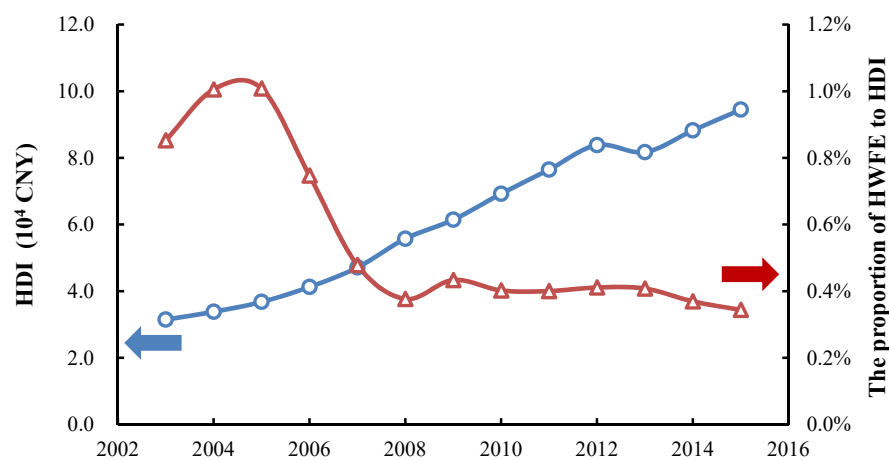


Figure 9. The curves of the HDI and the proportion of HWFE to HDI during the periods from 2003 to 2015.

As shown in the residential conserved water proportion curve in Figure 8, with the increase in price raising coefficient, the residential conserved water proportion increases with a slowdown gradually. This is because the closer residential water use to the basic

water demand, the more difficult water conservation, and the more insensitive residential water use to price raising. When the proportion of HWFE to HDI increases from 0.34 to 0.84%, residential water conservation increases from 0 to $0.36 \times 10^8 \text{ m}^3$, and the largest conserved water proportion is 12.5%. It is indicated in [42] that, when the proportion of HWFE to HDI was less than 1%, the increased conserved water would not less than $0.2 \times 10^8 \text{ m}^3$ with the proportion increased by 0.5%, which matches the results achieved in this paper.

5.3. Uncertainty Analysis of Price Elasticity of Residential Water

In the optimization model of PSRW, price elasticity coefficient, which reflects the level of residential sensitivity to price raising, is an important factor to determine the price raising coefficient. The absolute value of current price elasticity coefficient of residential water in Tianjin is relatively low, which means that the level of residential sensitivity to price raising is low. In order to further analyze the impact of price elasticity coefficient on PSRW, another two price elasticity coefficients, -0.15 and -0.18 , are used, and the corresponding results are compared with the price elasticity coefficient of -0.12 , as shown in Figure 10.

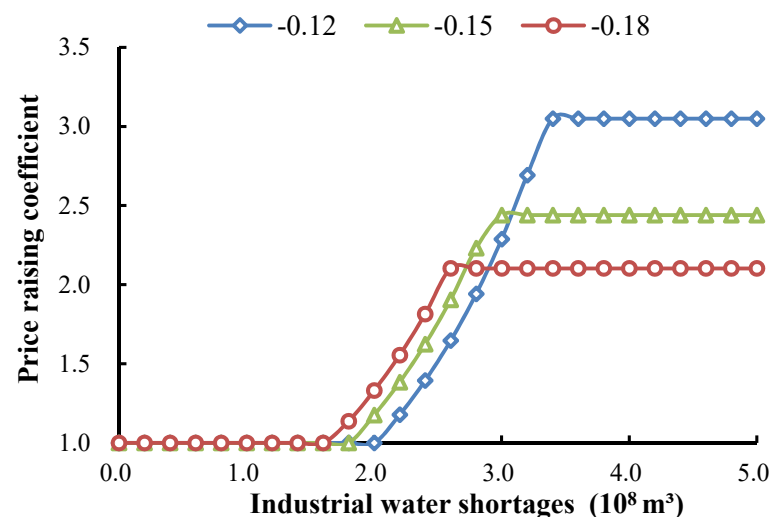


Figure 10. The impact of price elasticity of residential water on PSRW.

