Water-saving service supply chain cooperation under social welfare maximization

Zhisong Chen and Huimin Wang

ABSTRACT

The water-saving service (WSS) supply chain equilibrium and cooperative decision models under the scenario without/with the social welfare maximization (SWM) goal are developed, analyzed, and compared, respectively, the numerical and sensitivity analyses for all models are conducted and compared, and the corresponding management insights and policy implications are summarized in this paper. The research results indicate that: (1) the cooperation strategy outperforms the equilibrium strategy regarding the water-consumption reduction, operational performance of WSS supply chain, the corresponding social welfare, consumer surplus, and positive externalities, regardless of whether the SWM is considered or not; (2) a subsidy threshold policy under which the government only subsidizes the WSS supply chain adopting the cooperation strategy is recommended to be designed to maximize social welfare with higher positive externalities; (3) subsidizing the WSS to pursue the SWM contributes to enhancing the water-consumption reduction, improving the operational performance of WSS supply chain and its members, the corresponding social welfare, consumer surplus, and positive externalities; (4) the WSS provider would have an internal incentive to provide WSS without government subsidy when the fixed cost of WSS is low, otherwise, the WSS provider would not have an internal incentive to provide WSS unless with a government subsidy.

Key words | cooperation, Nash bargaining, social welfare maximization (SWM), subsidy, supply chain, water-saving service

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INTRODUCTION

In the context of global climate change and population increase, water resources are becoming increasingly scarce in the face of rapid development of modern industries. The 'World Water Resources Development Report' pointed out that there is very serious global water abuse, and the global water deficit is estimated to be as high as 40% by 2030, based on current water use ratio (the United Nations 'World Water Assessment Programme (WWAP)' 2015). In many developing countries, the extensive development mode has brought about a serious waste of water resources. As the speed of development is increasingly restricted by the capacity constraint of water resources, various water resources saving/conservation plans and schemes for industrial, agricultural, and municipal users are being launched in many developed and developing countries in the world from the perspective of sustainable development. In China, the regulation concerning 'implementation of the most stringent water resources management system' was issued by the China State Council in 2012 (China State Council 2012). Under this regulation, the most stringent water resources

doi: 10.2166/wcc.2019.188

management system will be implemented, the scale of industries and cities will be developed under the constraints of a water resources cap, and a water-saving/conservation society will be built (Liu *et al.* 2018). As well, the advice on 'promotion of water-saving management contract and development of water-saving service industry' was issued by the China National Development and Reform Commission, China Ministry of Water Resources and China State Taxation Administration in 2016 (China National Development and Reform Commission 2016). Against this background, the specialized third-party, water-saving service (WSS) provider, came into being. Under the water-saving management contract, WSS providers raise capital, integrate advanced technologies, provide water-saving reforms and management services for water users in the high water-consumption industries, and share water-saving benefits for a return on investments and revenues. For example, Beijing Guotai Water-Saving Development Co. Ltd, a comprehensive and professional WSS enterprise, provides WSS solutions for water users in high water-consumption industries. To date, this company has successfully completed several WSS projects (e.g., a water-saving and water pollution control project for Beijing Shougang Electromechanical Co. Ltd, a medical wastewater treatment project for Shuangyashan People's Hospital, a WSS project for Hebei University of Engineering, a water ecological restoration project for Tianjin Hucang River, etc.), yielding great economic, social, and ecological benefits. Shenzhen Daneng Co. Ltd has provided comprehensive services of water-saving testing and maintenance, engineering design and construction, and after-sales maintenance services, by integrating 16 water-saving patents and an experienced professional team. To date, this company has successfully completed several WSS projects (e.g., water-saving projects for South China Agricultural University, Guangdong University of Technology, Shaoguan University, Huasheng Middle School in Changxing, Zhejiang, etc.) and achieved an overall water-saving rate of 30–40% in WSS projects. Dayu Water-Saving Group Co. Ltd is a comprehensive solution provider of agricultural water-saving irrigation, rural sewage treatment, farmers' drinking water safety, water conservancy information, and smart water platform. This company has successfully completed several WSS projects (e.g., water-saving and efficiency project in Etuoke City, small farmland water conservancy and water-saving irrigation project in Erguna City, water-saving irrigation project in Liangzhou District, Wuwei City, etc.) and reaped great economic, social, and ecological benefits.

Obviously, a water-saving management contract, which helps reduce the cost of water resources and improve the comprehensive efficiency of water resources in high water-consumption industries, has important economic, social, and ecological benefits for the sustainable development of the whole of society. Against the background of these initiatives and policies, water users in high water-consumption industries would have an external incentive to seek a WSS to reduce the cost of water resources input.

At the industrial level, water users in high water-consumption industries (such as steel, washing, printing and dyeing, leather, coal chemical, etc.) are charged with the increasing block rate price, so once the water consumption exceeds the block quantity, the users would be charged with a higher block price. As well, the water users in the high water-consumption industries are regulated by the government's water quota management, so the water consumption as to a certain output value cannot exceed the corresponding quota. Furthermore, products with lower water consumption, are often favored by environmentally friendly customers. Thus, customers of these products would expect the manufacturers to provide lower water-consumption products. Apparently, these manufacturers also experience supply chain driving forces to reduce water consumption in the product-manufacturing process. Based on the foregoing motivations, the water user (manufacturer) in high water-consumption industries would have the external pressure and the internal incentive to reduce water consumption in the product manufacturing/service providing process.

Against this background, the water user (manufacturer) in high water-consumption industries may seek a water-saving service (WSS) from the WSS provider to reduce water consumption in the product-manufacturing process and reduce the corresponding cost of water input. Furthermore, the government may set aside money to subsidize the cost input for the WSS provider's water-saving effort. Hence, how much effort should the WSS provider put in to reduce the water consumption in the scenario of the supply chain, what kind of operational strategy should be adopted for the WSS supply chain, when should the government subsidize the water-saving effort to pursue social welfare maximization (SWM), and what is the impact of a government subsidy on the WSS supply chain? These are urgent problems that need to be addressed in the operations management of the WSS supply chain.

Therefore, this paper will try to explore the operational strategies, internal incentives, and subsidy policies of the WSS supply chain under the scenario with SWM. The following section presents a literature review. The notations and assumptions for a generic WSS supply chain models are defined next. Then WSS supply chain cooperative and equilibrium decision models without and with SWM are developed and analyzed. Numerical and sensitivity analyses of a real-world-mimicking case for all models is conducted and the results and comparisons are synthesized. The management insights and policy implications are then discussed. Finally, the research contributions and foresights are synthesized and concluded.

LITERATURE REVIEW

Based on the research background discussed earlier, the operational strategies, internal incentives, and subsidy policies are key issues for the WSS supply chain under the scenario with SWM. However, studies regarding the operational strategies, internal incentives, and subsidy policies for the WSS supply chain from the game-theoretical perspective are still scarce. Thus, three streams of literature are related to our research: the first stream concerns the game-theoretical modeling of water saving; the second, the policies of water saving; and the third, resources-/energy-saving supply chain.

Regarding the first stream, the issues of the modeling of water saving have mainly focused on the optimization modeling of water saving, for example, Peterson & Ding (2005) developed a risk-programming model to quantify the effect of irrigation efficiency on irrigation water use in the High Plains, taking into account irrigation timing and well capacity limits. Fang & Nuppenau (2009) developed a spatial mathematical programming model to optimize irrigation projects with water-saving technologies considering both the economic and environmental objectives. Gao *et al.* (2014) applied a multi-objective optimization method to optimize improved integrated water resource management (IWRM), which investigated the reduction of freshwater consumption and the total water supply cost. Luckmann *et al.* (2016) analyzed a cascading wastewater reclamation system using a computable general equilibrium (CGE) model and provided a measure to estimate the shadow price of sewage. Monaco *et al.* (2016) applied a multi-objective linear optimization model to explore the trade-offs between conflicting objectives of environmental and economic concerns in a rice-growing area adopting water-saving techniques in northern Italy. Zhang & Guo (2016) studied the quantification of agriculture water-savings under water integrated optimal management and analyzed the economic increment of agriculture water savings. Zhou *et al.* (2017) studied the optimization of a dyeing production schedule using genetic algorithm to reduce freshwater consumption by optimization of scheduling based on dyeing color and depth. Novak *et al.* (2018) discussed the design of the behavioral change and incentive model combining smart meter data with consumption visualization and gamified incentive mechanisms to stimulate water saving based on the computer simulation method. However, few studies can be found regarding game-theoretical analysis of water saving using game theory. For example, Amit & Ramachandran (2010) designed a two-period principal-agent contract for demand management to mitigate market failure in urban water systems by using subgame perfect Nash equilibrium (SPNE) as the solution concept. Madani (2010) reviewed the applicability of game theory to water resources management and conflict resolution through a series of non-cooperative water resource games, and illustrated the dynamic structure of water resource problems and the importance of considering the game's evolution path while studying such problems. Varouchakis *et al.* (2018) proposed a two-player, zero-sum game model between the water enterprise and residents to explore a water tariff policy of motivating residents toward water saving. Xin & Sun (2018) studied the dual-decision of production planning and water-saving problem using the differential oligopoly game, analyzed the static, open-loop, closed-loop, and feedback equilibria to show optimal production plans and water-saving decisions, and analyzed the impact of oligopoly competition on social welfare.

