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Novel Water Pricing Model for Water Network Projects: A Case Study of Jiaodong Water Diversion Project in China

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Abstract: The uneven distribution of water resources in time and space restricts the development of society, which is a universal problem facing the world. To improve the ability to regulate water resources in water diversion projects and alleviate the contradiction between water resources and social development, China has decided to build water network projects (WNPs). A WNP is an integrated water supply system that includes multiple water sources and network water supply lines and integrates the functions of water supply, water delivery, and optimal allocation of water resources into a system that can supply water to many users. An appropriate water pricing mechanism is the key to ensuring the sustainable operation of water network projects. This paper presents a comprehensive water pricing model (WPM) for WNPs. The purpose of this model is to unify the water price measurement standard of WNPs and lay the foundation for water price marketization in the future. By applying the model to the Jiaodong WNP, it is found that the model is expected to improve the unbalanced use of water sources and the large difference in prices at water supply points (WSPs) in the project. This study not only provides a theoretical basis for water pricing reform but also has great potential to improve the efficiency of water resource use.

Keywords: water network project; water pricing model; water supply points; comprehensive water price

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1. Introduction

As a prerequisite for sustaining life, water resources play a central role in society [1]. In recent decades, climate change, economic development, population growth and mismanagement have exacerbated the global water crisis, with some 4 billion people experiencing severe water shortages for at least one month each year [2]. Developing countries face an even greater water crisis.

The total water resources of China are relatively large but unevenly distributed, with a per capita share of only a quarter of the world's per capita share. There is a serious water shortage in the north. The Jiaodong area of Shandong Province is an area of severe water scarcity in the north, with per capita water resources only one-sixth of the national average [3]. To alleviate water-related constraints on economic and social development, China decided to build a four-level network of projects, including the national, provincial, municipal, and county levels [4]. Shandong Province is a pioneering area for national water network construction. The Jiaodong WNP is an important part of the "T" shaped water diversion artery in Shandong Province, which consists of five water diversion projects [5], including the Yellow River to Qingdao Water Diversion Project (YRQWDP), the Yellow River to the East Water Diversion Project (YREWDP), the Jiaodong Water Diversion Project (JWDP), the Yellow River to Xiashan Water Diversion Project (YRXWDP) and (part of) the South-to-North Water Diversion Project (SNWDP) (see Abbreviations). By connecting the five major projects, a water diversion project network has been formed in the Jiaodong area. This is the first WNP built in Shandong Province, which is expected to ease the pressure on water resources in Qingdao, Yantai, Weifang, and Weihai.

Most water diversion projects around the world use an independent pricing model. The price of water for a particular project is based on its production costs, a reasonable profit, and taxes. For example, the SNWDP in China [6], the North-South Water Diversion Project in the USA [7], and the West-East Water Diversion Project in Egypt [8] all adopt this pricing model. The traditional pricing model has created a number of problems. In the actual operation of WNPs, due to the diversification of investments, the difference in water supply prices and the administrative nature of the water market, it is possible to have multiple forms of water pricing within the same project [9]. This has created some management problems for water utilities, such as water tariff collection, distribution of water sources, distribution of profits, and so on [10]. This has been a major obstacle to the development of WNPs.

Most of the existing studies have analyzed the rationality of water supply pricing for a particular stand-alone water project from different perspectives [11]. Chen et al. found an advantage for a two-tier pricing scheme through a Stackelberg game model study. A two-tier pricing scheme can effectively coordinate water allocation and generate multiple desirable co-products [6]. Liu et al. proposed an improved cost-sharing method based on the water continuity equation and the engineering cost balance equation of upstream and downstream users, which was applied to the SNWDP. They found that research can overcome the non-convergence problem of existing sharing equations and reduce the difference in sharing costs between upstream and downstream users [12]. Du et al. studied two water supply chains under the completed SNWDP in China and found that under the two-part pricing contract, the parameters of the entire supply chain system decreased as the intensity of competition increased [13]. Most of the literature focuses on the appropriateness of water pricing for specific projects, and few studies consider water pricing under the integrated water network mechanism [14].

The water network is one of the four major infrastructure networks that affect human life in modern society, along with the transport network, the energy network, and the internet [15]. Electricity, natural gas, and water networks are all important public utilities in the development of the national economy and are characterized by network-based natural monopolies [16]. Electricity and natural gas networks have been formed for a long time, and their price formation mechanisms are mature. Electricity and gas price reforms have proven effective in improving resource management efficiency and promoting market-based resource transactions [17]. Compared to other infrastructure networks, water network pricing has the shortest history of reform. This prompted us to project the experience of water price reform from those of electricity and natural gas, which was also a source of inspiration for this study.

The current water pricing mechanism has hampered the development of WNPs and the achievement of the goal of sustainable development of water resources. Other countries internationally, such as India, South Korea, and Japan, have established a large number of water diversion projects to form water supply networks. They face the same challenges. In this paper, we have completed different water pricing schemes for the different characteristics of WNPs. Through the analysis of application results in the Jiaodong area, it was found that WNPs have a significant effect on improving management efficiency, reducing water price differences and promoting water price marketization.

The remainder of the paper is structured as follows. Section 2 presents the methodology and model construction; Section 3 summarizes the main results; Section 4 discusses the benefits of the comprehensive WPM; and Section 5 presents the main conclusions of this study.

2. Materials and Methods

2.1. Methodology

2.1.1. WNP Characteristics

The calculation basis for a comprehensive water price is the project operating cost and the original resource cost, so it is necessary to distinguish the relationship of the engineering lines and the number of water sources. WNPs can be divided into three categories according to the complexity of the water diversion project's backbone lines and water supply sources: primary WNPs, intermediate WNPs, and advanced WNPs. The primary WNPs consist of a backbone water supply line and a main water supply source. Intermediate WNPs consist of two intersecting lines and multiple water supply sources. Advanced WNPs consist of three or more intersecting lines and multiple water supply sources. Table 1 shows the characteristics of the three types of WNPs.

Table 1. Classification and characteristics of WNPs.