When the price elasticity coefficient is -0.12 , the industrial water shortage levels corresponding to the starting and stopping points of price raising are 2.0×10^8 and $3.4 \times 10^8 \text{ m}^3$, respectively, the difference between upper bound and lower bound is $1.4 \times 10^8 \text{ m}^3$, and the maximum price raising coefficient is 3.05. When price elasticity coefficient is -0.15 , the industrial water shortage levels corresponding to the starting and stopping points of price raising are 1.8×10^8 and $3.0 \times 10^8 \text{ m}^3$, respectively, the difference between upper bound and lower bound is $1.2 \times 10^8 \text{ m}^3$, and the maximum price raising coefficient is 2.44. When price elasticity coefficient is -0.18 , the industrial water shortage levels corresponding to the starting and stopping points of price raising are 1.6×10^8 and $2.6 \times 10^8 \text{ m}^3$, respectively, the difference between upper bound and lower bound is $1.0 \times 10^8 \text{ m}^3$, and the maximum price raising coefficient is 2.10. It shows that the larger the absolute value of price elasticity coefficient is, the earlier price raising starts and ends, the lower the maximum price raising coefficient is, the narrower the industrial water shortage range corresponding to the price raising is.

5.4. Uncertainty Analysis of Output Elasticity of Industrial Water

In the optimization model of PSRW, the output elasticity coefficient of industrial water is an important parameter to determine the marginal benefit of industrial water and could influence the change of price raising coefficient implicitly. The output elasticity coefficient

of industrial water applied currently is based on the research results in the literature [41]. In order to further analyze the impact of the output elasticity coefficient on PSRW, two output elasticity coefficients, 0.139 and 0.239, are set by floating 0.05 up or down based on the current coefficient (0.189). The three corresponding results are compared, as shown in Figure 11. When the output elasticity coefficient is 0.139, the industrial water shortage levels corresponding to starting and stopping points of price raising are 2.2×10^8 and 3.8×10^8 m³, respectively. When the output elasticity coefficient is 0.189, the industrial water shortage levels corresponding to starting and stopping points of price raising are 2.0×10^8 and 3.4×10^8 m³, respectively. When the output elasticity coefficient is 0.239, the industrial water shortage levels corresponding to starting and stopping points of price raising are 1.8×10^8 and 3.2×10^8 m³, respectively. In the above three cases, the maximum price raising coefficient is all 3.05, but the larger the output elasticity coefficient of industrial water results in the earlier appearances of starting and stopping points of price raising. Under the same industrial water shortage, the larger the output elasticity coefficient, the greater the marginal benefit of industrial water, and the higher the corresponding price raising coefficient.

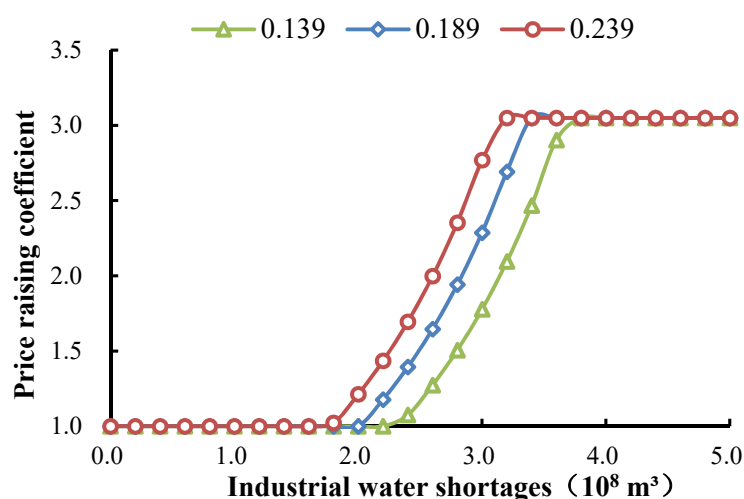


Figure 11. The impact of output elasticity of industrial water on PSRW.