Furthermore, regarding the second stream, the issues of water-saving policies in available studies are mainly investigated from four different aspects: water-pricing policies, water-taxation policies, water-saving subsidy policies and water demand management (WDM) policies. (i) Water-pricing policies: water-saving incentives, behaviors, and effects have been largely influenced by water-pricing policies. Thus, there is much research in this direction. For example, Brennan (2010) explored the potential for improving irrigation scheduling decisions and adoption of more efficient irrigation systems using a bioeconomic simulation model of lettuce production. Kampas *et al.* (2012) used a nonlinear optimization model that incorporates rain-fed, irrigated and fodder crops to examine the impacts of water pricing and CAP reform on cropping patterns, water use, irrigation technology use, and farm returns in the region of Thessaly, Greece. Lee *et al.* (2016) presented insights of the water pricing in India and China, and concluded that in contrast to fixed charges, a water tariff policy that relies on volumetric consumption promotes water conservation. (ii) Water-taxation policies: another instrument for promoting water saving is taxation, and many studies have assessed various tariff policies and their potential effects in diverse communities of the world. For example, Berrittella *et al.* (2008) included water as a production factor in a multi-region, multi-sector computable general equilibrium model (GTAP) to assess a series of water tax policies. Schuerhoff *et al.* (2013) examined the Dutch national groundwater tax (GWT) – a 'win-win, green' tax that promised to reduce distortions by simultaneously reducing the income tax burden and improving environmental outcomes. Endo (2015) found that the main policy tools in Orange County Water District (OCWD, California, USA) are tax and artificial recharge, and the pump tax does not reduce groundwater demand because the tax rate is set lower than the price of imported water. Yu *et al.* (2018) illustrated the general ideas and strategies of groundwater protection and management in China, and advocated that tax measures should be promoted to encourage the development of highly efficient water-saving industries with low pollution and low water consumption, economic compensation policies should be adopted to boost the application of water-saving crafts, water-saving appliances, and water-saving irrigation technologies, the costs of groundwater should be higher than those of surface water, and the costs of groundwater in overexploited areas should be higher than those in non--overexploited areas. (iii) Water-saving subsidy policies: financial subsidy policies have an important impact on water saving incentives, behaviors, and effects. Thus, there has been much research in this direction. For example, Foster *et al.* (2005) advocated that a financial subsidy should be introduced into the setting of agriculture water price by the government to reduce the burden of water fees on farmers and to protect social stability. Scheierling *et al.* (2006) conducted a detailed empirical assessment of the impacts of hypothetical subsidies on the relevant hydrologic, agronomic, and economic variables. Ma & Xu (2009) developed an incentive model of water saving on the premise of financial subsidy to explore a financial subsidy approach on agricultural water and agriculture water price mechanism suitable for the present situation. Wang *et al.* (2010) examined the practice of providing incentives to managers and increasing the participation of farmers to identify the impact of water management reform on crop water use. Mombeni *et al.* (2015) examined the effects of subsidy policy on reducing water use, by using a time series model (SARIMA) to model water use before targeted subsidies and the Wilcoxon sign rank test for comparison of estimated and actual amounts of water for a period after targeted subsidies. (iv) WDM policies: many researchers have regarded WDM policy as an important strategy to reduce water consumption in recent decades. For example, Bithas (2008) proposed an operational definition of WDM with five components, and described WDM as a policy framework aiming at limiting water use to the amount that meets the socioeconomic needs without squandering resources, at reasonable cost and without stripping other areas and future generations of critical natural resources. Willis *et al.* (2011) revealed the relationship between environmental and water conservation attitudes: strong positive environmental and water conservation attitudes resulted in significantly lower total water consumption, and provided WDM professionals with an understanding of where educational programs should be targeted to obtain the highest effective household water savings. Stavenhagen *et al.* (2018) used a mixed-methods approach to identify successful WDM policies, and found that the WDM policies rated as of highest impact were renovation and maintenance of networks, and campaigns for water-saving technologies, followed by universal installation of water meters, rapid leak detection, public awareness campaigns, and municipal regulations.

Regarding the third stream, the issues of resources/energy saving in the supply chain scenario in available studies mainly focused on the design of cost saving and sharing contracts with/without the government subsidy/regulation and the trade-offs between key decisions and operational indicators. For example, Corbett & Decroix (2001) analyzed equilibrium effort levels, consumption, and total profits under saving-sharing contracts currently in use for purchasing chemicals. Corbett *et al.* (2005) formalized shared-savings contracts using the double moral hazard framework, in which both parties decide how much effort to exert by trading off the cost of their effort against the benefits that they will obtain from reduced consumption, and also extended the double moral hazard framework to analyze a broader class of cost-of-effort functions. Xie (2015) investigated the coordination of a green supply chain with energy-saving regulation under two different structures, considering the trade-off between energy savings and profits. Yi & Li (2018) investigated the cooperation mechanism based on carbon emissions and energy-saving cost-sharing contract for energy saving and emissions' reduction of a supply chain under the government's subsidies and carbon taxes.

Nevertheless, the available studies rarely touch upon the issues of operational strategies, internal incentives, and subsidy policies for WSS supply chains to pursue the goal of SWM. Specifically, the following critical factors in the WSS supply chain have not been taken into consideration in the existing literature: (1) the equilibrium/optimal water-consumption reduction (water-saving) effort in the WSS supply chain; (2) the optimal operation strategies for the WSS supply chain; (3) the impact of government subsidy on water-saving conducting and the operational decisions/performance of the WSS supply chain. In the face of these research shortcomings identified in the existing literature, the equilibrium decision models and the cooperative decision models for the WSS supply chain under SWM are developed and solved to explore the operational strategies, internal incentives, and subsidy policies for the WSS supply chain.

NOTATIONS AND ASSUMPTIONS FOR A STYLIZED WATER-SAVING SERVICE (WSS) SUPPLY CHAIN

A stylized water-saving service (WSS) supply chain is generally composed of a water user and a WSS provider. The water user is a typical manufacturer in high water-consumption industries, whose product manufacturing/service providing process needs the input of water resources. The WSS provider provides a water-saving service for the water user and shares the benefit from the water user's water saving. The raw material and manufacturing cost of product is c_0, the water consumption quantity per unit product is e_0 (can be seen as the water saving reference point), and the cost of unit water is c, the retail price of the product is p, the water-consumption reduction (water-saving) effort of WSS provider is e, and $e < e_0$. The water-consumption reduction level (water-saving level) for unit product is assumed to be the linear form: $r(e) = \alpha + \beta e$. Simplified without loss of generality, we can just let $\alpha = 0$, $\beta = 1$ for their exogeneity. Accordingly, the functional forms of water-consumption reduction quantity function w.r.t water-saving effort are simplified as $r(e) = e$, which can still capture the key characteristics of water-saving effort. On this basis, the demand function of the product is assumed to be the linear form: $q(p) = a - bp + dr(e)$, where a is the choke quantity of product, b is the reaction extent of the ordering quantity (demand) w.r.t. the change of retail price, d is the reaction extent of the ordering quantity (demand) w.r.t. the change of the water-consumption reduction quantity (water-saving level), and $a > 0$, $b > d > 0$. Generally, the resources/energy saving cost function is assumed to be a quadratic form, such as quadratic cost function of energy saving (Xie 2015; Yi & Li 2018), quadratic cost function of water saving (Xin & Sun 2018). Following Xin & Sun (2018), the cost of water saving for the manufacturer is assumed to be a quadratic form: $c(e) = \frac{1}{2}\kappa e^2$, where κ is the cost coefficient of water-saving effort. The fixed cost of WSS service is c_f. The government only subsidizes water-saving effort (water-consumption reduction) in the supply chain without compensation for the fixed cost of WSS. The government subsidy for unit water-consumption reduction effort (water-saving effort) is s, and the government's total subsidy is $TS(e) = se$. A positive externality is the positive effect an activity imposes on an unrelated third party (Varian 2010). A positive externality arises when a person is engaged in an activity that beneficially influences the well-being of a bystander but neither pays nor receives any compensation for that effect (Mankiw 2011). The water-consumption reduction (water-saving effort) in high water-consumption industries has positive influences and increasing marginal impacts on well-being of a bystander, bringing important social, ecological, and environmental benefits. Thus, there exists a positive relationship between the positive externality and the water-saving effort (water-consumption reduction) with increasing marginal impact. Without loss of generality, the positive externalities effort is assumed to be a quadratic form: $PE(e) = \frac{1}{2}ge^2$, where g is the positive externalities coefficient of water-saving effort, and $\kappa > g > 0$. The benefit of water saving is shared between the water user and the WSS provider, the water user will share a proportion of his water-saving benefit ϕ to the water-saving-service provider, and $\phi \in (0, 1)$. The water user's bargaining power is τ, and $\tau \in (0, 1)$. Based on the parameters' setting, the profit functions of the water user, WSS provider, and WSS supply chain can be expressed as follows:

$$\Pi_u(p, e, \phi) = [p - c_0 - c(e_0 - e) - \phi ce]q(p, e)$$

$$\Pi_{wss}(e, s, \phi) = \phi ceq(p, e) + se - \frac{1}{2}\kappa e^2 - c_f$$

$$\Pi_{wsc}(p, e, s) = [p - c_0 - c(e_0 - e)]q(p, e) + se - \frac{1}{2}\kappa e^2 - c_f$$

According to the classical economic theory (Varian 2010; Mankiw 2011), the corresponding consumer surplus and social welfare in the WSS supply chain can be expressed as:

$$CS(q) = \frac{1}{2b}q^2$$

$$SW(q, e) = \frac{1}{b}\{[a - b(c_0 + ce_0)] + (d + bc)e\}q - \frac{1}{2b}q^2 - \frac{1}{2}(\kappa - g)e^2 - c_f$$

WATER-SAVING SERVICE (WSS) SUPPLY CHAIN DECISION MODELS WITH SWM

To investigate the operational strategies, internal incentives, and subsidy policies for the WSS supply chain under SWM, WSS supply chain cooperative and equilibrium decision models under the scenarios of without and with SWM are developed, analyzed, and compared, respectively, in this section.

WSS supply chain decision models without SWM

Here, the scenario without SWM is considered, i.e., $s = 0$, the WSS supply chain cooperative and equilibrium decision models under the scenario without SWM are developed and analyzed (superscript or subscript c: cooperative decision, superscript or subscript d: equilibrium decision).

WSS supply chain cooperative decision model without SWM

Under this scenario, the government does not subsidize the WSS provider, i.e., $s = 0$. The detailed decision sequences are as follows: the WSS provider and the water user will first bargain over the cost sharing rate using Nash bargaining game approach to achieve cooperative operations; and then, the WSS supply chain decides the retail price of the product and the water-consumption reduction effort. According to the classical Nash bargaining theory (Nash 1950; Kalai & Smorodinsky 1975; Osborne & Rubenstein 1994; Muthoo 1999), the Nash bargaining game model for the WSS supply chain without SWM can be formulated as:

$$\max_{\phi} \ \Omega(\phi) = [\Pi_u^c(p_c, e_c, \ q_c, \phi)]^{\tau}[\Pi_{wss}^c(e_c, \ q_c, \phi)]^{1-\tau}$$

$$s.t. \begin{cases} \Pi_u^c(p_c, e_c, \ q_c, \phi) + \Pi_{wss}^c(e_c, \ q_c, \phi) = \Pi_{wsc}^c \\ s.t. \begin{cases} p_c, e_c, \ q_c \text{ and } \Pi_{wsc}^c \text{ are derived from} \\ \text{solving the following problem} \\ \max\limits_{p,e} \ \Pi_{wsc}(p, e) \end{cases} \end{cases}$$

Solving this Nash bargaining problem, we can obtain the optimal water-consumption reduction effort e_c, the optimal retail price p_c, the optimal ordering quantity q_c, and the bargaining cost sharing rate ϕ_c. The profits of the water user, WSS provider, and WSS supply chain can be calculated as Π_u^c, Π_{wss}^c, and Π_{wsc}^c. The corresponding social welfare SW_c, consumer surplus CS_c and positive externalities effort PE_c can also be calculated. (See Table 1 for the mathematical functions and their derivations can be seen in the Appendix in Supplementary Materials).

Table 1 | Analytical modeling results of WSS supply chain without SWM

Scenario	Cooperative decision	Equilibrium decision
e_c	$e_c = \frac{d+bc}{2b\kappa-(d+bc)^2}[a-b(c_0+ce_0)]$	$e_d = \frac{\phi_c c[a-b(c_0+ce_0)]}{2\{\kappa-\phi_c c[d+(1-\phi_c)bc]\}}$
p_c	$p_c = \frac{\kappa-(d+bc)c}{2b\kappa-(d+bc)^2}[a-b(c_0+ce_0)]+(c_0+ce_0)$	$p_d = \frac{2\kappa-\phi_c c[d+3(1-\phi_c)bc]}{4b\{\kappa-\phi_c c[d+(1-\phi_c)bc]\}}[a-b(c_0+ce_0)]+(c_0+ce_0)$
q_c	$q_c = \frac{b\kappa}{2b\kappa-(d+bc)^2}[a-b(c_0+ce_0)]$	$q_d = \frac{2\kappa-\phi_c c[d+(1-\phi_c)bc]}{4\{\kappa-\phi_c c[d+(1-\phi_c)bc]\}}[a-b(c_0+ce_0)]$
ϕ_c	$\phi_c = \frac{\kappa}{(d+bc)c}-\tau\left[\frac{2b\kappa-(d+bc)^2}{2bc(d+bc)}-\frac{b\kappa c_f}{(d+bc)cq_c^2}\right]$	ϕ_c
Π_u^c	$\Pi_u^c = \tau\Pi_{wsc}^c$	$\Pi_u^d = \frac{1}{b}q_d^2$
Π_{wss}^c	$\Pi_{wss}^c = (1-\tau)\Pi_{wsc}^c$	$\Pi_{wss}^d = \frac{2(\phi_c c)^2\{\kappa-\phi_c c[d+(1-\phi_c)bc]\}}{\{2\kappa-\phi_c c[d+(1-\phi_c)bc]\}^2}q_d^2-c_f$
Π_{wsc}^c	$\Pi_{wsc}^c = \frac{2b\kappa-(d+bc)^2}{2b^2\kappa}q_c^2-c_f$	$\Pi_{wsc}^d = \left\{\frac{1}{b}+\frac{2(\phi_c c)^2\{\kappa-\phi_c c[d+(1-\phi_c)bc]\}}{\{2\kappa-\phi_c c[d+(1-\phi_c)bc]\}^2}\right\}q_d^2-c_f$
SW_c	$SW_c = \frac{3b\kappa^2-(\kappa-g)(d+bc)^2}{2b^2\kappa^2}q_c^2-c_f$	$SW_d = \left\{\frac{3}{2b}+\frac{2(\phi_c c)^2\{(\kappa+g)-\phi_c c[d+(1-\phi_c)bc]\}}{\{2\kappa-\phi_c c[d+(1-\phi_c)bc]\}^2}\right\}q_d^2-c_f$
CS_c	$CS_c = \frac{1}{2b}q_c^2$	$CS_d = \frac{1}{2b}q_d^2$
PE_c	$PE_c = \frac{1}{2}ge_c^2$	$PE_d = \frac{1}{2}ge_d^2$

WSS supply chain equilibrium decision model without SWM

In order to make the results comparable, the cost sharing rate ϕ under the equilibrium decision is set to equal that under cooperative decision, i.e., $\phi = \phi_c$.

Under this scenario, the government does not subsidize the WSS provider, i.e., $s = 0$. The detailed decision sequences are as follows: given the cost sharing rate, the WSS provider will first decide the water-consumption reduction effort, and then the water user decides the retail price of the product. The Stackelberg game model for the WSS supply chain without SWM can be formulated as:

$$\begin{cases} \max\limits_{e}\ \Pi_{wss}(e, q_d(e), \phi_c) \\ s.t. \begin{cases} p_d(e) \text{ and } q_d(e) \text{ are derived from} \\ \text{solving the following problem} \\ \max\limits_{p}\ \Pi_u(p, e, \phi_c) \end{cases} \end{cases}$$

Solving this Stackelberg game problem, we can obtain the equilibrium water-consumption reduction effort e_d, the equilibrium retail price p_d, and the equilibrium ordering quantity q_d. The profits of the water user, WSS provider, and WSS supply chain can be calculated as Π_u^d, Π_{wss}^d, and Π_{wsc}^d. The corresponding social welfare SW_d, consumer surplus CS_d, and positive externalities effort PE_d can also be calculated. (See Table 1 for the mathematical functions and their derivations can be seen in the Appendix).