WNP	Number of Water Supply Sources	Backbone Water Diversion Line Characteristics	Management Model	Dispatch Objectives	Degree in Engineering Networking
Primary	Single	Single and clear	Single	Single	Low level
Intermediate	Multiple	Two and crossed	Multiple	Multiple	Intermediate level
Advanced	Multiple	Three or more with crossed	Multiple	Multiple	Advanced level

As the pricing mechanism for primary WNPs is relatively well developed, this study examines a pricing mechanism for intermediate and advanced WNPs. These WNPs are highly interconnected and are characterized by multiple sources of water supply, multiple routes of water transmission, multiple modes of management, and multiple planning objectives. Of these, diversified water supply is the source, multi-route water transmission is the design, multi-modal management is the means, and multi-objective planning is the process. At the same time, these determine the complexity of their water pricing mechanisms. Table 1 shows the characteristics of the three types of WNPs.

At present, with the successive construction and implementation of several WNPs, the formulation of water pricing is faced with a large number of pressing problems, mainly including the following: (i) As the variety of water sources increases, it is difficult for water suppliers to allocate resources due to the different prices of different water sources. Under the traditional integrated water supply model of abstraction and transmission, the downstream recipient receives a bundled service of transport and sale. It is difficult for them to distinguish which water sources the purchased water comes from, leading to difficulties in confirming and settling subsequent prices. (ii) As the current projects differ in terms of construction time, investment structure, and management systems, they also have different forms of water pricing. The cross-fertilization of water supply lines will change the original independent management and operation. If the traditional pricing mechanism is used, customers will face unnecessary problems such as multiple charge rates, multiple charge units, and double payment. How can pricing models be established to unify accounting standards for water pricing in the network? (iii) As other major utilities, such as electricity and natural gas, have achieved increasingly effective market-based reforms, how can the water network catch up with them through price reform and establish a reasonable pricing mechanism? To sum up, we hope to establish a comprehensive water management system to address the above difficulties.

2.1.2. Study Area

The case we have chosen for the WPM study is the Jiaodong Area WNP in Shandong Province, which has relatively complex water network characteristics. The Jiaodong WNP mainly consists of five water diversion projects: the JWDP, the SWDP, the YREWDP, the YRQWDP and the YRXWDP. Figure 1 shows the arrangement of the backbone WNPs in the Jiaodong area. Among them, WSP refers to the water supply point, which is the minimum target node of the project to supply water to each region. The YRQWDP is the backbone project, starting from the Boxing Pumping Station in Binzhou City, passing through Weifang City and ending at the Ji Hongtan Reservoir. The SNWDP intersects with the backbone project at the Xiaoqing River Sluice, where the Yangtze River water (YARW) flows into the project. The YREWDP takes the Yellow River water (YERW) from Caodian-Mawan Pumping Station, joins the backbone project at Songzhuang Sluice, and passes through Dongying City. The JWDP draws water from Songzhuang sluice gate through Yantai City and Weihai City to Mishan Reservoir. The main user of the YRXWDP is Xiashan Reservoir, which draws water from Songzhuang sluice. The five projects are connected horizontally and vertically, showing obvious network characteristics, which improves the connectivity of each water catchment area and enables interaction between YERW and YARW. By analyzing the characteristics of the Jiaodong WNP, it was identified as an advanced WNP.

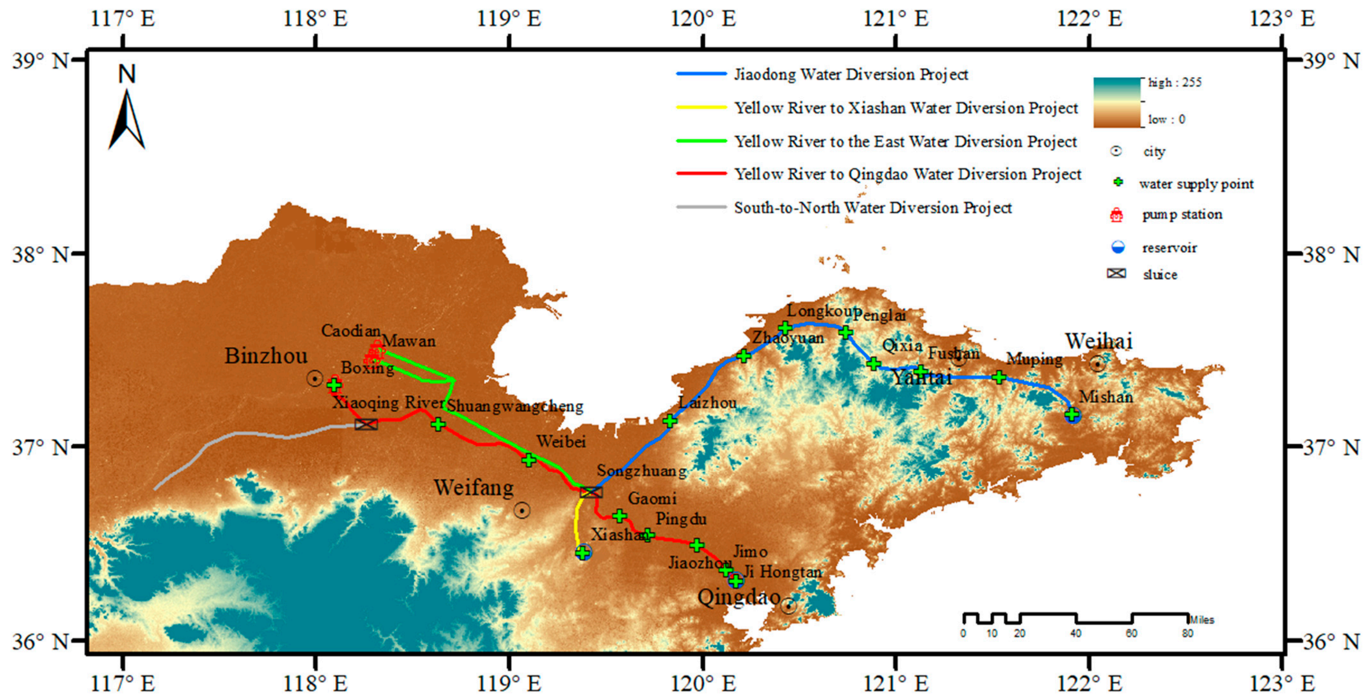

Figure 1. The general arrangement of Jiaodong WNP.

