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Research on decision-making of water diversion supply chain considering both social welfare and water quality utility

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When water diversion projects become important part of the water network around the world, the effective operation and management of the projects play important roles in giving full play to the optimal allocation of water resources. For the operation and management of water transfer, the decision-making of water supply chain under the scenario of economic benefit, producer surplus, and water quality utility should be considered simultaneously. According to the idea of supply chain, this paper regards water transfer operation management as a water supply chain composed of water transfer companies, water supply companies, and consumers. From the perspective of social welfare and water quality utility, a comprehensive optimization and coordination decision model for water transfer is proposed. Taking the South-to-North Water Diversion Project as the research object, the cost-sharing contract is designed, and the Stackelberg game method is used to optimize the decision-making and coordination of the water supply chain. The results show that when the concern coefficient and the cost-sharing ratio are evaluated within a given feasible value region, the profits of both the water transfer company and the water supply company can be improved. The feasible value interval of the concern coefficient decreases with the increase in the cost-bearing proportion. When the concern coefficient increases, the profit of the water transfer company decreases, while profit of the water supply company, water quality, consumer surplus, water quality utility, and utility of the water transfer company increase gradually. The results provide valuable references for water transfer decision-making.

KEYWORDS

water division supply chain, decision-making research, social welfare, water quality utility, Stackelberg game

1 Introduction

Under the circumstances of global climate change, population growth, and uneven regional distribution of natural water resources, the construction and operation of large-scale inter-basin water transfer projects have alleviated the problems of water resource shortage and uneven spatial distribution. Among them, the most typical cross-basin water diversion projects include the California State Water Project, the Quebec Water Transfer Project in Canada, the Snowy Mountains Scheme in Australia, and the South-to-North Water Diversion Project (SNWDP) in China (Yang, 2003). SNWDP, as the largest water diversion project in China, is a systematic, quasi-public, and basic large-scale project, involving various aspects such as economy, society, resources, and environment. The water transmission line of SNWDP is 4,350 km, crossing the four major river basins of the Yangtze River, Huaihe River, Yellow River, and Haihe River (Xu and Zeng, 2022). As of February 2023, the SNWDP has accumulatively transferred more than 60 billion cubic meters of water, directly benefiting more than 150 million people (Wang, 2023), effectively alleviating the water shortage problem in Beijing, Tianjin, and other cities (Guo et al., 2020; Niu et al., 2022). The main objectives and tasks of the project construction and operation are to achieve water supply and water saving, ecological security, and spiritual culture, and the government, enterprises, citizens, and other parties are jointly involved. As a large-scale and complex water diversion project across river basins, multi-subjects, and multi-objectives, it covers a wide range, involves many stakeholders, and has high operational and management complexity (Kattel et al., 2019). In operation and management practices, the management department often considers the economic benefits of the project as the primary factor when making decisions on issues, such as water price formulation, water volume scheduling, and water allocation. Although social factors, such as population migration, land requisition, and social welfare, and environmental factors, such as geological landforms, ecological environment, and water quality and quantity, are also taken into consideration, the influence of these factors on decision-making is still limited (Chen and Wang, 2019; Song et al., 2019). Therefore, how to consider social and environmental factors for the improvement of the operation management mechanism and decision-making efficiency is an urgent problem to be solved.

The operation of water diversion projects needs to realize the effective allocation of water resources on the basis of coordinating the interests of all parties, which can be analyzed by applying the theory of cost reduction and efficiency increase in supply chain management theory and the mechanism of interest negotiation. It is also of great practical significance to the SNWDP, a complex supply chain system with multiple basins, multiple water sources, multiple subjects, and environmental and social benefits. Many scholars have used supply chain theory to conduct research studies on the operation and management issues of SNWDP. The research topics involve the operational decision-making and applicability of the water resource supply chain (Sheng and Webber, 2018; Sheng et al., 2022), profit distribution (Sheng and Webber, 2021), policy research evaluation (Peng et al., 2018; Sheng and Qiu, 2022), benefit analysis (Yang et al., 2021), and many other aspects. It can be seen that the existing supply chain theory is mainly used in the analysis of economic goals. However, in fact, the SNWDP is not only a water resource allocation project but also a welfare project that guarantees social benefits and improves ecological benefits (Xu et al., 2021; Lu Q. et al., 2022; Liu et al., 2022). However, the existing research has limited discussions on its social and environmental dimensions and cannot fully match the needs of the SNWDP to achieve multiple goals (Koberg and Longoni, 2019). The sustainable supply chain theory focuses on the influence of “social and environmental” factors, which is highly consistent with the operational goals of SNWDP and also appropriately reflects the conflict of interests that urgently need to be resolved in the water transfer supply chain system (Chen and Wang, 2020). Therefore, it is quite necessary to introduce the theoretical model of sustainable supply chain and explore it from multiple dimensions of society and the environment.

Social needs and social interests exist widely in water conservancy projects, covering aspects such as daily life, agriculture, industry, flood control, ecological environment, and disaster management (Wang et al., 2022; Wang et al., 2023). Before the 1970s, international scholars’ research on the impact of engineering projects mainly focused on economic aspects (He et al., 2018). As the social problems caused by engineering projects are receiving more and more attention, some scholars have proposed that in the impact research of engineering projects, both economic development and social impact should be emphasized (Ge et al., 2020b). Research on social factors related to hydraulic engineering includes social impact assessment, social risk assessment, and social welfare (De Nicolás, 2016; Liu et al., 2016). Water resources have the characteristics of quasi-public goods, and water conservancy projects have the characteristics of public welfare. In the operation of cross-basin water diversion projects, it is crucial to make better use of water resources to solve the water resource shortage problem and the contradiction between the supply and demand and promote economic development outside. Meanwhile, it is more essential to improve the ecological environment and achieve coordinated development among regions to improve public interests and social welfare (Chen and Chen, 2020).