6. Discussion and Conclusions

In this paper, a pricing strategy for residential water (PSRW) in drought years is proposed to promote residential water conservation and the reallocation of water resources between residents and industrial sectors. PSRW is a water tariff changing on annual time scale, which is more realistic and feasible for most regions at present. The PSRW could be determined by an optimization model which is constructed based on the marginal benefit of water use. Tianjin, a city with a severe shortage of water resources, is taken as a case study. Industrial water shortage is taken as the identification index for drought levels. The optimal price raising coefficients for 26 scenarios with different industrial water shortage levels are determined. The results indicate that there is an “S-type” relationship between the price raising coefficient and the industrial water shortage level in drought years. It reflects the inherent connection between water prices and the scarcity of water resources, and clarifies the three issues of “when to start”, “how much to increase”, and “when to stop” for PSRW. “When to start” depends on the non-negative net benefit, and “when to stop” is affected by the acceptability of users for PSRW. In addition, residential water price elasticity coefficient and industrial output elasticity coefficient are proven to have great impacts on the starting point and stopping point of “S-type” curve. Above all, this paper not only develops a PSRW in drought years for Tianjin, but also provides a general method framework that can be applied in other regions.

However, our research still has some limitations, which are clarified as below.

- (1) The identification of drought years is a prerequisite for the annual-scale scarcity pricing strategy, which depends on the availability of long-term forecasting information. The current long-term forecasting technology is not skillful enough to provide accurate streamflow information. However, the forecasting accuracy of streamflow levels provided by data-driven model or general circulation models (GCMs) [44–49], i.e., the high, normal, and low annual inflow, is tolerable. With the development of technology and methodology, the availability of forecasting information and the accuracy of forecasting models could be continuously improved, which can provide better data support for water price establishment and be used to reduce uncertainties. With the development of science and technology and further deployment of real-time monitoring equipment for residential water, the real-time dynamic water price similar to peak-valley electricity prices would become a better choice.
- (2) With the PSRW proposed in this paper, the conserved residential water could be reallocated to low-priority water users, whose demands are largely unsatisfied during droughts. However, it does not indicate that residents could conserve a great quantity of water. The water use constraint is set in the model according to statistical data to ensure the normal life of residents. The conserved water originates from the portion exceeding the basic residential water demand, e.g., the waste of water resources caused by poor habits in residential water use. Compared to the low-priority users with severe losses due to water shortage, the benefit loss caused by residential water conservation is far less than the additional benefit generated from transferring this amount of conserved water to low-priority users. This is the core idea of water right transfer, i.e., the transfer of water from low water value users to high water value users, which is the key to improve the efficiency and benefit of water resources utilization. Due to the benefit loss caused by residential water conservation is negligible and not considered in this paper, there exists the possibility that the increased benefit of price raising may be overvalued.
- (3) We pay attention to the acceptability of residents to price raising, which is reflected by two factors: the lowest water use standard for households and the maximum proportion of HWFE to HDI. Although the considerations for them are relatively simple, it is these two factors that determine the stopping point in the non-linear “S-type” curve, which could tell decision-makers when to stop price increase in the process of policy making. If there are more detailed data in the future, the acceptability of residents can be considered more accurately, thus making PSRW more feasible.
- (4) The assumption that the residential consumers’ incomes are homogeneous masks the fact that poorer households will pay much more than 1% of their income in water bills. We conducted surveys on the correlation between water consumption and income in other cities in China, and found that the water consumption of low-income groups is generally low, and their water saving potential is small. Therefore, in the specific implementation of PSRW, a lower limit of water consumption can be added. That is, when the user’s water consumption is less than the lower limit, the water price will not increase to ensure that low-income groups are not affected.

At last, it is undeniable that improvements in industrial processes including a better water cycling, or investments in water infrastructure, could be good engineering measures for reducing urban water shortage. However, how to stimulate residents’ awareness of water saving through price mechanism, one kind of non-engineering measure, is also a problem worthy of attention. Residents’ water saving should be a long-term behavior, and water price serves as a reminder. At present, the amount of water saved through price increase may not be much, but with the improvement of living standards, the proportion of residential water in urban water is gradually growing, and the amount of residential conservation water will also become considerable. Therefore, the improvements in industrial processes and the conservation of residential water are both important.