At present, the water price accounting for the Jiaodong WNP is all based on the water diversion project before the project was networked, and the two-part water price combining the measured water price and the basic water price is used at the water supply points. However, with the construction of the WNP, this mechanism has brought various problems to the project.

(1) Different water prices for the same water source

Due to the difference in project investment structure, there is a significant difference in water supply cost between JWDP and YREWDP. Two-thirds of YREWDP's investments are in commercial loans, and its debt servicing costs are much higher. This ultimately results in a large difference in the price of water between the two projects. When YERW is transported to each user through the Jiaodong WNP, how to determine the water price to ensure fairness of water use is an urgent problem to be solved.

(2) Different water prices for the same project

In the Jiaodong WNP, the price of YARW and YERW varies widely due to the price of raw water and the distance of diversion. Under the current water pricing policy, there are already three types of water prices at some WSPs. The current pricing model can easily lead to water users competing for lower-priced water rather than higher-priced water. A review of the YERW Resources Bulletin and the Shandong Provincial Water Resources Bulletin shows that Shandong Province has exceeded the YERW diversion target from 2013 to 2021, while the YARW diverted by the SNWDP has not been fully utilized. YERW accounts for 28% of total water consumption. YARW accounts for only 15% of the total local water supply, and less than 8% of actual water consumption [18]. This phenomenon is particularly serious in the Jiaodong area.

According to the Shandong Provincial Water Development Plan, there is an urgent need to build a modern water network that meets the requirements of high-quality development. The current traditional water pricing system cannot meet the increasing annual water demand in Shandong Province, nor can it ensure the smooth implementation of the water resources plan, and a new comprehensive water pricing system is urgently needed to address these issues.

2.1.3. Data Sources

Data on investment and the distance of water diversion lines in the WNP were provided by the Water Transfer Project Operation and Maintenance Centre of Shandong Province; data on electricity and natural gas prices used in the Section 4 were obtained from the official website of the National Development and Reform Commission of the People's Republic of China (https://www.ndrc.gov.cn/ accessed on 1 January 2023); data on YERW were obtained by consulting the official website of the Yellow River Network (http://www.yrcc.gov.cn/other/hhgb/ accessed on 1 October 2022) for the YERW Resources Bulletin; and data on YARW were obtained from field research.

2.2. Model Development

2.2.1. Theoretical Foundation of the WPM

To address the shortcomings in the pricing of WNPs, we examined the pricing mechanisms and reform history of China's electricity and natural gas networks. By reviewing a large amount of information on the subject, we found commonalities in their pricing mechanisms, namely the separate accounting of commodity costs and transportation costs. For example, the Interim Measures for the Administration of Sales Prices stipulate that the sales price at the terminal is composed of the feed-in price, the transmission and distribution price, and some other prices. In addition, the Measures for the Administration of Natural Gas Pipeline Transportation Prices stipulate that national pipeline network groups should separate their pipeline transportation business from other businesses. In recent years, electricity and natural gas prices have been reformed along the same lines, transport services have been controlled, and the purchase and sale of resources have been liberalized [19,20].

In the natural gas pricing mechanism, resource supply services are priced separately from transportation services. Gas distribution companies can design the best mix of services based on the specific needs of their customers, thereby improving pricing efficiency. At the same time, it is also conducive to the market-oriented reform of natural gas prices. Before pricing them separately, highly regulated and non-transparent prices had limited the development of China's natural gas industry [21]. Separate pricing reduces government control over the price of natural gas resources and facilitates free trade in natural gas [22]. Since the introduction of market-based reforms, gas pricing mechanisms have become more predictable and transparent [23,24].

At the same time, electricity price reform is having an obvious impact. Before separate pricing, the electric power company was in charge of the whole process of selling and transmitting electricity. They profited on the difference by buying and selling electricity [25,26]. The mechanism for the separate approval of transmission and distribution tariffs and feed-in tariffs has changed the profit model of grid companies [27]. After the reform, it became possible for electricity producers and large consumers or distributors to trade electricity products directly, and the dividends released by the reduction in feed-in tariffs for electricity production could be redirected directly to the consumer side [28]. Grid enterprises should focus on improving transmission and distribution services and reducing operating costs to achieve reasonable returns [29]. After the implementation of the transmission tariff reform in 2018, grid enterprises cumulatively reduced their allowed revenue by about CNY 60 billion, and the degree of marketization significantly increased [30].

As mentioned above, the apparent success of the electricity and natural gas network pricing reforms have confirmed the advanced nature of their pricing mechanisms [31]. Through the analysis, we decided to adopt the pricing mechanism for raw water price-diversion water prices to determine a comprehensive water price.

2.2.2. Comprehensive Water Pricing Model

Taking into account the characteristics of different WNPs, we divided the WPMs into five schemes based on the different ways of accounting for the diversion water price.

(1) Scheme A: Sub-WSP pricing

If the number of WSPs in a WNP is small, accounting for water prices for each WSP will not put too much pressure on management, and the costs of each WSP are relatively clear. Thus, scheme A can be considered. However, as the project is small-scale and not very risk resilient, it is crucial to achieve cost recovery and sustainable operation of the project through pricing. Taking into account the principle of fair and reasonable cost sharing, the diversion water price for each WSP is calculated based on the water diversion distance.

Let there be a total of n WSPs in the WNP. Then, the comprehensive water price for the ith WSP is:

$$DCP_i = DOP_i + DTP_i \tag{1}$$

$$DOP_i = \frac{DTO_i}{DW_i} \tag{2}$$

$$DTP_i = \frac{TC}{\sum_{k=1}^{n}(DW_k \times D_k)} \times D_i \tag{3}$$

where DCP_i is the comprehensive water price for the ith WSP (CNY/m^3), DOP_i is the comprehensive raw water price for the WSP (CNY/m^3), DTP_i is the comprehensive water diversion price for the WSP (CNY/m^3); in Equation (2), DW_i is the total volume of water diverted by the WSP through the WNP for all types of surface water (m^3), DTO_i is the comprehensive raw water fee, that is, the sum of the raw water fees for these sources; in (3), TC is the sum of the total cost of the WNP in addition to the raw water fee (CNY), D_i is the distance the water resource is delivered from the initial intake of the project to the WSP (m).