The book American Dictionary of Social Work defines social welfare as a national system of programs, benefits, and services designed to assist people in meeting their social, economic, educational, and health needs (Barker, 2003). Its main function is to meet the needs of a better life, and it is also the most basic and important social institutional arrangement. The cross-basin water diversion project reduces the environmental capacity of the water source area and has an adverse impact on the ecological environment of the water source area. However, changes in the ecological environment along the water diversion project will have adverse effects on the interaction of stakeholders and policy formulation, which will inevitably affect social welfare (Mu, 2018). Studies chose game theory and coordination theory to study the cross-basin water transfer supply chain from a social welfare maximization perspective and provide theoretical advice for the improvement of business performance and social welfare optimization of supply chain participants (Chen and Pei, 2018; Chen et al., 2019a). One of the goals of the SNWDP is to fully guarantee the life, production, and ecological security of the people in the water source area and the water-receiving area (Xu and Zeng, 2022), which is the embodiment of social welfare when the government sets the project goals. Similarly, for enterprises, actively paying attention to social welfare undertakings and assuming corporate responsibilities are also necessary for the sustainable development of enterprises (Peng et al., 2022). Therefore, how does the government intervene in the realization of social welfare goals (such as planning capital investment, formulating social security and welfare policies, optimizing supervision and evaluation mechanisms), how do the enterprises play their social responsibility role to return to the society (such as sustainable management of water resources, cooperation with stakeholders, and promotion of social investment projects), and more importantly how to coordinate and cooperate with various roles in the supply chain to ensure that the public benefits from the green operation of water transfer projects and maximize social welfare are urgent issues to be discussed (Li C. et al., 2022).

As a large-scale cross-basin water diversion project, the SNWDP will have a series of ecological and environmental impacts on the water ecosystem. Therefore, it is crucial to maintain the health of ecosystems while meeting human water demands (Guo et al., 2020). Guo et al. (2019) found that water diversion may have a chain reaction on fish communities, and more attention should be paid to the long-term ecological effects of future water diversion. Du et al. (2021) analyzed the changes in the water cycle, groundwater level, climatic factors, and subsidence patterns in the Beijing area after the implementation of the SNWDP Middle Route. Liu et al. (2020) proposed a comprehensive water footprint index and discussed the adverse impacts of water diversion projects on ecosystems and the environment. Feng and Zhao (2020) believed that, from the perspective of ecological footprint, organic agriculture can effectively promote the ecological security of the water source area of the SNWDP. Among many environmental factors, surface water quality plays a vital role in determining the ecological environment, public health, and socioeconomic development (Wu et al., 2020). Water diversion projects focus on ecological environmental factors during construction and operation and take measures to protect and maintain the health of the water ecosystem, ensuring good water quality effects. At the same time, the protection and improvement of water quality also help maintain and promote the health of the ecological environment. Apparently, water ecosystems and water quality are interdependent and jointly promote sustainable water use and ecological balance.

The water quality utility of the water diversion project refers to the management and control of the water quality during the water diversion process to ensure that the quality of the delivered water meets specific requirements and standards. The water quality utility of water diversion projects includes ensuring water quality safety, water quality maintenance, water quality adjustment, water quality monitoring and management, and water quality environmental protection. In the water transfer supply chain, water quality is a key factor that affects the demand for water resources and the benefits of enterprises along the route. Through effective water quality management, water diversion projects can provide water quality that meets requirements and standards and social needs and protect the health of the water environment and ecosystem. Water quality safety is a key factor related to the success or failure of long-distance water diversion projects. With the development of society and economy, the contradiction among population, resources, and environment has become increasingly prominent (Wu et al., 2021; Zhang et al., 2022). The shortage of water resources is increasingly manifested as new problems, such as shortage of water quality, shortage of projects, and shortage of institutions. Brouwer and De Blois (2008) gave an overview of sources of uncertainty in the analysis of least-cost approaches to improving water quality, and their findings showed that the interaction between environmental and economic uncertainties is complex. In the past, the traditional water resource allocation model that only considered water volume is no longer suitable for the needs of rapid social and economic development (Jin-yan et al., 2021; Shen et al., 2021). The rational and effective use of water resources must take into account the quantity and quality of water resources and implement joint scheduling and control from the source (Aiqing et al., 2020). Therefore, it is one of the key factors in the water quality investment and pricing decision-making process of each main enterprise in the water supply chain to study the dispatching and allocation of water resources by using water quality utility.

It can be seen from the aforementioned research results that social welfare and water quality are the key issues that should be considered in water diversion projects. Existing studies have investigated the management decision-making aspects of water diversion projects. For example, some studies have described in detail the challenges faced by the SNWDP in terms of water demand, water supply quality, and management policies when incorporated into water supply plans (Chen and Wang, 2012). There are also studies using multiple linear regression analysis (Nong et al., 2020), factor analysis (Kuo et al., 2019), multivariate statistical techniques (Guo et al., 2020), water quality index (WQI) (Qu et al., 2020), catastrophe theory (Wu et al., 2020), data envelopment analysis (Su and Chen, 2021), and other methods for water quality evaluation and decision-making research of water diversion projects and provide suggestions for policy formulation. However, most of these studies are only observed from a single perspective (Chen and Pei, 2018; Chen et al., 2019b), and there are few comprehensive multi-angle studies. Chen et al. (2023) explored the coordination mechanism of the SNWDP supply chain from two aspects of economic benefits and social responsibilities. The results showed that the overall profit and the profit of suppliers and distributors under the centralized decision-making situation are higher than those under the decentralized decision-making. Meanwhile, the profits from the dual perspectives are also higher than those from a single economic perspective. Studies have also shown better simulation (Li et al., 2021), or evaluation results are obtained by using comprehensive evaluation models (Ge et al., 2020a; Ge et al., 2022) or considering multiple perspectives (Zhang et al., 2023). The main participants in SNWDP are the government and enterprises (water source companies and water supply companies), in which the government is committed to maintaining social welfare and public interests while enterprises pursue economic interests. In the process of balancing the relationship between social welfare, public interests, and economic interests, social welfare and water quality utility are crucial factors in the decision-making of water diversion projects.

This paper attempts to discuss the optimal decision-making and coordination issues of the SNWD supply chain from the dual perspectives of social welfare and water quality utility, establishes the corresponding Stackelberg decentralized decision-making model and cost-sharing contract model, and discusses how to realize economic benefits under the premise of considering ecological benefits and social benefits. It also maximizes and provides decision-making reference for relevant decision-makers.