WSS supply chain decision models with SWM

In this section, the scenario with SWM is considered, i.e., $s > 0$, the WSS supply chain cooperative and equilibrium decision models under the scenario with SWM are developed and analyzed (superscript or subscript s: social welfare maximization, superscript or subscript c: cooperative decision, superscript or subscript d: equilibrium decision).

WSS supply chain cooperative decision model with SWM

Under this scenario, the government subsidizes the WSS provider, i.e., $s > 0$. The detailed decision sequences are as follows: the government will first announce a subsidy rate for the WSS provider; then, the WSS provider and the water user will bargain over the cost sharing rate using Nash bargaining game approach to achieve cooperative operations; finally, the WSS supply chain decides the retail price of the product and the water-consumption reduction effort. The two-stage Stackelberg–Nash bargaining game model for the WSS supply chain with SWM can be formulated as:

$$\max_{s} SW(q_c^s(s), e_c^s(s))$$
$$s.t.\begin{cases} \max_{\phi} \Omega(\phi) = [\Pi_u^{sc}(p_c^s(s), e_c^s(s), q_c^s(s), \phi)]^{\tau}[\Pi_{wss}^{sc}(e_c^s(s), q_c^s(s), s, \phi)]^{1-\tau} \\ s.t.\begin{cases} \Pi_u^{sc}(p_c^s(s), e_c^s(s), q_c^s(s), \phi) + \Pi_{wss}^{sc}(e_c^s(s), q_c^s(s), s, \phi) = \Pi_{wsc}^{sc}(s) \\ s.t.\begin{cases} p_c^s(s),\ e_c^s(s), q_c^s(s) \text{ and } \Pi_{wsc}^{sc}(s) \text{ are derived} \\ \text{from solving the following problem} \\ \max_{p,e} \Pi_{wsc}(p, e, s) \end{cases} \end{cases} \end{cases}$$

Solving this two-stage Stackelberg–Nash bargaining game problem, we can obtain the optimal subsidy factor s_c, the optimal water-consumption reduction effort e_c^s, the optimal retail price p_c^s, the optimal ordering quantity q_c^s, and the bargaining cost sharing rate ϕ_c^s. The profits of the water user, WSS provider, and WSS supply chain can be calculated as Π_u^{sc}, Π_{wss}^{sc}, and Π_{wsc}^{sc}. The corresponding social welfare SW_c^s, consumer surplus CS_c^s, total government subsidy TS_c^s and positive externalities effort PE_c^s can also be calculated. (See Table 2 for the mathematical functions and their derivations can be seen in the Appendix).

WSS supply chain equilibrium decision model with SWM

In order to make the results comparable, the cost sharing rate ϕ under the equilibrium decision is set to equal that under cooperative decision, i.e., $\phi = \phi_c^s$.

Under this scenario, the government subsidizes the WSS provider, i.e., $s > 0$. The detailed decision sequences are as follows: the government will first announce a subsidy rate for the WSS provider; then, given the cost sharing rate, the WSS provider will decide the water-consumption reduction effort; finally, the water user decides the retail price of product. The two-stage Stackelberg game model for the WSS supply chain with SWM can be formulated as:

$$\max_{s} SW(q_d^s(s), e_d^s(s))$$
$$s.t.\begin{cases} p_d^s(s),\ e_d^s(s), q_d^s(s),\ \Pi_u^{sd}(s) \text{ and } \Pi_{wss}^{sd}(s) \text{are} \\ \text{derived from solving the following problem} \\ \max_{e} \Pi_{wss}(e, s, q_d^s(e), \phi_c^s) \\ s.t.\begin{cases} p_d^s(e) \text{ and } q_d^s(e) \text{ are derived from} \\ \text{solving the following problem} \\ \max_{p} \Pi_u(p, e, \phi_c^s) \end{cases} \end{cases}$$

Solving this two-stage Stackelberg game problem, we can obtain the equilibrium subsidy factor s_d, the equilibrium water-consumption reduction effort e_d^s, the equilibrium retail price p_d^s, and the equilibrium ordering quantity q_d^s. The profits of the water user, WSS provider, and WSS supply chain can be calculated as Π_u^{sd}, Π_{wss}^{sd}, and Π_{wsc}^{sd}. The corresponding social welfare SW_d^s, consumer surplus CS_d^s, total government subsidy TS_d^s, and positive externalities effort PE_d^s can also be calculated. (See Table 2 for the mathematical functions and their derivations can be seen in the Appendix).

Comparisons and discussions of analytical results

The analytical results of WSS supply chain decision models without/with SWM, including the optimal/equilibrium profits and social welfare, are compared to derive operational strategies, internal incentives, and subsidy policies for the WSS supply chain as follows below.

Cooperation strategy vs. equilibrium strategy

- Under the scenario without SWM, when $\Pi_u^c \geq \Pi_u^d$, $\Pi_{wss}^c \geq \Pi_{wss}^d$, the cooperation strategy outperforms equilibrium strategy regarding the profits of WSS supply chain members; the WSS supply chain members would have the internal incentive to adopt a cooperation strategy.
- Under the scenario with SWM, when $\Pi_u^{sc} \geq \Pi_u^{sd}$, $\Pi_{wss}^{sc} \geq \Pi_{wss}^{sd}$, the cooperation strategy outperforms equilibrium strategy regarding the profits of WSS supply chain members; the WSS supply chain members would have the internal incentive to adopt a cooperation strategy.

Table 2 | Analytical modeling results of WSS supply chain with SWM

Scenario	Cooperative decision	Equilibrium decision
s_c	$s_c = \frac{(\kappa + 2g)(d + bc)[a - b(c_0 + ce_0)]}{4b(\kappa - g) - 3(d + bc)^2}$	$s_d = \frac{6\kappa[d + (1 - \phi_c^s)bc] - 3\phi_c^s c[d + (1 - \phi_c^s)bc]^2 + 4\phi_c^s gbc}{2\{4b(\kappa - g) - 4\phi_c^s bc[d + (1 - \phi_c^s)bc] - 3[d + (1 - \phi_c^s)bc]^2\}}[a - b(c_0 + ce_0)]$
e_c^s	$e_c^s = \frac{3(d + bc)[a - b(c_0 + ce_0)]}{4b(\kappa - g) - 3(d + bc)^2}$	$e_d^s = \frac{2\phi_c^s bc + 3[d + (1 - \phi_c^s)bc]}{4b(\kappa - g) - 4\phi_c^s bc[d + (1 - \phi_c^s)bc] - 3[d + (1 - \phi_c^s)bc]^2}[a - b(c_0 + ce_0)]$
p_c^s	$p_c^s = \frac{2(\kappa - g) - 3(d + bc)c}{4b(\kappa - g) - 3(d + bc)^2}[a - b(c_0 + ce_0)] + (c_0 + ce_0)$	$p_d^s = \frac{2(\kappa - g) - 3[d + (1 - \phi_c^s)bc]c + 2\phi_c^s dc}{4b(\kappa - g) - 4\phi_c^s bc[d + (1 - \phi_c^s)bc] - 3[d + b(1 - \phi_c^s)c]^2}[a - b(c_0 + ce_0)] + (c_0 + ce_0)$
q_c^s	$q_c^s = \frac{2b(\kappa - g)[a - b(c_0 + ce_0)]}{4b(\kappa - g) - 3(d + bc)^2}$	$q_d^s = \frac{2b(\kappa - g) - \phi_c^s bc[d + (1 - \phi_c^s)bc]}{4b(\kappa - g) - 4\phi_c^s bc[d + (1 - \phi_c^s)bc] - 3[d + (1 - \phi_c^s)bc]^2}[a - b(c_0 + ce_0)]$
ϕ_c^s	$\phi_c^s = (1 - \tau)\frac{2(\kappa - g)}{3(d + bc)c} + \tau\left[\frac{(\kappa - 4g)(d + bc)}{4b(\kappa - g)c} + \frac{2b(\kappa - g)c_f}{3(d + bc)c(q_c^s)^2}\right]$	ϕ_c^s
Π_u^{sc}	$\Pi_u^{sc} = \tau\Pi_{wsc}^{sc}$	$\Pi_u^{sd} = \frac{1}{b}(q_d^s)^2$
Π_{wss}^{sc}	$\Pi_{wss}^{sc} = (1 - \tau)\Pi_{wsc}^{sc}$	$\Pi_{wss}^{sd} = \frac{\{\kappa - \phi_c^s c[d + (1 - \phi_c^s)bc]\}\{2\phi_c^s bc + 3[d + (1 - \phi_c^s)bc]\}^2}{2b^2\{2(\kappa - g) - \phi_c^s c[d + (1 - \phi_c^s)bc]\}^2}(q_d^s)^2 - c_f$
Π_{wsc}^{sc}	$\Pi_{wsc}^{sc} = \frac{8b(\kappa - g)^2 - 3(\kappa - 4g)(d + bc)^2}{8b^2(\kappa - g)^2}(q_c^s)^2 - c_f$	$\Pi_{wsc}^{sd} = \left\{\frac{1}{b} + \frac{\{\kappa - \phi_c^s c[d + (1 - \phi_c^s)bc]\}\{2\phi_c^s bc + 3[d + (1 - \phi_c^s)bc]\}^2}{2b^2\{2(\kappa - g) - \phi_c^s c[d + (1 - \phi_c^s)bc]\}^2}\right\}(q_d^s)^2 - c_f$
SW_c^s	$SW_c^s = \frac{12b(\kappa - g)^2 - 9(\kappa - g)(d + bc)^2}{8b^2(\kappa - g)^2}(q_c^s)^2 - c_f$	$SW_d^s = \left\{\frac{6b(\kappa - g) + 3\phi_c^s bc[d + (1 - \phi_c^s)bc] + 4(\phi_c^s bc)^2}{2b^2\{2(\kappa - g) - \phi_c^s c[d + (1 - \phi_c^s)bc]\}} - \frac{(\kappa - g)\{2\phi_c^s bc + 3[d + (1 - \phi_c^s)bc]\}^2}{2b^2\{2(\kappa - g) - \phi_c^s c[d + (1 - \phi_c^s)bc]\}^2}\right\}(q_d^s)^2 - c_f$
CS_c^s	$CS_c^s = \frac{1}{2b}(q_c^s)^2$	$CS_d^s = \frac{1}{2b}(q_d^s)^2$
TS_c^s	$TS_c^s = s_c e_c^s$	$TS_d^s = s_d e_d^s$
PE_c^s	$PE_c^s = \frac{1}{2}g(e_c^s)^2$	$PE_d^s = \frac{1}{2}g(e_d^s)^2$