In Equation (3), it is the determination of the diversion distance D_i that needs to be discussed. Depending on D_i, the water pricing scheme A can be divided into Scheme A1 and Scheme A2.

Scheme A1:

For primary, intermediate, and some simple advanced WNPs, the cost recovery and sustainable operation of the project are key. Calculating the price of water delivery based on the actual diversion distance from the water source can effectively ensure the cost recovery of the project and fair cost sharing. Therefore, in this scheme, D takes the actual distance that the water source is diverted from the initial intake to the WSP.

Scheme A2:

In Scheme A1, some of the WSPs may be too far away from the intake. The difference in water prices between proximal WSP and remote WSP may be very large. As a result, the water at the end of the project may be under-utilized. With the construction of the WNP, the distribution of water sources in the project is also more balanced. At this time, in order to balance the water cost for each user in the project and reduce the difference in water prices, we can consider designing a generalized central point in the project. D_i can take the distance of water delivery from the WSP to the center point. For example, in the Jiaodong WNP, the Songzhuang sluice is an important node of the project that receives water from various projects upstream and distributes water downstream in the direction of Qingdao and Jiaodong water diversion, so it is used as the generalized center point of the Jiaodong WNP. It is important to note that this scheme is only applicable to advanced WNPs, as the scheme requires a high degree of networking.

(2) Scheme B: Sub-area pricing

As the scale of the WNP increases, the number of WSPs involved in the WNP also increases. As the number of WSPs increases, the number of businesses and administrations involved in the management of the WNP will also increase, and if we remain with Scheme A at this time, differences in the management of water prices between WSPs may limit the development of the WNP. By studying the experience with electricity and gas pricing, we consider calculating area water prices.

Let there be m_j WSPs in the jth area of the WNP. Then, the comprehensive water price for the area is

$$RCP_j = ROP_j + RTP_j \tag{4}$$

$$ROP_j = \frac{\sum_{i=1}^{m_j} DTO_i}{\sum_{i=1}^{m_j} DW_i} \tag{5}$$

$$RTP_j = \frac{\sum_{i=1}^{m_j} D_i}{n} \times \frac{TC}{\sum_{k=1}^{m_j} (DW_i \times D_i)} \tag{6}$$

In (4), for the jth area, RCP_j is the comprehensive water price (CNY/m^3), ROP_j is the comprehensive raw water price (CNY/m^3), and RTP_j is the comprehensive price of water diversion (CNY/m^3).

Similarly to Scheme A, Scheme B can be divided into two schemes depending on the distance of water delivery.

Scheme B1:

The water delivery distance in Scheme B1 takes the physical water delivery distance. It is suitable for cross-area WNPs, where each area is priced independently. And we can choose a county-level area, a municipal area, or a provincial area depending on the size of the project. This scheme is, therefore, suitable for cross-area primary, intermediate, and advanced WNPs.

Scheme B2:

Similarly to Scheme A2, the distance in Scheme B2 takes the generalized delivery distance. Since the D_i for this scheme is taken as a generalized distance, it requires a higher degree of networking for the project. Therefore, it is suitable for cross-area intermediate WNPs and advanced WNPs.

(3) Scheme C: Unified Pricing

A unified pricing scheme means that the total cost of the WNP is shared equitably by all users of the project, and it is a highly comprehensive water pricing system. This means that customers in different WSPs pay the same price for the water they use from the network, regardless of the project, city, or water source.

Scheme C:

$$NCP = NOP + NTP \tag{7}$$

$$NOP = \frac{\sum_{i=1}^{n} DTO_i}{\sum_{i=1}^{n} DW_i} \tag{8}$$

$$NTP = \frac{TC}{\sum_{i=1}^{n} DW_i} \quad (9)$$

where NCP is the comprehensive water price of the WNP (CNY/m^3), NOP is the comprehensive raw water price of the WNP (CNY/m^3), and NTP is the comprehensive water price of the WNP for water diversion (CNY/m^3).

In Scheme C, the cost is equally shared by the users of the water network. The scheme is suitable for water receiving areas with little difference in economic development level. This scheme requires a high degree of networking of the project, and is suitable for advanced WNPs. The non-differential pricing scheme also facilitates unified management and coordinated dispatch. However, as the unified pricing scheme requires a high degree of networking in the WNP, whether it can be applied in the future needs further research. Table 2 shows the types of projects for which the various schemes are applicable.

Table 2. Water pricing scheme features and applicable projects.

Scheme	Projects Characteristics	Applicable Projects
A1	Suitable for WNP with a small number of WSPs	Primary Intermediate Advanced
A2	Suitable for WNP with a high degree of networking	Intermediate Advanced
B1	Suitable for inter-area WNP	Primary Intermediate Advanced
B2	Suitable for highly networked and inter-area WNP	Intermediate Advanced
C	Suitable for WNP where there is little difference in the economic development of the water-receiving area	Advanced

3. Results

3.1. Sub-WSP Water Price

Table 3 shows the comprehensive water pricing scheme when each WSP is priced independently. Scheme A1 is a comprehensive water pricing scheme that calculates the water delivery price according to the physical delivery distance, and scheme A2 is a comprehensive water pricing scheme that calculates the water delivery price according to the generalized distance. By analyzing the distribution of WSPs and the operation of the WNP in the Jiaodong area, we decided to take the Songzhuang diversion gate as the center and the technical delivery distance from each gate to it as the generalized distance.

Table 3. Sub-WSP water pricing schemes (CNY/m^3).