Based on the aforementioned discussion, the remainder of this paper is organized as follows: Section 2 describes the water transfer supply chain model, Stackelberg game model, and contract sharing model. Section 3 obtains the visualization results of the model through numerical simulation. Section 4 analyzes and discusses the results. Finally, conclusion of the paper is given in Section 5.

2 Research methodology

In order to reveal how enterprises of all parties to the water diversion supply chain maximize their profits under the premise of considering social welfare and water quality effectiveness, a model is designed and analyzed.

2.1 General engineering situation

The SNWDP (South-to-North Water Diversion Project) is a strategic water transfer project in China. It was conceived in 1952 when President Mao Zedong inspected the Yellow River to solve the water shortage problem in the northern part of China, especially in the Yellow, Huai, and Hai River basins. After numerous planning schemes, three water transfer lines are identified: East, Middle, and West, which are linked to the Yangtze River, Yellow River, Huai River, and Hai River, forming a general layout with "four horizontal and three vertical" to help realize a rational allocation pattern of China's water resources from north to south and from east to west. The starting point of the East Route Project is located at the Jiangdu Hydrojunction in Yangzhou, Jiangsu Province. The Middle Route Project starts from Danjiangkou Reservoir in the middle and upper reaches of the Han River, and the catchment areas are Henan, Hebei, Beijing, and Tianjin. The middle route of the SNWDP and the eastern route of the SNWDP (Phase 1) have been completed and will transfer water to the north, while the western route is still in the planning stage. The total length of the East, Middle and West trunk lines planned for the project is 4,350 km. The total length of the trunk line of the East and Middle Routes of the SNWDP (Phase 1) is 2,899 km, with approximately 2,700 km of complementary branch canals at the first level in six provinces and cities along the line. The SNWDP planning area involves a population of 438 million people and a water diversion scale of 44.8 billion cubic meters. South water has become the main source of water for more than 150 million people in more than 280 counties and urban areas in more than 40 large- and medium-sized cities, including Beijing and Tianjin, since its completion in 2014. The water resources brought by the SNWDP not only meet people's basic living needs but also provide important support for the agricultural development in North China and improve the social welfare benefits of the water-receiving areas. At the same time, it has established a complete water quality monitoring network at key locations such as river sources, reservoirs, water delivery channels, and water sources and adopted water purification measures to ensure the stability and safety of water quality.

2.2 Overall model construction

A supply chain is an integrated manufacturing process in which raw materials are transformed into final products, which are then delivered to customers (Beamon, 1998). Wang et al. (2005) first introduced supply chain theory and contract design into the operation and management of the SNWDP. From the perspective of the supply chain, the East Route Project of SNWDP was regarded as a supply chain composed of water suppliers and distributors, and its applicability and wide application prospects were discussed. In most studies on water transfer supply chains, supply chain participants are divided into "water supply-distribution" or "water transfer-water supply" structures, which is in line with the actual operation of SNWDP (Chen et al., 2019b; Lu Y. et al., 2022). Drawing on ideas from related articles, this paper divides the participants in the SNWDP water supply chain into three categories: water transfer companies, water supply companies, and consumers, taking into account the practical operation of the SNWDP in China and drawing on the idea of supply chain operation. Water transfer companies cover all participants in the supply of water resources at the source. Water transfer companies, which cover all participants in the supply of water resources at the source, are concerned about water quality utility, their own profits, and consumer surplus, and their decision variables are the price of water diversion, water quality, and the concern coefficient about water quality utility and consumer surplus. Water supply companies, which cover the organizational managers of water resource utilization in the catchment areas along the SNWDP, are concerned with their own profits and set market water prices based on water demand. Consumers cover all end-users of SNWDP water resources. The water transfer company transports water resources from the water source to the water supply company, and then the water supply company distributes the water resource products to consumers. The supply chain structure of water resources in the SNWDP is shown in Figure 1. Relevant symbols in the paper and their meanings are explained in Table 1.

Assuming that the water demand in the catchment area decreases as the water price increases and increases as the water quality increases, the water demand function is given as

$$Q = a - bp + rm, \tag{1}$$

where a, b, r are positive variables, while water demand Q, water price p, and water quality m are non-negative variables. Water transfer companies improve water quality, and the cost function is given as

$$C(m) = 0.5km^2, k > 0. \tag{2}$$

Using Eq. 1, it can be found that the consumer surplus generated by the consumer's purchase of water resources is

$$S = \int_p^{\frac{a+rm}{b}} (a - bp + rm) dp = \frac{(a - bp + rm)^2}{2b}. \tag{3}$$

Multiplying water quality utility H, water demand Q, and water quality m, we obtain

$$H = Qm = (a - bp + rm)m. \tag{4}$$

Furthermore, assuming that the unit water transfer cost of the water transfer company is c_1, the transfer price is w, and the unit water supply cost of the water supply company is c_2, then the profit function π_1 of the water transfer company and the profit function π_2 of the water supply company are

$$\pi_1 = (a - bp + rm)(w - c_1) - 0.5km^2, \tag{5}$$

$$\pi_2 = (a - bp + rm)(p - w - c_2). \tag{6}$$

Social welfare consists of producer surplus and consumer surplus, where the producer surplus is represented by the profit

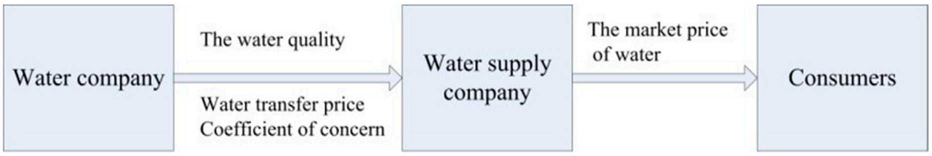

FIGURE 1
Illustration of the monitoring and assessment information system for reservoir resettlement.

TABLE 1 Symbol description table.

Symbol	Meaning description	Symbol	Meaning description
p	Market water price in the receiving area	a	Potential water demand
Q	Water demand in the receiving area	b	Water price preference coefficient
m	Water quality	r	Water quality preference coefficient
S	Consumer surplus	k	Water quality improvement cost coefficient
H	Water quality utility	c_1	Unit cost of water transfer
w	Water wholesale price	c_2	Unit cost of water supply
π_1	Water transfer company profits	λ	Concern coefficient of water diversion company
π_2	Water supply company profits	U	Utility of the water supply company

function of the water transfer company and the water supply company. Assuming that the water supply company only cares about its own profits, while the water transfer company cares about its own profits as well as consumer surplus and water quality utility, in the dual perspective of social welfare and water quality utility, the utility function of the water transfer company is designed as

$$U = \pi_1 + \lambda(S + H), \tag{7}$$

where λ denotes the concern coefficient of the water transfer company for water quality, utility, and consumer surplus, $\lambda \geq 0$. When $\lambda = 0$, the utility function degenerates the profit function of the water transfer company.