Internal incentives of providing and subsidizing WSS

The fixed costs of WSS service have an important impact on the incentives of providing and subsidizing WSS. Therefore, due to different fixed costs of WSS, there are two possible cases, as follows.

Low-cost case (Case 1):

- Under the equilibrium decision, when $\Pi_{wss}^{sd} > \Pi_{wss}^{d} > 0$, the WSS provider would have the internal incentive to provide WSS without government subsidy; thus, the government does not need to subsidize WSS if there is no corresponding subsidy budget; besides, when $SW_d^s \geq SW_d$, the government would have the internal incentive to subsidize WSS, if there is some corresponding subsidy budget.
- Under the coordination decision, when $\Pi_{wss}^{sc} > \Pi_{wss}^{c} > 0$, the WSS provider would have the internal incentive to provide WSS without government subsidy; thus, the government does not need to subsidize WSS if there is no corresponding subsidy budget; besides, when $SW_c^s \geq SW_c$, the government would have the internal incentive to subsidize WSS, if there is some corresponding subsidy budget.

High-cost case (Case 2):

- Under the equilibrium decision, when $\Pi_{wss}^{sd} > 0 > \Pi_{wss}^{d}$, the WSS provider would not have the internal incentive to provide WSS unless the government subsidizes WSS; thus, the government has to input a subsidy budget to subsidize WSS and pursue SWM; besides, when $SW_d^s \geq SW_d$, the government would have the internal incentive to subsidize WSS.
- Under the coordination decision, when $\Pi_{wss}^{sc} > 0 > \Pi_{wss}^{c}$, the WSS provider would not have the internal incentive to provide WSS unless the government subsidizes WSS; thus, the government has to input a subsidy budget to subsidize WSS and pursue SWM; besides, when $SW_c^s \geq SW_c$, the government would have the internal incentive to subsidize WSS.

NUMERICAL AND SENSITIVITY ANALYSES

Based on the actual characteristics of real WSS in high water-consumption industries, the relationships between the WSS provider and the water user in the WSS supply chain are set to mimic the real-world case, and the values of parameters relating to the WSS supply chain are set for the numerical analysis as follows: the raw material and manufacturing cost of product c_0 is 50 Yuan/unit, the water consumption quantity per unit product (the water saving reference point) e_0 is 8 m^3/unit, and the cost of unit water c is 2.5 Yuan/m^3, the cost coefficient of water-saving effort κ is 4,000, the positive externalities coefficient of water-saving effort g is 100, and the fixed cost of WSS c_f is 2,000 Yuan. The choke quantity of product a is 40,000, the reaction extent of the ordering quantity (demand) w.r.t. the change of retail price b is 500, the reaction extent of the ordering quantity (demand) w.r.t. the change of the water-consumption reduction (water-saving effort) d is 10. The water user's bargaining power τ is 0.6.

Numerical analysis

Table 3 shows the numerical analysis results of the WSS supply chain equilibrium and cooperative decision models under the scenario without/with SWM.

The numerical analysis results show that:

1. Comparing the numerical results between the equilibrium decision and the cooperative decision under the scenario without SWM, (i) the water-consumption reduction (water-saving effort) under the cooperative decision is higher than that under the equilibrium

Table 3 | Numerical results of WSS supply chain without/with SWM

	Without SWM		With SWM	
Scenario	Equilibrium	Cooperation	Equilibrium	Cooperation
s^*	–	–	7,354.19	8,711.97
e^*	1.49	2.61	3.23	6.22
p^*	74.74	71.76	72.94	67.28
q^*	2,642.57	4,145.25	3,562.80	6,420.39
Π_u^*	13,966.31	11,235.75	25,387.07	34,325.11
Π_{wss}^*	1,973.56	7,490.50	14,746.16	22,883.41
Π_{wsc}^*	15,939.87	18,726.25	40,133.23	57,208.52
SW^*	23,033.69	36,250.34	29,585.48	46,152.90
CS^*	6,983.15	17,183.09	12,693.54	41,221.37
PE^*	110.67	341.00	522.05	1,936.18
TS^*	–	–	23,763.34	54,213.18
ϕ^*	0.85	0.85	0.48	0.48

decision; (ii) the retail price under the cooperative decision is lower than that under the equilibrium decision; (iii) the ordering quantity under the cooperative decision is higher than that under the equilibrium decision; (iv) the profit of the water user under the cooperative decision is lower than that under the equilibrium decision, and the profit of the WSS provider under the cooperative decision is higher than that under the equilibrium decision; (v) the profit of the WSS supply chain under the cooperative decision is higher than that under the equilibrium decision; (vi) the social welfare under the cooperative decision is higher than that under the equilibrium decision; (vii) the consumer surplus under the cooperative decision is higher than that under the equilibrium decision; (viii) the positive externalities of water saving under the cooperative decision is higher than that under the equilibrium decision.

2. Comparing the numerical results between the equilibrium decision and the cooperative decision under the scenario with SWM, (i) the water-consumption reduction (water-saving effort) under the cooperative decision is higher than that under the equilibrium decision; (ii) the retail price under the cooperative decision is lower than that under the equilibrium decision; (iii) the ordering quantity under the cooperative decision is higher than that under the equilibrium decision; (iv) the profits of the water user and the WSS provider under the cooperative decision are higher than those under the equilibrium decision; (v) the social welfare under the cooperative decision is higher than that under the equilibrium decision; (vi) the consumer surplus under the cooperative decision is higher than that under the equilibrium decision; (vii) the positive externalities of water saving under the cooperative decision are higher than that under the equilibrium decision; (viii) the total subsidy for the water saving under the cooperative decision is higher than that under the equilibrium decision.
3. Comparing the numerical results between the scenario without SWM and the scenario with SWM, be it under the equilibrium decision or the cooperative decision, (i) the water-consumption reduction (water-saving effort) under the scenario with SWM is higher than that under the scenario without SWM; (ii) the retail price under the scenario with SWM is lower than that under the scenario without SWM; (iii) the ordering quantity under the scenario with SWM is higher than that under the scenario without SWM; (iv) the profits of the water user and the WSS provider under the scenario with SWM are higher than those under the scenario without SWM; (v) the social welfare under the scenario with SWM is higher than that under the scenario without SWM; (vi) the consumer surplus under the scenario with SWM is higher than that under the scenario without SWM; (vii) the positive externalities of water saving under the scenario with SWM are higher than that under the scenario without SWM; (viii) the total subsidy for the water saving under the scenario with SWM is higher than that under the scenario without SWM; (ix) under the cooperative decision, the cost sharing rate under the scenario with SWM is higher than that under the scenario without SWM.