WSP	Scheme A1				Scheme A2			
	Physical Water Delivery Distance (km)	Water Delivery Price	Raw Water Price	Comprehensive Water Price	Generalized Water Delivery Distance (km)	Water Delivery Price	Raw Water Price	Comprehensive Water Price
Boxing	0.00	0.00	0.14	0.14	77.88	0.90	0.14	1.03
Shuang Wangcheng	69.39	0.52	0.94	1.46	8.48	0.10	0.94	1.04
Weibe	73.39	0.54	0.98	1.52	4.49	0.05	0.98	1.03
iLaizhou	112.24	0.83	1.23	2.06	34.37	0.40	1.23	1.63
Zhaoyuan	118.68	0.88	1.29	2.17	40.81	0.47	1.29	1.76
Longkou	149.32	1.11	1.31	2.42	71.44	0.82	1.31	2.13
Xiashan	151.72	1.13	1.00	2.13	73.85	0.85	1.00	1.85
Penglai	177.60	1.32	1.32	2.64	99.73	1.15	1.32	2.47
Qixia	190.00	1.41	1.32	2.73	112.13	1.29	1.32	2.61
Fushan	206.63	1.53	1.32	2.86	128.76	1.48	1.32	2.80
Gaomi	207.38	1.54	1.31	2.84	129.51	1.49	1.31	2.79

Table 3. *Cont.*

WSP	Scheme A1				Scheme A2			
	Physical Water Delivery Distance (km)	Water Delivery Price	Raw Water Price	Comprehensive Water Price	Generalized Water Delivery Distance (km)	Water Delivery Price	Raw Water Price	Comprehensive Water Price
Pingdu	214.00	1.59	1.30	2.89	136.13	1.56	1.30	2.86
Jiaozhou	249.61	1.85	1.33	3.19	171.74	1.97	1.33	3.31
Jimo	252.36	1.87	1.35	3.22	174.49	2.01	1.35	3.35
Muping	252.09	1.87	1.32	3.19	174.21	2.00	1.32	3.33
Ji Hongtan	290.00	2.15	1.58	3.73	212.13	2.44	1.58	4.02
Mishan	306.61	2.28	1.32	3.60	228.73	2.63	1.32	3.95

It can be seen in the table that, as the delivery distance increases, the price of the delivery water increases, but the total water price fluctuates slightly due to the different raw water prices. In addition, there is a large difference in water prices between WSPs in Scheme A1, with the maximum price difference reaching CNY 3.59/m^3, while the distribution of water prices between WSPs is more concentrated in Scheme A2.

3.2. Sub-Area Water Price

In the calculations for Scheme B, as the Jiaodong WNP covers a large number of counties, accounting for water prices on a county basis would lead to complex results, so we considered accounting for water prices on a city basis.

Table 4 shows the comprehensive water pricing scheme when each area is priced independently. The basis for calculating the water delivery price is the physical delivery distance in Scheme B1 and the generalized distance in Scheme B2. We can see that the distribution of prices in Scheme B2 is more concentrated compared to Scheme B1, with a significant reduction in the gap between water prices in each city.

Table 4. Sub-area water pricing schemes (CNY/m^3).

City	WSP	Scheme B1			Scheme B2		
		Raw Water Price	Water Delivery Price	Comprehensive Water Price	Raw Water Price	Water Delivery Price	Comprehensive Water Price
Binzhou	Boxing	0.14	0.00	0.14	0.14	0.90	1.03
Weifang	Shuang Wangcheng Weibei Xiashan Gaomi	1.02	0.93	1.95	1.02	0.62	1.64
Yantai	Laizhou Zhao Longkou Penglai Qixia Fushan Muping	1.30	1.28	2.59	1.30	1.90	3.21
Qingdao	Pingdu Jiaozhou Jimo Ji Hongtan	1.47	2.89	4.36	1.47	2.00	3.47
Weihai	Mishan	1.32	2.28	3.60	1.32	2.63	3.95

As local affordability was not taken into account when setting the comprehensive water price for each city, we considered using the GDP of each city to adjust the water price. Table 5 shows the prices after adjusting in Scheme B1 and Scheme B2.

Table 5. Adjusted water pricing scheme (CNY/m^3).

City		Binzhou	Weifang	Yantai	Weihai	Qingdao
Before adjustment	Scheme B1	0.14	1.95	2.59	3.60	3.34
	Scheme B2	1.04	1.64	3.21	3.96	3.47
Gross Domestic Product (Hundred million CNY)		2975.20	7306.40	9515.90	3408.20	14,900.00
Percentage of Gross Domestic Product		0.39	0.96	1.25	0.45	1.96
After adjustment	adjScheme B1	0.91	2.23	2.91	1.04	4.55
	adjScheme B2	1.04	2.55	3.32	1.19	5.20

It can be seen that before the adjustment, Qingdao had high income and low water prices, and Weihai had low income and high water prices. After the adjustment, the comprehensive water price in each city was proportional to the GDP. The comprehensive water price can reflect the local level of economic development to some extent.

Figure 2 shows the degree of change in water prices in each city before and after adjustment. It can be seen that Schemes B1 and B2 cannot reflect the economic development level of each city, and adjSchemes B1 and B2 are positively correlated with the GDP of each city.

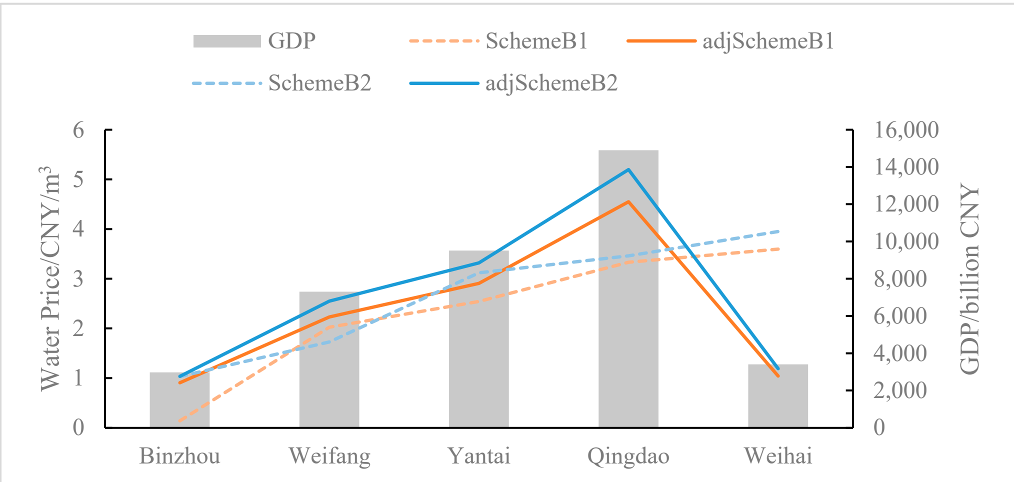

Figure 2. Adjustment of water prices in various regions.