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Appendix A

The raw water cost of inter-basin water from Hanjiang River is much higher than that from Luan River for its longer water delivery distance, and the two sources are diverted to different water treatment works (WTW). The longer the distance from the diversion main point to WTW, the higher the water supply cost will be. To achieve the optimal operation of two kinds of inter-basin water, a model based on the topology network of “Source-WTW-RegionUser” water-supply system (as shown in Figure A1) is formulated.

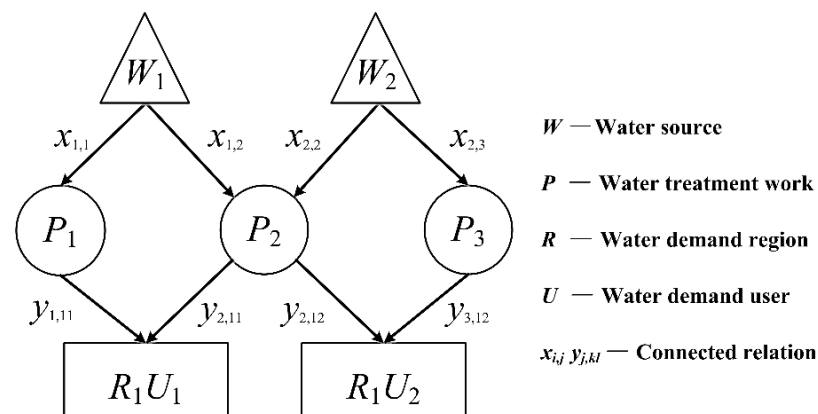


Figure A1. The sketch of Tianjin water supply system’s topology network.

In Figure A1, W represents water source; P represents water treatment work; R represents water demand region; U represents water demand user. Topological relationship matrices are established to reveal topology information. The topological relationship matrix of the inter-basin water distributed to WTWs is represented by X, where x_{ij} represents the supply relationship between inter-basin water source i and WTW j . If WTW j is supplied by inter-basin water source i , then $x_{ij} = 1$, otherwise $x_{ij} = 0$. The topological relationship matrix of WTWs and users of each region is defined as Y, where $y_{j,kl}$ represents the supply relationship of WTW j and user l of region k . If user l of region k is supplied by WTW j , $y_{j,kl} = 1$, otherwise $y_{j,kl} = 0$. For example, the topological relationship matrices of Figure A1 are shown as follows:

$$X = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}; Y = \begin{bmatrix} 1 & 0 \\ 1 & 1 \\ 0 & 1 \end{bmatrix} \tag{A1}$$

1. Objective functions

One objective is minimizing the water supply system’s water shortage:

$$\text{minShortageIndex} = \frac{\sum \text{water deficit in a period}}{\sum \text{water demand in a period}} \tag{A2}$$

$$\sum water\ deficit\ in\ a\ period = \sum_{k=1}^K \sum_{l=1}^L \sum_{t=1}^T D_{kl,t} - \sum_{j=1}^J \sum_{k=1}^K \sum_{l=1}^L \sum_{t=1}^T S_{j,kl,t} \times y_{j,kl} \quad (A3)$$

$$\sum water\ demand\ in\ a\ period = \sum_{k=1}^K \sum_{l=1}^L \sum_{t=1}^T D_{kl,t} \quad (A4)$$

The other objective is minimizing annual water supply cost of two kinds of inter-basin water:

$$\min Cost = \sum_{i=1}^I \sum_{j=1}^J \sum_{t=1}^T W_{i,j,t} \times x_{i,j} \times C_{i,j} \quad (A5)$$

where $D_{kl,t}$ (m^3) represents inter-basin water demand (total water demand deducts the desalination yield of other water sources) of user l of region k at period t ; $S_{j,kl,t}$ (m^3) represents the inter-basin water diverted to user l of region k through WTW j at period t ; $W_{i,j,t}$ (m^3) represents the water diverted to WTW j from inter-basin water source i at period t ; $C_{i,j}$ (CNY) represents the cost of water diverted to WTW j from inter-basin water source i , which is calculated and provided by Tianjin government through considering several factors, including capital costs (e.g., Land, Water conveyance project, Buildings) and operation and maintenance costs (e.g., Energy consumption, Labor, Insurance); L , K , J , I , and T represent the number of users, regions, WTWs, inter-basin water sources and periods, respectively.