Sensitivity analysis

Tables 4 and 5 show the sensitivity analysis results of the water cost for the WSS supply chain equilibrium and

Table 4 | The sensitivity analysis of the water cost (without SWM)

Scenario	c	ϕ^*	e^*	p^*	q^*	Π_u^*	Π_{wss}^*	Π_{wsc}^*	SW^*	CS^*	PE^*
Equilibrium decision	2.40	0.90	1.57	74.43	2,802.79	15,711.25	2,565.37	18,276.62	26,255.07	7,855.62	122.82
	2.50	0.85	1.49	74.74	2,642.57	13,966.31	1,973.56	15,939.87	23,033.69	6,983.15	110.67
	2.60	0.82	1.41	75.08	2,475.56	12,256.81	1,426.53	13,683.34	19,910.49	6,128.41	98.74
	2.70	0.78	1.32	75.42	2,301.85	10,597.00	920.80	11,517.80	16,903.35	5,298.50	87.06
Cooperative decision	2.40	0.90	2.58	71.53	4,258.84	12,598.65	8,399.10	20,997.75	39,467.44	18,137.74	331.94
	2.50	0.85	2.61	71.76	4,145.25	11,235.75	7,490.50	18,726.25	36,250.34	17,183.09	341.00
	2.60	0.82	2.64	72.00	4,028.20	9,917.82	6,611.88	16,529.71	33,104.16	16,226.37	348.08
	2.70	0.78	2.66	72.24	3,906.25	8,643.75	5,762.50	14,406.25	30,017.82	15,258.79	352.78

Table 5 | The sensitivity analysis of the water cost (with SWM)

Scenario	c	ϕ^*	s^*	e^*	p^*	q^*	Π_u^*	Π_{wss}^*	Π_{wsc}^*	SW^*	CS^*	PE^*	TS^*
Equilibrium decision	2.40	0.51	6,780.43	3.09	72.82	3,620.42	26,214.87	13,597.40	39,812.27	32,448.62	13,107.44	477.26	20,948.35
	2.50	0.48	7,354.19	3.23	72.94	3,562.80	25,387.07	14,746.16	40,133.23	29,585.48	12,693.54	522.05	23,763.34
	2.60	0.45	7,910.75	3.37	73.04	3,512.68	24,677.84	15,938.80	40,616.64	26,827.54	12,338.92	569.48	26,697.49
	2.70	0.43	8,459.51	3.52	73.13	3,471.27	24,099.48	17,202.57	41,302.05	24,170.88	12,049.74	620.52	29,801.42
Cooperative decision	2.40	0.51	8,053.17	5.75	67.75	6,180.12	32,720.80	21,813.86	54,534.66	48,058.98	38,193.90	1,654.43	46,324.00
	2.50	0.48	8,711.97	6.22	67.28	6,420.39	34,325.11	22,883.41	57,208.52	46,152.90	41,221.37	1,936.18	54,213.18
	2.60	0.45	9,544.52	6.82	66.61	6,765.47	36,993.67	24,662.44	61,656.11	44,681.75	45,771.60	2,323.92	65,069.88
	2.70	0.43	10,656.72	7.61	65.60	7,276.12	41,471.31	27,647.54	69,118.85	43,839.55	52,941.91	2,897.08	81,118.29

cooperative decision models under the scenario without/with SWM. Tables 6 and 7 show the sensitivity analysis results of the fixed cost of WSS for the WSS supply chain equilibrium and cooperative decision models under the scenario without/with SWM. Tables 8 and 9 show the sensitivity analysis results of the cost coefficient of water-saving effort for the WSS supply chain equilibrium and cooperative decision models under the scenario without/with SWM.

The sensitivity analysis results of the water cost for the WSS supply chain equilibrium and cooperative decision models under the scenario without/with SWM (Tables 4 and 5) show that: (i) the cost sharing rate decreases as the water cost increases, be it under the equilibrium decision or under the cooperative decision; (ii) under the scenario without SWM, the water-consumption reduction (water-saving effort) decreases as the water cost increases under the equilibrium decision, while the water-consumption reduction (water-saving effort) increases as the water cost increases under the cooperative decision; under the scenario with SWM, the water-consumption reduction (water-saving effort) increases as the water cost increases, be it under the equilibrium decision or under the cooperative decision; (iii) under the scenario without SWM, the retail price increases as the water cost increases, be it under the equilibrium decision or under the cooperative decision; under the scenario with SWM, the retail price increases as the water cost increases under the equilibrium decision, while the retail price decreases as the water cost increases under the cooperative decision; (iv) under the scenario without SWM, the ordering quantity decreases as the water cost increases, be it under the equilibrium decision or under the cooperative decision; under the scenario with SWM, the ordering quantity decreases as the water cost increase under the equilibrium decision, while the ordering quantity increases as the water cost increases under the cooperative decision; (v) under the scenario without SWM, the profits of the water user, the WSS provider, and the WSS supply chain decrease as the water cost increases, be it under the equilibrium decision or under the cooperative decision; under the scenario with SWM, the profit of the water user decreases as the water cost increases, while the profits of the WSS provider and the WSS supply chain increase as the water cost increases under the equilibrium decision; besides, the profits of the water user, the WSS provider

Table 6 | The sensitivity analysis of the fixed cost of WSS (without SWM)

Scenario	c_f	ϕ^*	e^*	p^*	q^*	Π_u^*	Π_{wss}^*	Π_{wsc}^*	SW^*	CS^*	PE^*
Equilibrium decision	2,000	0.85	1.49	74.74	2,642.57	13,966.31	1,973.56	15,939.87	23,033.69	6,983.15	110.67
	2,500	0.87	1.50	74.76	2,633.06	13,866.00	1,549.47	15,415.47	22,460.48	6,933.00	112.01
	3,000	0.88	1.51	74.78	2,623.39	13,764.37	1,124.79	14,889.16	21,884.65	6,882.18	113.30
	3,500	0.89	1.51	74.80	2,613.57	13,661.53	699.50	14,361.03	21,306.32	6,830.76	114.53
	4,000	0.90	1.52	74.82	2,603.61	13,557.59	273.56	13,831.16	20,725.65	6,778.80	115.69
	4,500	0.91	1.53	74.84	2,593.52	13,452.67	−153.06	13,299.62	20,142.76	6,726.34	116.80
Cooperative decision	2,000	0.85	2.61	71.76	4,145.25	11,235.75	7,490.50	18,726.25	36,250.34	17,183.09	341.00
	2,500	0.87	2.61	71.76	4,145.25	10,935.75	7,290.50	18,226.25	35,750.34	17,183.09	341.00
	3,000	0.88	2.61	71.76	4,145.25	10,635.75	7,090.50	17,726.25	35,250.34	17,183.09	341.00
	3,500	0.89	2.61	71.76	4,145.25	10,335.75	6,890.50	17,226.25	34,750.34	17,183.09	341.00
	4,000	0.90	2.61	71.76	4,145.25	10,035.75	6,690.50	16,726.25	34,250.34	17,183.09	341.00
	4,500	0.91	2.61	71.76	4,145.25	9,735.75	6,490.50	16,226.25	33,750.34	17,183.09	341.00

and the WSS supply chain increase as the water cost increases under the cooperative decision; (vi) the social welfare decreases as the water cost increases; (vii) under the scenario without SWM, the consumer surplus decreases as the water cost increases, be it under the equilibrium decision or under the cooperative decision; under the scenario with SWM, the consumer surplus decreases as the water cost increases under the equilibrium decision, while the consumer surplus increases as the water cost increases under the cooperative decision; (viii) under the scenario without SWM, the positive externalities decrease as the water cost increases under the equilibrium decision, while the positive externalities increase as the water cost increases under the cooperative decision; under the scenario with SWM, the positive externalities increase as the water cost increases, be it under the equilibrium decision or under the cooperative decision; (ix) under the scenario with SWM, the government subsidy increases as the water cost increases, be it under the equilibrium decision or under the cooperative decision.