3.3. Unified Water Price

The unified pricing scheme is an ideal situation, that is, in the WNP, the project lines are densely distributed, the water source is evenly distributed, and the economic development level of each user in the project is not too different. At this point, the cost of reaching each water user is basically the same. However, the dense construction routes and the large number of water sources can complicate the pricing process and put a lot of pressure on the management of the project. In order to reduce the pressure on water network management and to enable water network users to distribute water fairly, we considered using Scheme C in Section 2.2.2 to set a unified price for each user in the WNP.

Table 6 shows the comprehensive water pricing scheme when delivery water prices and raw water prices are unified. The price of raw water is calculated according to the total cost of water resources and the total water supply of the project, and the calculation of water delivery price is based on the project cost in addition to the water resources cost and the total water supply of the project. In this scheme, regardless of region or WSP, each user in the WNP incurs a water price according to the unified pricing scheme.

Table 6. Unified water pricing scheme (CNY/m^3).

Water Delivery Price	Raw Water Price	Comprehensive Water Price
1.58	1.29	2.87

3.4. Cost Recovery

Within the European Community, Directive 2000/60/EC states that water pricing policies must encourage the efficient use of water resources by users and contribute to the recovery of the costs of water supply services [32]. In the case of water diversion projects, the cost of the water supply service consists mainly of the construction and operating costs of the project. To verify the effectiveness of the WPM in cost recovery, we introduced an index of the degree of cost recovery (DCR), i.e., the ratio of the costs recovered by the WPM to the total costs of the project.

As can be seen from Table 7, Schemes A1, A2, and C cover costs effectively, while Scheme B1 is not conducive to cost recovery. Schemes B2, adjB1, and adjB2 can achieve benefits on the basis of full cost recovery.

Table 7. Degree of cost recovery.

Scheme	A1	A2	B1	B2	adjB1	adjB2	C
DCR	100%	100%	96%	101%	103%	116%	100%

4. Discussion

4.1. Unify the Prices of Water Sources by Type

At present, most of China's water diversion projects are priced according to the source of the water. However, due to the geographical location of different water sources, the ease of water extraction, and other differences, there are large differences in the cost of water diversion. As a result, the use of local or nearby water sources is more competitive for the receiving area than the use of diverted water sources, which has resulted in many water diversion projects failing to properly deliver their benefits, particularly in the use of YARW and YERW. To investigate the price difference between YARW and YERW and its use, we chose Shandong Province as our study area. The SNWDP is an important initiative to solve the serious water shortage problem in northern China. However, due to the long distance of water diversion, the price of YARW is much higher than that of YERW in Shandong Province. We summarized the implementation policies of the Shandong Provincial Price Bureau regarding the measured water prices for the two types of water sources.

As shown in Figure 3, the metered price of YARW is generally higher than the metered price of YERW in Shandong. To examine the impact of water pricing on water use, we defined the water supply attainment rate (WSAR), which is the ratio of actual water use to government allocation, to determine the actual efficiency of the use of different water sources in Shandong. To gain a clearer picture of the extent to which different types of water resources are being used above or below standard, we defined full production attainment (FPA), which is the proportion of water actually used as a proportion of water allocated by the government.

Since the price of YARW is generally higher than that of YERW and the quality of YERW is better than that of YARW, users are more inclined to use YERW, resulting in the overuse of YERW and abandonment of YARW [32]. As shown in Figure 4, the YARW has been under-utilized for many years, with WSARs of less than 60% from 2013 to 2020, while the YERW has been over-utilized every year, with an over-utilization probability of up to 49%.

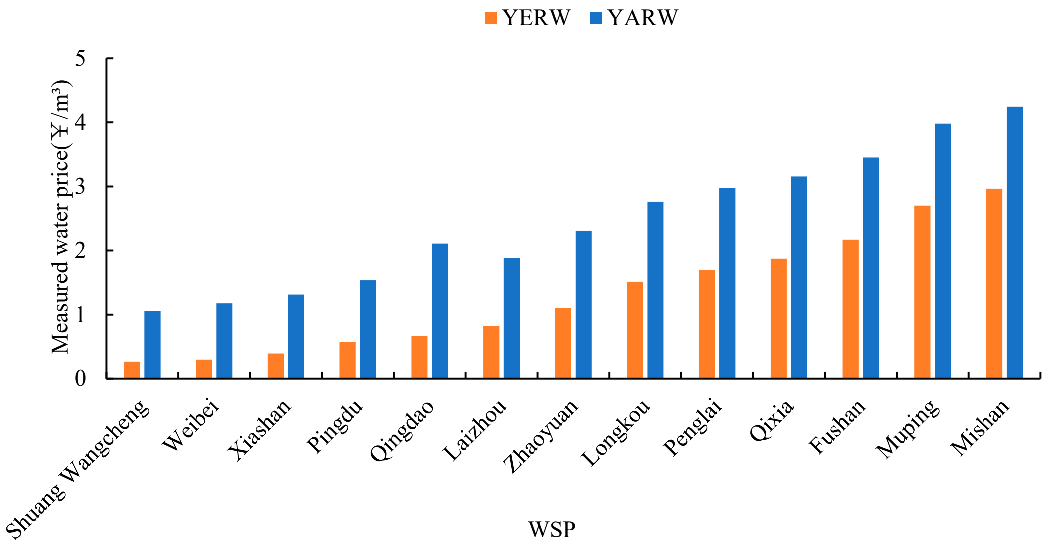

Figure 3. Metered water prices of some WNPs in Shandong.