2.3 Stackelberg game model

The decision-making models currently used in the study of water transfer supply chains include the IDR model (Ouyang et al., 2019), differential game model (Sheng and Webber, 2021), and Stackelberg game model (Xin et al., 2022). The optimal allocation of water resources by the IDR model is affected by the selection of indicators. The calculation accuracy of the differential game model is slightly lower, while the Stackelberg game model has been relatively mature in the study of water transfer supply chain decision-making and has shown good results. Wang et al. (2008) first used the Stackelberg game to establish a pricing model for the supply chain on the eastern route of the SNWDP and obtained the Pareto optimality of the eastern route supply chain. Du et al. (2019) studied the production, operation, and management of water resources in SNWDP based on the two-stage Stackelberg game method, regarding the East Route Project and the Middle Route Project as two water resource supply chain systems, and explored the chain-to-chain competition model. The theory of supply under competition was expanded. Chain operation provides management enlightenment for the sustainable development of water resources. Related research also shows that the Stackelberg game model is very consistent with the dispatching research of power and water conservancy systems (Li Y. et al., 2022; Sun et al., 2023). It can be seen that it is appropriate and effective to apply the Stackelberg game model to the research of the water transfer supply chain.

Assuming that the water transfer company is the leader of the Stackelberg game and the water supply company is the follower, the reverse induction method is used for the solution. The optimal market water price reaction function is derived from the first-order condition $\frac{\partial \pi_2}{\partial p} = 0$ as follows:

$$p = \frac{(w + c_2)b + rm + a}{2b}. \tag{8}$$

Substituting the market water price response function 8 into the water transfer company utility function 7, the Hessian matrix of the utility function U concerning w and m is expressed as

$$\begin{pmatrix} \frac{\partial^2 U}{\partial w^2} & \frac{\partial^2 U}{\partial w \partial m} \\ \frac{\partial^2 U}{\partial m \partial w} & \frac{\partial^2 U}{\partial m^2} \end{pmatrix} = \begin{pmatrix} -b + \frac{1}{4}\lambda b & \frac{(-2b - r)\lambda}{4} + \frac{r}{2} \\ \frac{(-2b - r)\lambda}{4} + \frac{r}{2} & \frac{(4\lambda r - 4k)b + \lambda r^2}{4b} \end{pmatrix}. \tag{9}$$

Under the Hessian matrix negative definite condition, the first-order master equation is less than zero and the Hessian matrix determinant is greater than zero. The calculation yields

$$-b+\frac{1}{4}\lambda b<0, \tag{10}$$

$$-b^2\lambda^2+((-k-2r)\lambda+4k)b-r^2>0. \tag{11}$$

Under the Hessian matrix negative definite condition, the first order condition $\frac{\partial U}{\partial w}=0$ and $\frac{\partial U}{\partial m}=0$, by the water transfer company utility function can be solved for the optimal wholesale price $w^\star$ and the optimal water quality $m^\star$. (The optimal result of the Stackelberg game model is indicated by the superscript *)

$$\begin{aligned}w^\star=&(-b^2c_2\lambda^2+(a\lambda^2+(-kc_2+r(c_1-c_2))\lambda-2k(c_1-c_2))b\\&+a(k+r)\lambda+c_1r^2-2ak)\big/(b^2\lambda^2+((k+2r)\lambda-4k)b+r^2),\end{aligned} \tag{12}$$

$$m^\star=\frac{((c_1+c_2)b-a)(\lambda b+r)}{b^2\lambda^2+((k+2r)\lambda-4k)b+r^2}. \tag{13}$$

Substituting $w^\star$ and $m^\star$ into Eq. 8 yields the optimal water price as

$$p^\star=\frac{(a\quad\lambda^2+r(c_1+c_2)\lambda-k(c_1+c_2))b+a(k+r)\lambda+(c_1+c_2)r^2-3ak}{b^2\lambda^2+((k+2r)\lambda-4k)b+r^2}. \tag{14}$$

Substituting $m^\star$, $w^\star$, and $p^\star$ into Eqs 3–7, the optimal profits of the water transfer company and the water supply company, the optimal profits of the supply chain system, the optimal water quality utility, the optimal consumer surplus, and the optimal utility of the water transfer company can be derived as follows:

$$\pi_1^\star=-\frac{3k\left(b^2\lambda^2+\left(\left(\frac{2k}{3}+\frac{4r}{3}\right)\lambda-\frac{4k}{3}\right)b+\frac{r^2}{3}\right)(a-(c_1+c_2)b)^2}{2\left(b^2\lambda^2+((k+2r)\lambda-4k)b+r^2\right)^2}, \tag{15}$$

$$\pi_2^\star=\frac{k^2(a-(c_1+c_2)b)^2b}{\left(b^2\lambda^2+((k+2r)\lambda-4k)b+r^2\right)^2}, \tag{16}$$

$$\pi_1^\star+\pi_2^\star=-\frac{3k(a-(c_1+c_2)b)^2\left(b^2\lambda^2+\left(\left(\frac{2k}{3}+\frac{4r}{3}\right)\lambda-2k\right)b+\frac{r^2}{3}\right)}{2\left(b^2\lambda^2+((k+2r)\lambda-4k)b+r^2\right)^2}, \tag{17}$$

$$S^\star=\frac{k^2((-c_1-c_2)b+a)^2b}{2\left(b^2\lambda^2+((k+2r)\lambda-4k)b+r^2\right)^2}, \tag{18}$$

$$H^\star=\frac{(\lambda b+r)k(a-(c_1+c_2)b+a)^2b}{\left(b^2\lambda^2+((k+2r)\lambda-4k)b+r^2\right)^2}, \tag{19}$$

$$U^\star=-\frac{k((-c_1-c_2)b+a)^2}{2b^2\lambda^2+((2k+4r)\lambda-8k)b+2r^2}. \tag{20}$$