The sensitivity analysis results of the fixed cost of WSS for the WSS supply chain equilibrium and cooperative decision models under the scenario without/with SWM (Tables 6 and 7) show that: (i) the cost sharing rate increases as the fixed cost of WSS increases, be it under the equilibrium decision or under the cooperative decision; (ii) under the scenario without SWM, the water-consumption reduction (water-saving effort) increases as the fixed cost of WSS increases under the equilibrium decision, while the water-consumption reduction (water-saving effort) does not change as the fixed cost of WSS increases under the cooperative decision; under the scenario with SWM, the water-consumption reduction (water-saving effort) decreases as the fixed cost of WSS increases under the equilibrium decision, while the water-consumption reduction (water-saving effort) does not change as the fixed cost of WSS increases under the cooperative decision; (iii) under the scenario without SWM, the retail price increases as the fixed cost of WSS increases under the equilibrium decision, while the retail price does not change as the fixed cost of WSS increases under the cooperative decision; under the scenario with SWM, the retail price increases as the fixed cost of WSS increases under the equilibrium decision, while the retail price does not change as the fixed cost of WSS increases under the cooperative decision; (iii) under the scenario without SWM, the ordering quantity decreases as the fixed cost of WSS increases under the equilibrium decision, while the ordering quantity does not change as the fixed cost of WSS increases under the cooperative decision; under the scenario with SWM, the ordering quantity decreases as the fixed cost of WSS increases under the equilibrium decision, while the ordering quantity does not change as the fixed cost of WSS increases under the cooperative decision; (iv) the profits of the water user, the WSS provider, and the WSS supply chain decrease as the fixed cost of WSS increases, be it under the equilibrium decision or under the cooperative decision; (v) the social welfare decreases as the fixed cost of WSS increases, be it under the equilibrium decision or under the cooperative decision; (vi) under the scenario without SWM, the

Table 7 | The sensitivity analysis of the fixed cost of WSS (with SWM)

Scenario	c_f	ϕ^*	s^*	e^*	p^*	q^*	Π_u^*	Π_{wss}^*	Π_{wsc}^*	SW^*	CS^*	PE^*	TS^*
Equilibrium decision	2,000	0.48	7,354.19	3.23	72.94	3,562.80	25,387.07	14,746.16	40,133.23	29,585.48	12,693.54	522.05	23,763.34
	2,500	0.48	7,292.54	3.22	72.96	3,552.49	25,240.35	14,109.89	39,350.24	29,018.82	12,620.18	517.87	23,469.47
	3,000	0.49	7,231.25	3.21	72.98	3,542.25	25,095.01	13,475.05	38,570.06	28,452.51	12,547.50	513.72	23,178.77
	3,500	0.49	7,170.32	3.19	73.00	3,532.07	24,951.01	12,841.63	37,792.64	27,886.53	12,475.51	509.60	22,891.22
	4,000	0.49	7,109.76	3.18	73.02	3,521.96	24,808.36	12,209.60	37,017.96	27,320.89	12,404.18	505.52	22,606.77
	4,500	0.50	7,049.56	3.17	73.04	3,511.91	24,667.04	11,578.95	36,245.99	26,755.58	12,333.52	501.47	22,325.40
Cooperative decision	2,000	0.48	8,711.97	6.22	67.28	6,420.39	34,325.11	22,883.41	57,208.52	46,152.90	41,221.37	1,936.18	54,213.18
	2,500	0.48	8,711.97	6.22	67.28	6,420.39	34,025.11	22,683.41	56,708.52	45,652.90	41,221.37	1,936.18	54,213.18
	3,000	0.49	8,711.97	6.22	67.28	6,420.39	33,725.11	22,483.41	56,208.52	45,152.90	41,221.37	1,936.18	54,213.18
	3,500	0.49	8,711.97	6.22	67.28	6,420.39	33,425.11	22,283.41	55,708.52	44,652.90	41,221.37	1,936.18	54,213.18
	4,000	0.49	8,711.97	6.22	67.28	6,420.39	33,125.11	22,083.41	55,208.52	44,152.90	41,221.37	1,936.18	54,213.18
	4,500	0.50	8,711.97	6.22	67.28	6,420.39	32,825.11	21,883.41	54,708.52	43,652.90	41,221.37	1,936.18	54,213.18

Table 8 | The sensitivity analysis of the cost coefficient of water-saving effort (without SWM)

Scenario	κ	ϕ^*	e^*	p^*	q^*	Π_u^*	Π_{wss}^*	Π_{wsc}^*	SW^*	CS^*	PE^*
Equilibrium decision	2,000	0.56	2.87	73.44	3,306.53	21,866.29	3,019.80	24,886.10	36,232.18	10,933.15	412.94
	2,500	0.63	2.24	73.99	3,029.80	18,359.33	2,415.13	20,774.45	30,205.57	9,179.66	251.46
	3,000	0.70	1.89	74.32	2,858.94	16,347.11	2,148.71	18,495.82	26,847.38	8,173.56	178.00
	3,500	0.78	1.65	74.56	2,737.09	14,983.28	2,025.48	17,008.75	24,637.22	7,491.64	136.83
	4,000	0.85	1.49	74.74	2,642.57	13,966.31	1,973.56	15,939.87	23,033.69	6,983.15	110.67
	4,500	0.93	1.36	74.90	2,565.26	13,161.16	1,960.73	15,121.89	21,795.08	6,580.58	92.61
Cooperative decision	2,000	0.56	15.28	56.06	12,124.15	35,172.45	23,448.30	58,620.76	217,284.27	146,995.04	11,668.47
	2,500	0.63	6.90	66.44	6,850.07	19,350.20	12,900.13	32,250.33	81,557.59	46,923.40	2,383.86
	3,000	0.70	4.46	69.47	5,310.11	14,730.33	9,820.22	24,550.55	53,742.63	28,197.27	994.80
	3,500	0.78	3.29	70.92	4,575.40	12,526.21	8,350.81	20,877.01	42,353.94	20,934.31	542.62
	4,000	0.85	2.61	71.76	4,145.25	11,235.75	7,490.50	18,726.25	36,250.34	17,183.09	341.00
	4,500	0.93	2.16	72.32	3,862.79	10,388.38	6,925.59	17,313.97	32,469.11	14,921.17	233.96

Table 9 | The sensitivity analysis of the cost coefficient of water-saving effort (with SWM)

Scenario	κ	ϕ^*	s^*	e^*	p^*	q^*	Π_u^*	Π_{wss}^*	Π_{wsc}^*	SW^*	CS^*	PE^*	TS^*
Equilibrium decision	3,000	0.38	12,640.37	6.68	69.92	5,107.95	52,182.25	48,180.98	100,363.24	44,298.52	26,091.13	2,228.29	84,384.13
	3,500	0.43	9,256.32	4.39	71.93	4,081.24	33,313.08	24,251.57	57,564.65	34,536.33	16,656.54	964.26	40,649.13
	4,000	0.48	7,354.19	3.23	72.94	3,562.80	25,387.07	14,746.16	40,133.23	29,585.48	12,693.54	522.05	23,763.34
	4,500	0.53	6,055.99	2.53	73.55	3,252.31	21,155.01	9,867.51	31,022.52	26,599.61	10,577.50	319.99	15,320.40
	5,000	0.58	5,061.76	2.06	73.95	3,047.17	18,570.43	6,967.95	25,538.39	24,607.56	9,285.22	212.22	10,428.26
	5,500	0.63	4,241.04	1.72	74.23	2,902.75	16,851.87	5,072.75	21,924.62	23,187.53	8,425.93	148.61	7,311.64
Cooperative decision	3,000	0.38	19,436.95	18.22	52.40	13,979.95	146,994.64	97,996.43	244,991.07	102,849.60	195,438.89	16,602.31	354,182.68
	3,500	0.43	11,442.18	9.28	63.50	8,344.79	55,680.59	37,120.39	92,800.98	60,585.90	69,635.47	4,303.54	106,154.09
	4,000	0.48	8,711.97	6.22	67.28	6,420.39	34,325.11	22,883.41	57,208.52	46,152.90	41,221.37	1,936.18	54,213.18
	4,500	0.53	7,334.29	4.68	69.19	5,449.32	25,448.53	16,965.68	42,414.21	38,869.91	29,695.10	1,095.80	34,335.21
	5,000	0.58	6,503.61	3.75	70.35	4,863.81	20,712.07	13,808.05	34,520.12	34,478.60	23,656.68	703.91	24,402.11
	5,500	0.63	5,948.12	3.13	71.12	4,472.27	17,803.16	11,868.77	29,671.93	31,542.04	20,001.22	490.03	18,621.13

consumer surplus decreases as the fixed cost of WSS increases under the equilibrium decision, while the consumer surplus does not change as the fixed cost of WSS increases under the cooperative decision; under the scenario with SWM, the consumer surplus decreases as the fixed cost of WSS increases under the equilibrium decision, while the consumer surplus does not change as the fixed cost of WSS increases under the cooperative decision; (vii) under the scenario without SWM, the positive externalities increase as the fixed cost of WSS increases under the equilibrium decision, while the positive externalities do not change as the fixed cost of WSS increases under the cooperative decision; under the scenario with SWM, the positive externalities decrease as the fixed cost of WSS increases under the equilibrium decision, while the positive externalities do not change as the fixed cost of WSS increases under the cooperative decision; (viii) under the scenario with SWM, the government subsidy decreases as the fixed cost of WSS increases under the equilibrium decision, while the government subsidy does not change as the fixed cost of WSS increases under the cooperative decision.