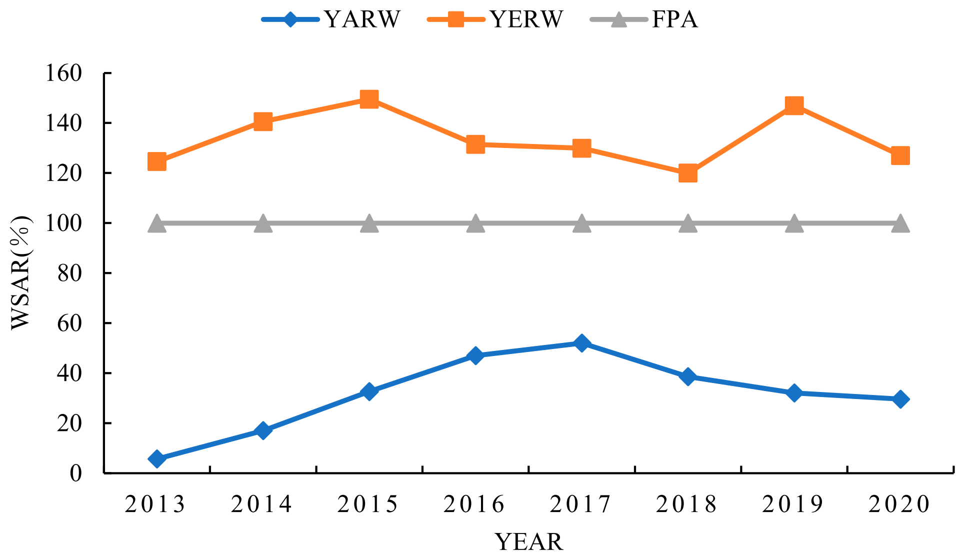

Figure 4. WSAR of some WSPs in Shandong.

In the short term, the under-utilization of YARW will affect the benefits and sustainable operation of the SNWDP. In the long term, it is not conducive to achieving the goal of water allocation by overusing water systems. As a result of the current split-source pricing model, the receiving areas do not follow the government's water allocation targets to use water, making excessive use of lower-priced water resources and less use of higher-priced water resources. It can be seen that the water pricing model based on the source has hindered the effectiveness of the water supply. There is an urgent need to move away from the current approach of allocating water resources solely by administrative fiat to manage the balanced use of all water resources from a pricing perspective.

Therefore, when calculating water prices using WPM, we implemented a uniform raw water price for all types of water sources by considering that there is no distinction between water sources so that the high-priced YARW receives an invisible subsidy in price. This pricing method will encourage water users to use a variety of water sources, thereby promoting the efficiency of the project water supply and achieving the purpose of improving the efficiency of water use. Our model can also be generalized to similar projects.

4.2. Maintain Equity in Water Access

Human rights are equal, the right to life is equal, so the right to use water is equal. Essentially, WNPs are fluid physical networks based on water, and therefore, the fundamental attribute of equity in water resources must be taken into account when setting water prices [33]. How to promote fair trade in water resources through pricing in WNPs is thus one of the key objectives of WNP price reform.

The degree of price reform currently varies between public goods. Electricity and natural gas have a long history of price reform, with natural gas price reform starting in 1987 and electricity price reform starting in 1978. Efforts to set WNP water prices can learn from their relatively sound pricing mechanism. To compare the price differentials of the three resources, we calculated the standard deviation (SD) of natural gas and electricity prices for each province in the Shaanxi-Beijing pipeline and the national grid and the water prices in the SNWDP.

Table 7 shows the factory price of natural gas as the benchmark price; the specific factory price can fluctuate within 10%, and the transport price is set by the government. Table 8 shows the implementation of electricity prices between 2020 and 2022. It can be seen that the price difference between provinces and cities for electricity and natural gas is small; the SD is only 0.079 and 0.09. Second, the prices also appropriately reflect the affordability of provinces and cities, from Shanxi to Tianjin and Beijing; the economy is becoming more and more developed, and transport prices have been appropriately increased. As can be seen from Table 9, the standard deviation of water prices is 0.61, which is much larger than the standard deviation of electricity prices and natural gas prices.

Table 8. Gas prices and SD in some provinces and cities of the Shaanxi-Beijing pipeline (CNY/m^3).

Province and City	Shaanxi	Shanxi	Shandong	Hebei	Beijing	Tianjin	SD
Factory price	0.83	0.83	0.83	0.83	0.83	0.83	
Transport price	0.143	0.209	0.295	0.306	0.341	0.373	
Comprehensive price	0.973	1.039	1.125	1.136	1.171	1.203	0.079

Table 9. Electricity prices and SD in some provinces and cities of the grid (CNY/kW·h).

Province and City	Shanxi	Hebei	Shaanxi	Shandong	Tianjin	Beijing	SD
Feed-in price	0.008	0.011	0.0212	0.0089	0.020	0.025	
Transport price	0.127	0.167	0.1581	0.1993	0.240	0.386	
Comprehensive price	0.135	0.178	0.179	0.208	0.260	0.411	0.090

The south of China is rich in water resources and economically developed, and there are many large-scale water diversion projects. China's northern regions, where water is scarce and economic development is slow, often have to pay high water supply costs to transfer water across basins. The price of water varies considerably in different receiving areas, due to differences in topography and distances between projects. Some of the more water-scarce and economically backward central and western areas are particularly affected. For example, the Luliang Mountain area is the receiving area of the Jinzhong Yellow River diversion project. The region is economically underdeveloped and suffers from widespread water shortages. However, the Yellow River diversion project and supporting water diversion project are more complicated, and the operation cost is higher in this area. The cost of water supply is generally higher for the WSPs located on the east–west trunk line and branch lines, especially for the WSPs located at the end of the route, such as Xixian, Fenxi, and Lingshi, where the cost of water supply is the highest [34]. The price of water in these areas is too high compared to other projects with simple water supply conditions and is even higher than the recent affordability of water for water users.

The project's price is the prerequisite and basis for setting customer water prices, and a reasonable project price helps to ensure that all customers have fair access to water. To make the differences between the pricing schemes more apparent, we calculated the SD for each scheme and compared the pricing schemes calculated using the traditional method with the comprehensive water pricing scheme.

As shown in Table 10, trad Schemes A1 and A2 are the prices of YARW and YERW calculated using the traditional method. adjSchemes B1 and B2 are the prices of Schemes B1 and B2 adjusted.

Table 10. SD for traditional and comprehensive water pricing schemes.

Scheme	Trad A1	Trad A2	A1	A2	B1	B2	Adj B1	Adj B2	C
SD	1.75	1.66	0.87	0.94	0.80	0.87	1.09	1.24	0.00

As can be seen from Table 11, the WPM has effectively reduced the SD of water prices between the WSPs in Jiaodong WNP, stabilizing the water price at a more balanced level. The SD of water prices has been reduced as the water pricing scheme has become more comprehensive.