2.4 Cost-sharing contract model

In the Stackelberg game model shown previously, the cost of improving water quality is borne entirely by the water transfer company. However, in the SNWDP practices, there is a basic cost-sharing model based on the principle of "who benefits, who bears costs" by dividing channels and levels. The ultimate goal of the water transfer supply chain is to improve competitiveness; hence, companies in the supply chain cannot develop their business without cooperation and cost-sharing (Stadtler, 2015). In order to stimulate the cooperation between the water transfer company and the water supply company, this article assumes that the water supply company shares a certain proportion of the cost of improving water quality, and the proportional coefficient is η $(0\le\eta\le1)$. When $\eta=0$, the water company does not bear the cost of improving water quality. When $\eta=1$, all the costs of improving water quality are fully borne by the water company. Therefore, the profit function of the water transfer company and the water supply company, together with the utility function of the water transfer company, is modified as

$$\pi_1=(a-bp+rm)(w-c_1)-\frac{1}{2}(1-\eta)km^2, \tag{21}$$

$$\pi_2=(a-bp+rm)(p-w-c_2)-\frac{1}{2}\eta km^2, \tag{22}$$

$$\begin{aligned}U=&(a-bp+rm)(w-c_1)-\frac{(1-\eta)k\quad m^2}{2}\\&+\lambda\left(\frac{(a-bp+rm)^2}{2b}+(a-bp+rm)m\right).\end{aligned} \tag{23}$$

Using Eq. 22, the market water price response function can be obtained from the first-order condition $\frac{\partial\pi_2}{\partial p}=0$ as

$$p=\frac{(w+c_2)b+rm+a}{2b}. \tag{24}$$

Substituting the water price response function 24 into the water transfer company utility function 23 , the Hessian matrix of utility U concerning w and m is given as

$$\begin{pmatrix}\frac{\partial^2U}{\partial w^2}&\frac{\partial^2U}{\partial w\partial m}\\\frac{\partial^2U}{\partial m\partial w}&\frac{\partial^2U}{\partial m^2}\end{pmatrix}=\begin{pmatrix}-b+\frac{1}{4}\lambda b&\frac{(-2b-r)\lambda}{4}+\frac{r}{2}\\\frac{(-2b-r)\lambda}{4}+\frac{r}{2}&\frac{(4\lambda r+4(-1+\eta)k)b+\lambda r^2}{4b}\end{pmatrix}. \tag{25}$$

The Hessian matrix 25 with negative definiteness is conditioned on

$$-b+\frac{1}{4}\lambda b<0, \tag{26}$$

$$-b^2\lambda^2+(((-1+\eta)k-2r)\lambda-4(-1+\eta)k)b-r^2>0. \tag{27}$$

In the Hessian matrix negative definite period, the optimal water transfer price w^{**} and the optimal water quality m^{**} can be solved by the first-order condition $\frac{\partial U}{\partial w}=0$ in conjunction with $\frac{\partial U}{\partial m}=0$ as follows (the optimal result of the cost-sharing contract model is denoted by the superscript **)

$$\begin{aligned}w^{**}=&\left(-b^2c_2\lambda^2+\left(2\left(\frac{1}{2}\lambda c_2+c_1-c_2\right)(-1+\eta)k\right.\right.\\&+\lambda(\lambda a+r(c_1-c_2)))b-a(\lambda-2)(-1+\eta)k\\&+a\lambda r+c_1r^2)/(b^2\lambda^2+(-(-4+\lambda)(-1+\eta)k)\\&+2\lambda r)b+r^2),\end{aligned} \tag{28}$$

$$m^{**}=-\frac{((-c_1-c_2)b+a)(\lambda b+r)}{b^2\lambda^2+((2r+(1-\eta)k)\lambda+4(-1+\eta)k)b+r^2}. \tag{29}$$

By substituting the optimal transfer price w^{**} and the optimal water quality m^{**} into the water price reaction function 24, the optimal water price can be obtained as

$$p^{**}=\frac{\begin{aligned}&(((-1+\eta)(c_1+c_2)k+\lambda(\lambda a+r(c_1+c_2)))b\\&-a(\lambda-3)(-1+\eta)k+r(\lambda a+r(c_1+c_2)))\end{aligned}}{(b^2\lambda^2+(-(-4+\lambda)(-1+\eta)k+2\lambda r)b+r^2)}. \tag{30}$$

Furthermore, the water transfer company profit π_1^{**}, water supply company profit π_2^{**}, supply chain system profit $\pi_1^{**} + \pi_2^{**}$, consumer surplus S^{**}, water quality effect H^{**}, and water transfer company utility U^{**} in the cost-sharing contract situation are as follows:

$$\pi_1^{''} = \frac{3\left(\left(-c_1 - c_2\right)b + a\right)^2\left(b^2\lambda^2 + \left(-\frac{2(\lambda-2)(-1+\eta)k}{3} + \frac{4\lambda r}{3}\right)b + \frac{r^2}{3}\right)(-1+\eta)k}{2\left(b^2\lambda^2 + \left(-(-4+\lambda)(-1+\eta)k + 2\lambda r\right)b + r^2\right)^2}, \tag{31}$$

$$\pi_2^{**} = -\frac{\left(b^2\eta\lambda^2 + \left(-2(-1+\eta)^2 k + 2r\eta\lambda\right)b + \eta r^2\right)\left(\left(-c_1 - c_2\right)b + a\right)^2 k}{2\left(b^2\lambda^2 + \left(-(-4+\lambda)(-1+\eta)k + 2\lambda r\right)b + r^2\right)^2}, \tag{32}$$

$$\begin{aligned}\pi_1^{**} + \pi_2^{**} = &\Bigg(\left(\lambda^2\left(\eta - \frac{3}{2}\right)b^2 + \left(\left(-(-1+\eta)^2 k + r(\eta-2)\right)\right)\lambda\right. \\ &\left. +3(-1+\eta)^2 k)b - \frac{r^2}{2}\right)\left(\left(-c_1 - c_2\right)(b+a)^2 k\right)/\left(\left(b^2\lambda^2\right.\right. \\ &\left.\left. +\left((2r + (1-\eta)k)\lambda + 4(-1+\eta)k\right)(b+\eta^2)^2\right)\right),\end{aligned} \tag{33}$$