The sensitivity analysis results of the cost coefficient of water-saving effort for the WSS supply chain equilibrium and cooperative decision models under the scenario without/with SWM (Tables 8 and 9) show that: (i) the cost sharing rate increases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (ii) the water-consumption reduction (water-saving effort) decreases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (iii) the retail price increases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (iv) the ordering quantity decreases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (v) the profits of the water user, the WSS provider, and the WSS supply chain decrease as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (vi) the social welfare decreases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision;

(vii) the consumer surplus decreases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (viii) the positive externalities decrease as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision; (ix) under the scenario with SWM, the government subsidy decreases as the cost coefficient of water-saving effort increases, be it under the equilibrium decision or under the cooperative decision.

MANAGEMENT INSIGHTS AND POLICY IMPLICATIONS

Based on the analytical and numerical results of the WSS supply chain cooperative and equilibrium decision models under the scenario without/with SWM, the following management insights and policy implications can be summarized:

1. If the government does not subsidize WSS, i.e., SWM is not considered, the cooperation strategy outperforms the equilibrium strategy regarding the water-consumption reduction, operational performance of WSS supply chain, the corresponding social welfare, consumer surplus, and positive externalities. However, the water user has to share most of the benefit from WSS and gains less profit under the cooperation strategy than that under the equilibrium strategy. Hence, the water user may not have the incentive to adopt a cooperation strategy under the scenario without SWM.
2. If the government subsidizes WSS, i.e., SWM is considered, the cooperation strategy outperforms the equilibrium strategy regarding the water-consumption reduction, operational performance of WSS supply chain and its members, the corresponding social welfare, consumer surplus, and positive externalities. Thus, both the water user and the WSS provider have the internal incentive to adopt a cooperation strategy, and the government would be more willing to subsidize the WSS supply chain adopting the cooperation strategy, although more subsidy budget has to be input. Therefore, a *subsidy threshold policy* under which the government only subsidizes the WSS supply chain adopting the cooperation strategy, is recommended to be designed to maximize social welfare with higher positive externalities.
3. Comparing the scenario with SWM and the scenario without SWM, if the fixed cost of WSS is low (low-cost case), the WSS provider would have the internal incentive to provide WSS without government subsidy, thus, the government does not need to subsidize WSS if there is no corresponding subsidy budget; if the fixed cost of WSS is high (high-cost case), the WSS provider would not have the internal incentive to provide WSS unless the government subsidizes WSS, thus, the government has to subsidize WSS and seek SWM.
4. Comparing the scenario with SWM and the scenario without SWM, subsidizing the WSS to pursue SWM contributes to enhancing the water-consumption reduction, improving the operational performance of the WSS supply chain and its members, the corresponding social welfare, consumer surplus, and positive externalities, regardless of whether the equilibrium strategy or the cooperation strategy is adopted. Besides, subsidizing the WSS reduces the water user's cost sharing rate under the scenario with SWM. Hence, the water user and the WSS provider would expect that the government subsidizes the WSS to improve their operational performance, and the government would have the incentive to subsidize WSS to pursue SWM and improve the corresponding consumer surplus and positive externalities.
5. Under the subsidy threshold policy, setting a higher water price (water cost for the water users) by the government, could effectively enhance the water-consumption reduction and improve the operational performance of the WSS supply chain and its members, the corresponding consumer surplus, and positive externalities. However, a higher water price induces a lower social welfare and a higher government subsidy. Therefore, the government would have to set an appropriate water price to balance these conflicting goals.
6. Under the subsidy threshold policy, reducing the fixed cost of WSS could effectively improve the operational performance of the WSS supply chain and its members and the corresponding social welfare; as well, reducing the cost of water-saving effort could effectively enhance the water-consumption reduction, improve the

operational performance of the WSS supply chain and its members, the corresponding social welfare, consumer surplus, and positive externalities. Furthermore, reducing the cost of water-saving effort could gain more subsidy from the government. In other words, the government would have the incentive to put in more subsidy to the WSS supply chain with a lower cost of WSS.

In summary, a subsidy threshold policy under which the government only subsidizes the WSS supply chain adopting the cooperation strategy is recommended to maximize the social welfare with higher positive externalities. Under the subsidy threshold policy, the cooperation strategy is recommended to be adopted by the WSS supply chain to improve operational performance of the WSS supply chain, the corresponding social welfare, consumer surplus, and positive externalities.

CONCLUSION

As water resources become increasingly scarce, water users in high water-consumption industries are trying to seek a water-saving service (WSS) from the WSS provider to help them reduce water consumption in the product manufacturing/service providing process. In this context, the WSS supply chain equilibrium and cooperative decision models under the scenario without/with the SWM goal are developed, analyzed, and compared, respectively, the corresponding numerical and sensitivity analyses for all models are conducted and compared, and the management insights and policy implications are summarized in this article. The research results indicate that: (1) under the scenario without SWM, the cooperation strategy outperforms the equilibrium strategy regarding the water-consumption reduction, operational performance of the WSS supply chain, the corresponding social welfare, consumer surplus, and positive externalities. However, the water user may not have the incentive to adopt the cooperation strategy, as he gains less profit under the cooperation strategy than that under the equilibrium strategy; (2) under the scenario with SWM, the cooperation strategy outperforms the equilibrium strategy regarding the water-consumption reduction, operational performance of the WSS supply chain and its members, the corresponding social welfare, consumer surplus, and positive externalities; (3) a subsidy threshold policy under which the government only subsidizes the WSS supply chain adopting the cooperation strategy, is recommended to be designed to maximize social welfare with higher positive externalities; (4) the WSS provider would have the internal incentive to provide WSS without government subsidy when the fixed cost of WSS is low, otherwise, the WSS provider would not have the internal incentive to provide WSS unless with a government subsidy; (5) subsidizing WSS to pursue SWM contributes to enhancing the water-consumption reduction, improving operational performance of the WSS supply chain and its members, the corresponding social welfare, consumer surplus, and positive externalities, regardless of whether the equilibrium strategy or the cooperation strategy is adopted; (6) under the subsidy threshold policy, reducing the fixed cost of WSS and the cost of water-saving effort could effectively improve the operational performance of the WSS supply chain and its members and the corresponding social welfare; as well, an appropriate water price should be set by the government to balance conflicting goals, and the WSS supply chain with a lower fixed cost of WSS could gain more subsidy from the government.

In terms of theoretical contributions, the available literature rarely touches upon the operational strategies, internal incentives, and subsidy policies of the WSS supply chain with SWM goal. This study designed a novel and useful game-theoretical approach to investigate operational strategies, internal incentives, and subsidy policies for the WSS supply chain from the perspective of SWM. The modeling analysis complements the current water-saving research literature with new knowledge regarding the effect of SWM goal on the operational strategies/decisions, internal incentives, and subsidy policies of the WSS supply chain. Furthermore, the numerical analysis not only validates the key findings from the modeling analysis but also provides a deeper understanding of the dynamic relationships among key variables and parameters of the decision models. These modeling and numerical analyses address the research gap in the operational management study of the WSS supply chain.

For the practical contributions, the modeling and numerical results provide guidelines and insights for government to design better policies for WSS practice; they also offer insightful decision-making logics for the WSS supply chain to make better supply chain strategy choices and related pricing and water-saving effort decisions to achieve higher supply chain operational performances.

Due to limited research funds and time constraints, this study undertook mainly the theoretical modeling and numerical analyses. The theoretical models consider only a single WSS supply chain under the scenario without/with SWM. The numerical and sensitivity analyses study uses only a real-world mimicking case based on the actual characteristics of real WSS in the high water-consumption industries and the actual relationships between the water-saving manufacturer and the retailer, to derive useful findings relevant to the theoretical models and draw managerial insights and policy implications. Thus, there are more areas this research can be extended to in the future. First, the empirical data may be collected from a pure real-world case to investigate the operational strategies, internal incentives, and subsidy policies of the WSS supply chain with SWM in future research. Second, the case of subsidizing the water-saving effort may be extended to subsidizing both the water-saving effort and the fixed cost of WSS in future research. Third, the case of a single WSS supply chain may be extended to the case of dual/multiple competing WSS supply chains in future research.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (71603125, 71433003), China Scholarship Council (201706865020), the National Key R&D Program of China (2017YFC0404600), the Natural Science Research Project of Colleges and Universities in Jiangsu Province (15KJB110012), Young Leading Talent Program of Nanjing Normal University.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wcc.2019.188.

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First received 16 June 2018; accepted in revised form 1 March 2019. Available online 29 March 2019