2. Constraint conditions

Supply and demand balance. The inter-basin water diverted to user l of region k should be equal to or less than its inter-basin water demand in every period.

$$d_{kl,t} = \sum_{j=1}^J S_{j,kl,t} \times y_{j,kl} \leq D_{kl,t} \quad (A6)$$

Water balance at WTW node. The water yield diverted to WTW j from all the inter-basin water sources should be equal to the water yield of all the users of regions supplied by WTW j in every period.

$$\sum_{i=1}^I W_{i,j,t} \times x_{i,j} = \sum_{k=1}^K \sum_{l=1}^L S_{j,kl,t} \times y_{j,kl} \quad (A7)$$

The capacity of water source. Because the inter-basin water from Hanjiang River could not be stored, so its water supply yield should not exceed its planning water supply capacity in every period. On the opposite, the inter-basin water from Luan River could be stored and regulated, so only annual capacity limitation should be considered.

The capacity at each period is

$$q_{i,t} = \sum_{j=1}^J W_{i,j,t} \times x_{i,j} \leq Q_{i,t} \quad (A8)$$

and the annual capacity is

$$\sum_{t=1}^T q_{i,t} \leq Q_{i,max} \quad (A9)$$

The capacity of WTW. The water yield should not exceed the treatment capacity of WTW in every period.

$$p_{j,t} = \sum_{i=1}^I W_{i,j,t} \times x_{i,j} \leq P_{j,t} \quad (A10)$$

The capacity of water supply pipe. In the real water supply system, water is firstly diverted through trunk pipes, then diverted to WTWs through branch pipes, and finally

diverted to users of every region. Both water supply capacity of trunk pipes and branch pipes should be taken into account as below.

The capacity of trunk pipe is

$$g_{im,t} = \sum_{j=1}^J W_{i,j,t} \times a_{im,j} \leq G_{im,t} \quad (\text{A11})$$

and the capacity of branch pipe is

$$W_{i,j,t} \leq B_{i,j,t}; S_{j,kl,t} \leq B'_{j,kl,t} \quad (\text{A12})$$

Nonnegative variable

$$W_{i,j,t} \geq 0; S_{j,kl,t} \geq 0 \quad (\text{A13})$$

In Equations (A1)–(A13), $d_{kl,t}$ (m^3) represents the received water of user l of region k at period t ; $q_{i,t}$ (m^3), $Q_{i,t}$ (m^3) represent the water supply and the capacity of inter-basin water source i at period t , respectively, while $Q_{i,max}$ (m^3) represents the annual capacity of inter-basin water source i ; $p_{j,t}$ (m^3), $P_{j,t}$ (m^3) represent the water supply and the capacity of WTW j at period t , respectively; $g_{im,t}$ (m^3), $G_{im,t}$ (m^3) represent the water supply and the capacity of trunk pipe im at period t , respectively; $a_{im,j}$ represents the supply relationship of trunk pipe im and WTW j . If WTW j is supplied by trunk pipe im , $a_{im,j} = 1$, otherwise $a_{im,j} = 0$. $B_{i,j,t}$ represents the capacity of branch pipe connecting inter-basin water source i and WTW j ; $B'_{j,kl,t}$ represents the capacity of branch pipe connecting WTW j and user l of region k .

The input data of the model include inter-basin water demands, historical streamflow series of the two inter-basin water transfer sources from Luan River and MSNWDP, the unit production cost of desalinated seawater, and the unit cost of inter-basin transferred water to each WTW. It is worth noting that yearly streamflow series from Luan River and monthly streamflow series from MSNWDP are used in the model. The NSGA-II (Non-dominated Sorting Genetic Algorithm II) proposed by Deb et al. [50] is applied to solve this multi-objective optimization problem, which has been proven effective in solving the wide range of water management problems.

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