$$S^{**} = \frac{b\left(\left(-c_1 - c_2\right)b + a\right)^2(-1+\eta)^2 k^2}{2\left(b^2\lambda^2 + \left(-(-4+\lambda)(-1+\eta)k + 2\lambda r\right)b + r^2\right)^2}, \tag{34}$$

$$H^{**} = -\frac{b\left(\left(-c_1 - c_2\right)b + a\right)^2(\lambda b + r)(-1+\eta)k}{\left(b^2\lambda^2 + \left((-k\eta + k + 2r)\lambda + 4(-1+\eta)k\right)b + r^2\right)^2}, \tag{35}$$

$$U^{**} = \frac{\left(\left(-c_1 - c_2\right)b + a\right)^2(-1+\eta)k}{2b^2\lambda^2 + \left(-2(-4+\lambda)(-1+\eta)k + 4\lambda r\right)b + 2r^2}. \tag{36}$$

Compared with the results of the Stackelberg game, the condition that the water transfer company and the water supply company can successfully and consciously achieve the cost-sharing contract is that both parties can improve their profits under the cost-sharing contract, which means $\pi_1^{**} > \pi_1^{*}$ and $\pi_2^{**} > \pi_2^{*}$, and the parameters and variables should be taken by the economic implication and should satisfy the Hessian matrix negative definite condition.

3 Results

Through numerical simulations, the Hessian matrix negative definite conditions, the conditions for the implementation of cost-sharing contracts for water quality improvement between the water transfer company and the water supply company, and the effect of the concern factor of the water transfer company on profits, producer surplus, and water quality effects are further explored. The parameters are taken as $a = 400$, $b = 2$, $c_1 = 6$, $c_2 = 4$, $k = 4$, and $r = 1$. From Eqs 10, 26 of the Hessian matrix negative definite condition and $\lambda \geq 0$, the parameter λ takes the value interval $[0, 4)$. The water quality improvement cost-sharing ratio η takes the value interval $[0, 1]$. Therefore, using the aforementioned parameter settings, the Hessian matrix negative definite condition in equalities Eqs 11, 27 and $\pi_1^{**} - \pi_1^{*} > 0$, $\pi_2^{**} - \pi_2^{*} > 0$ can be expressed as follows:

$$-4\lambda^2 - 12\lambda + 31 > 0, \tag{37}$$

$$-\lambda^2 + \frac{(-6+4\eta)\lambda}{2} + \frac{31}{4} - 8\eta > 0, \tag{38}$$

$$\frac{866400\left(4\lambda^2 - \frac{16(\lambda-2)(-1+\eta)}{3} + \frac{8\lambda}{3} + \frac{1}{3}\right)(-1+\eta)}{\left(4\lambda^2 - 8(\lambda-4)(-1+\eta) + 4\lambda + 1\right)^2} - \frac{866400\left(4\lambda^2 + 8\lambda - \frac{31}{3}\right)}{\left(4\lambda^2 + 12\lambda - 31\right)^2} > 0, \tag{39}$$

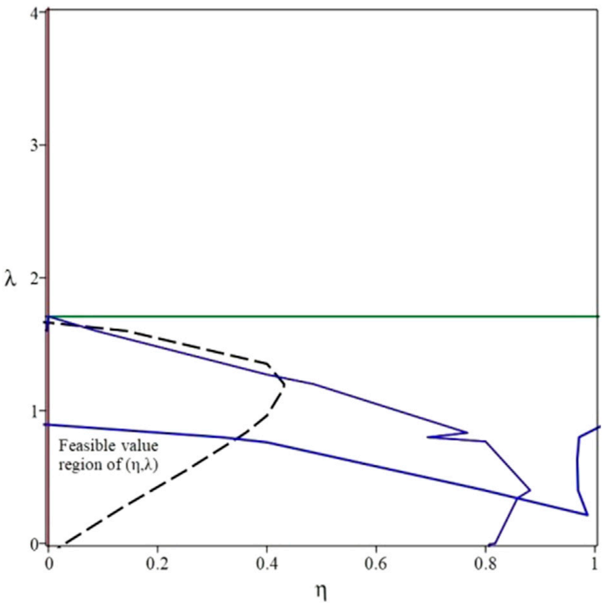

FIGURE 2
Feasible value region of (η, λ).

$$\frac{288800\left(-16\lambda^4 + 64\eta\lambda^2 - 96\lambda^3 + 320\lambda\eta - 24\lambda^2 - 1008\eta + 360\lambda + 31\right)\eta(2\lambda+1)^2}{\left(8\lambda\eta - 4\lambda^2 - 32\eta - 12\lambda + 31\right)^2\left(4\lambda^2 + 12\lambda - 31\right)^2} > 0. \tag{40}$$

The feasible value area of (η, λ) that simultaneously satisfies in Eqs 37–40 in the parameter space $(\eta, \lambda) \in [0, 1] \times [0, 4)$ is shown Figure 2, and its local enlargement is shown in Figure 3. The intersection point coordinates of the black dashed line and the blue solid line in Figure 3 are (0.33,0.78). The maximum feasible value of the sharing ratio η is 0.33. As η increases in the interval (0, 0.33), the feasible value of the concern coefficient λ becomes smaller. When the value of (η, λ) is outside the feasible value area as shown in Figure 3, or the Hessian matrix negative definite condition is not satisfied, the optimal solution is invalid. When the water transfer company and the water supply company cannot make the profit both sides through the cost-sharing contract, the cost-sharing contract does not attract both parties to perform consciously. Compared to the results of the Stackelberg game, the surfaces of the increase in profit of the water transfer company $\pi_1^{**} - \pi_1^{*}$ and the increase in profit of the water supply company $\pi_2^{**} - \pi_2^{*}$ with the parameter (η, λ) under the cost-sharing contract are shown in Figures 4, 5. It is clear from Figures 4, 5 that when the parameter (η, λ) is taken in the feasible value region as shown in Figure 3, the difference between the profits of both the water transfer company and the water supply company in the cost-sharing contract model and the profits in the Stackelberg game model is more than 0, meaning that both the water transfer company and the water supply company achieve a Pareto improvement in their profits. For a given cost-sharing ratio η, compared with the results of the Stackelberg game, Figure 4 shows that the increase in profit $\pi_1^{**} - \pi_1^{*}$ for the water transfer company decreases as the concern factor λ increases, and Figure 5 shows that the profit $\pi_2^{**} - \pi_2^{*}$ increases for the water supply company as the concern factor λ increases.