Table 11. Water prices and SD for zones of the SNWDP East Line (CNY/m^3).

Zones	South of Lake Nansi	Nansi Lower Lake	Nansihu Upper Lake–Changgou Pumping Station	Changgou Pumping Station–Dongping Lake	Dongping Lake–Linqing Qiu Tun Brake	Linqing Qiu Tun Brake–Datun Reservoir	East of Tung Ping Lake	SD
Basic water prices	0.16	0.28	0.33	0.4	0.69	1.09	0.82	
Metered water prices	0.2	0.35	0.4	0.49	0.65	1.15	0.83	
Comprehensive water prices	0.36	0.63	0.73	0.89	1.34	2.24	1.65	0.61

In the WPM, water supply costs and prices are no longer calculated on a project-by-project basis, but only on the total cost of the WNP. The total cost of the project is equitably shared among all water users who receive water from the WNP. The WPM effectively reduces or even eliminates the differences in water prices between WSPs and helps promote equitable use of water resources.

4.3. Market-Based Regulation of Water Prices

Natural resources are an important support for economic and social development. Agenda 21 clearly states that market mechanisms should be introduced into the natural resource market to achieve efficient resource allocation through the guiding role of price signals. At the same time, the market economy also stipulates that the basic orientation of natural resource price reform is market pricing [35]. The development of a unified and perfect resource trading market has become the inevitable way to improve the efficiency of resource use. At present, the degree of market development for different types of resources varies widely. Compared with other resources, water resources are relatively backward in terms of marketization, and enterprises cannot compete well in the market. WNPs achieve changes in water rights ownership through water diversion, but most of them are dominated by the government during the operation phase and cannot achieve full market-based trading of resources [36]. In the current project water supply price approval mechanism, the government takes water price cost as the basis for the formulation of water price standard. A price hearing will be held after the water price standard is issued, and public comments will be heard before changes are made. The government played a leading role in the whole process and did not introduce water prices into the water market for competition. Due to lack of competition among water enterprises, for a long time, high-cost companies had no incentive to reduce water supply costs and improve their management efficiency. The good results of market-based reforms in the electricity and gas networks provide ideas for market-based reforms in water pricing.

Drawing from the experience of electricity and natural gas reforms, we learned that the cost of raw materials can be marketized, but the transportation part of the resource cannot be directly traded on the market due to its certain monopolistic nature and requires government control. The same is true of water resources, where state control and market-based price management mechanisms are complementary. They promote a governance mechanism that serves both water management objectives and broader political and economic objectives [37].

The history of price reform in the electricity network reflects this. The market-based reform of electricity prices revolved around the liberalization of the feed-in price. Before the liberalization of the feed-in price, grid enterprises had very few competitors in the electricity sales market, and only a small number of direct customers could buy electricity directly from power generators. With the liberalization of the sales side of the feed-in price, the distribution of electricity in the area has gradually changed from planned development to market competition, and the increase in the number of distribution and sales companies has posed a major challenge to the grid enterprises. Enterprises should adapt to the reform environment in a timely manner and fully integrate into market competition. They must continuously improve their management efficiency and service level through a variety of means, market-oriented and efficiency-oriented. While maintaining the integrity of the industrial chain, enterprises need to maximize benefits [30]. Market reform can encourage enterprises to improve management efficiency, reduce price levels, and realize efficient allocation of resources.

From this, we can see that one of the preconditions for the marketization of resources is the distinction between the cost of the original resource and the cost of transport. In practice, traditional pricing mechanisms have only approved water prices within a single project, ignoring the role of market mechanisms and failing to ensure effective gaming between companies. The WPM addresses this shortcoming. Through the application of the WPM, the original resource supply link and the transport link are separated. It will not only accelerate the pace of water market cultivation and development but also promote the commercialization and marketization of water resources. Many countries in the world generally promote economic, social and environmentally sustainable development through price intervention in the resource market. Once the water market is established, a reasonable and comprehensive pricing mechanism can help achieve water resource management objectives. Various forms of intervention offer the possibility of achieving government water policy objectives and ensuring a balance between water supply and demand.

5. Conclusions

The WPM is a forward-looking forecast of the likely future development trend of water pricing for WNPs. It is conducive to the subsequent establishment of a unified backbone water network charge management platform, which is essential for the future measurement and collection of water charges at the end of the backbone water network. As our research focused on the water price of the project, we did not fully consider the factors related to the full-cost water price at the user end: for example, water loss and the polluter pays principle. These factors will be introduced in the research on comprehensive water prices for users. These need to be addressed in more detail in the future. As the severity of the world's water challenges increases, the use of multiple instruments, including water pricing, to ensure sustainable water development is equally important for countries around the world. As a unique pricing mechanism, the WPM will be more widely used for WNPs in the future.

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Abbreviations

WNP	Water Network Project
WPM	Water Pricing Model
WSP	Water Supply Point
SNWDP	South-to-North Water Diversion Project
YRQWDP	Yellow River to Qingdao Water Diversion Project
YREWDP	Yellow River to the East Water Diversion Project
JWDP	Jiaodong Water Diversion Project
YRXWDP	Yellow River to Xiashan Water Diversion Project
YERW	Yellow River Water
YARW	Yangtze River water
DCR	Degree of Cost Recovery
FPA	Full Production Attainment
SD	Standard Deviation
WSAR	Water Supply Attainment Rate
DCPi	Comprehensive water price for the *i*th WSP
DOPi	Comprehensive raw water price for the *i*th WSP
DTPi	Comprehensive water diversion price for the ith WSP
DTOi	Comprehensive raw water fee for the *i*th WSP
DWi	Total volume of water diverted by the *i*th WSP
TC	The sum of the total cost of the WNP in addition to the raw water fee
Di	The distance the water resource is delivered from the initial intake of the project to the WSP
RCPj	The comprehensive water price for *j*th area
ROPj	The comprehensive raw water price for *j*th area
RTPj	The comprehensive water diversion price for *j*th area
NCP	The comprehensive water price of the WNP
NOP	The comprehensive raw water price of the WNP
NTP	The comprehensive water price of the WNP for water diversion

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