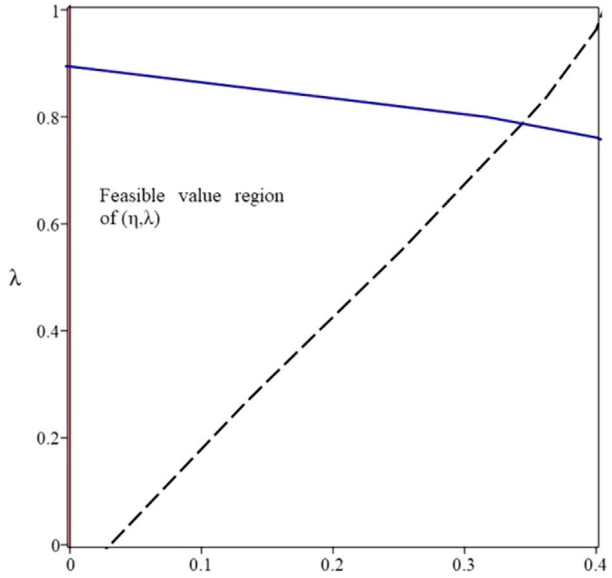

FIGURE 3
Local enlargement of the feasible value region of (η, λ).

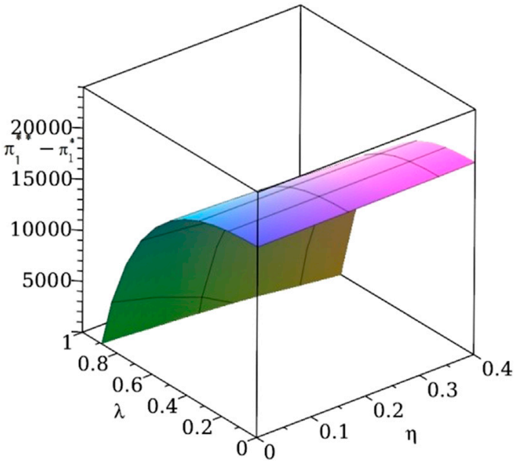

FIGURE 4
Pareto improvement surface of the water transfer company's profit.

Under the aforementioned parameter conditions, the optimal water quality, consumer surplus, water quality effect, and utility of the water transfer company in the cost-sharing contract model as a function of parameter (η, λ) are given as follows:

$$m^{**} = -\frac{380(2\lambda + 1)}{4\lambda^2 + 2(-4\eta + 6)\lambda - 31 + 32\eta}, \tag{41}$$

$$S^{**} = \frac{2310400(-1 + \eta)^2}{(4\lambda^2 - 8(\lambda - 4)(-1 + \eta) + 4\lambda + 1)^2}, \tag{42}$$

$$H^{**} = -\frac{1155200(-1 + \eta)(2\lambda + 1)}{(4\lambda^2 + 2(-4\eta + 6)\lambda - 31 + 32\eta)^2}, \tag{43}$$

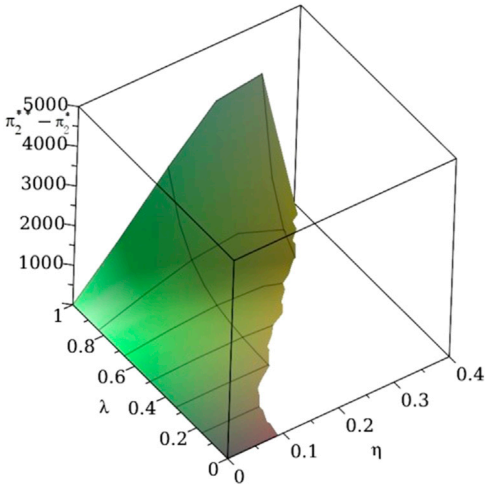

FIGURE 5
Pareto improvement surface of the water supply company's profit.

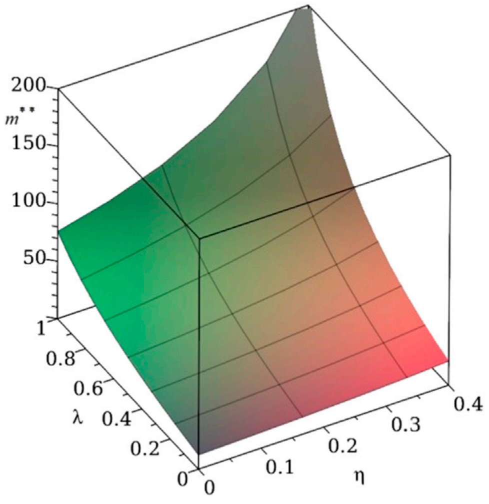

FIGURE 6
Water quality variation surface of (η, λ).

$$U^{**} = \frac{-577600 + 577600\eta}{8\lambda^2 - 16(\lambda - 4)(-1 + \eta) + 8\lambda + 2}. \tag{44}$$

Using Eqs 41–44, the surfaces of variation in water quality, consumer surplus, water quality effect, and water transfer company utility concerning parameters (η, λ) are plotted in Figures 6–9, respectively. It is evident from Figures 6–9 that for a given cost-bearing ratio η, water quality, consumer surplus, water quality effect, and water transfer company utility all increase with the increase in the concern factor λ.

4 Discussion

(1) According to Figures 2, 3, in the concern factor λ and water quality improvement cost-sharing ratio η taking the value

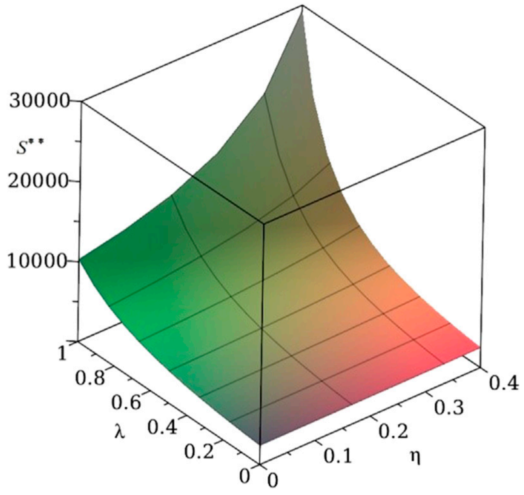

FIGURE 7
Consumer surplus variation surface of (η, λ).

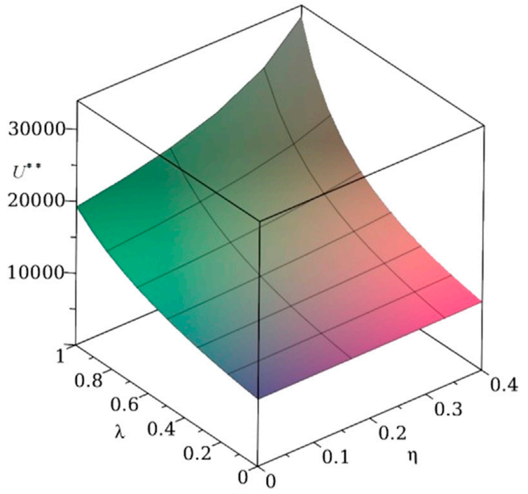

FIGURE 9
Water transfer company variation surface of (η, λ).

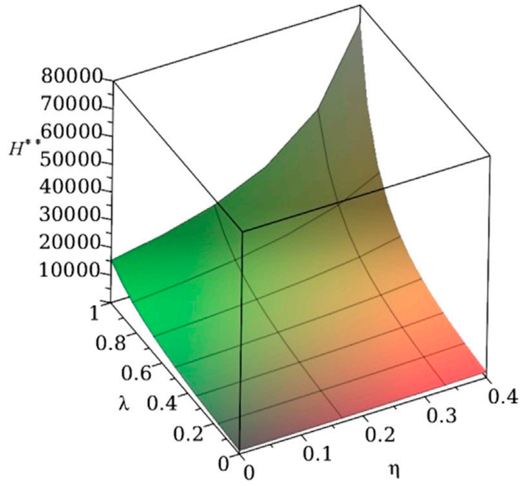

FIGURE 8
Water quality variation surface of (η, λ).

plane, there is a large feasible value region (η, λ), so that the water transfer company and the water supply company in the cost-sharing contract model can both obtain more profit than in the Stackelberg game model. In order to make the water diversion supply chain more profitable, the proportion η of water supply company's responsibility for water quality improvement should be less than 0.33. At present, the ratio of the water transfer company to the water supply company to bear the cost of water quality improvement in the actual project is not clear yet. Government management departments such as the South-to-North Water Diversion Office and provincial water conservancy departments need to encourage and supervise all participants in project operation and management (water transfer companies and water supply companies) to sign cost-sharing contracts for cooperation and cost-sharing.

(2) According to Figures 4–9, the concern factor and cost-sharing ratio have a complex effect on the game outcome, and both vary in dependence. For the optimal outcome of the cost-sharing contract model, when the cost-sharing ratio or concern factor is fixed, the optimal water quality, consumer surplus, water quality utility, and the total utility of the water transfer company all increase with the other party. Each interested individual will seek to maximize their own interests, but the state of each party's lack of cooperation will eventually lead to a reduction in operational efficiency [40]. Therefore, balancing the cost-sharing ratio under the cooperation between the two sides and jointly pursuing social welfare and water quality utility are a favorable means to improve the profits of water transfer and water supply companies and to achieve optimal coordination of the water transfer supply chain. Therefore, the water source companies on the eastern middle line of the SNWDP should actively strengthen information communication and information sharing with water supply companies in various regions, balance the cost-sharing ratio, and achieve Pareto improvement in the performance of the SNWD supply chain.

(3) Within the range of feasible parameters, the water transfer company shows an increase in concern coefficient to increase its total utility of interest, including economic benefits, water quality utility, and consumer surplus, but a decrease in its own profit, while there is an increase in the profit of the water supply company. This indicates that the water transfer company has to sacrifice some of its own profits to increase the total utility of concern while the water supply company's profits increase, which has a "free-rider" effect. This provides an incentive for the water transfer company to share some of its profits with the water supply company, thus allowing the water transfer company to increase its concern coefficient even further and indirectly increasing the profit level of the water supply

company. Therefore, in the SNWDP, in order to avoid the "free-ride" effect of destroying the benefits of each participant and affecting the realization of the company's own profits and social welfare, it is possible to coordinate and improve the interests of all participants in the supply chain by signing a revenue-sharing contract. The profit-sharing contract design of the water transfer supply chain is one of the future research directions.

(4) This paper introduces water quality utility and consumer surplus into the decision model, and the results of the study reflect not only the economic interests of the water supply company and the water transfer company but also the concern for ecological benefits and social welfare. The Stackelberg game is studied in a non-cooperative scenario between the water supply company and the water transfer company, and the optimal solution of the game is given. The conditions for cost-sharing contracts to improve the profits of both water suppliers and water transfer companies are also explored. However, numerical calculation of specific values in this paper is related to the parameter settings given in the text. For different parameter settings, the specific results should be further subjected to specific analysis.

5 Conclusion

The operation and management of water transfer projects play an important role in giving full play to the optimal allocation of water resources. From the perspective of both social welfare and water quality utility, based on supply chain and game theory, this paper proposes a management decision model considering a comprehensive objective of economic efficiency, producer surplus, and water quality utility. Taking the South-North water transfer as an example, the impact of designing a cost-sharing contract for water quality improvement on the decision outcome is explained through numerical simulation.

Within the feasible value region of (η, λ), as the proportion η of water quality improvement cost that is borne by the water supply company increases, the feasible value interval of concern coefficient λ of the water transfer company becomes smaller. As the concern coefficient increases, optimal water quality, consumer surplus, water quality utility, and the profit of the water supply company all increase, while the profit of the water transfer company decreases.

The results provide valuable references for water resources operation and management decisions of SNWDP and similar projects.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization and methodology: HJ and HZ; writing—original draft preparation: HJ, JZ, and HZ; software and visualization: JZ, YL, LC, and YC; investigation: LC and YC; writing—review and editing: JZ, YL, and HZ; supervision: HJ and HZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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