Decision Behavior of Different Participants in Industrial Water Recycling and the Sharing of Water Recycling Value

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Research Impact Statement: There are presented the decision-making models of industrial water recycling. Cooperation between reclaimed water user and expertized supplier can create surplus value.

ABSTRACT: Water reclamation and reuse are an important means to alleviate the shortage of water resources. This paper proposes several different decision-making models to investigate what different participants in industrial water recycling, including users, suppliers, and local governments, should do in different situations. In the models, different decision logics of the participants about water reclamation are presented. Finally, the models are used in a case study and some meaningful results are obtained. The study explains the gap between the relatively low utilization and the strong demand for water recycling.

(KEYWORDS: hydrologic cycle; sustainability; water use; water recycling; decision model; value sharing.)

INTRODUCTION

Many regions are experiencing water crisis due to unbalanced distribution of water resources and discordant economic development (World Economic Council 2019). Population growth, accelerated urbanization, and ecosystem restoration boost the demand for water, resulting a worse situation for water safety. Meanwhile, with the development of water treatment technologies, wastewater can be treated to any desired quality at an acceptable cost now, even for portable use. In water-scarce regions, water reclamation and reuse (or combined as water recycling) has become a logical option for conserving and expanding water supply (Angelakis et al. 2018).

China is a country that has been facing increasingly severe water scarcity, especially in the northern part of the country (Jiang 2009). In northern China, where water scarcity is more severe than in southern China, water recycling in water-intensive industries has become a realistic method to resolve water-scarce problems (Wang et al. 2017). China has approved several acts to promote water recycling in industrial field, such as Circular Economy Promotion Law (revised in 2018), Law on the Prevention and Control of Water Pollution (revised in 2017), Water Law (revised in 2016), Environmental Protection Law (revised in 2014) and Law on Promoting Clean Production (revised in 2012). Additionally, a lot of measures and plans are adopted, including the newly issued Action Plan on Industrial Water Saving in Beijing, Tianjin and Hebei by the Ministry of Industry and Information Technology, Ministry of Water Resources (MWR), Ministry of Science and Technology, and Ministry of Finance in 2019.

The ratio of industrial water consumption to the total water consumption in China decreased from 23.3% to 20.2% (MWR 2020) with those efforts and other water-saving measures, whereas the total
industrial output value increased dramatically in this period. However, it is argued that the substitution of reclaimed water for traditional water resources is insufficient, especially in industrial and urban miscellaneous use (Liu et al. 2017; Chang et al. 2020).

Technical factors at micro-level and policy factors at macro-level are widely discussed to explain the gap between the relatively low utilization of reclaimed water and the strong demand for water recycling (Asano et al. 2007; Frijns et al. 2016). Water recycling status of the whole of China (Lyu et al. 2016; Zhu and Dou 2018) and some specific industries (Jia et al. 2016) are also analyzed to address the opportunities and challenges for wastewater recycling. However, decision behaviors of different participants in water recycling, such as water users, independent reclaimed water suppliers, municipal water recycling facilities (MWRF), and local governments, which are crucial to understanding and expanding water recycling applications, are not described clearly yet (Maaß and Grundmann 2018; Ghofreh et al. 2019; Malisa et al. 2019).

In practice, industrial water can be internally recycled within the economic boundaries of a specific industrial facility (the user) or externally reclaimed by an independent water treatment company (the supplier) and transported back to the user, reused as cooling water, boiler feed water, landscape irrigation water, and/or process water. Municipal wastewater can also be recycled for industrial use if there is proper route between the MWRF and the user. Local governments usually encourage such behavior to obtain economic and environmental benefits from water recycling. This study aims to establish decision-making models for the above participants in industrial water recycling. Possible actions of the participants are listed. Conditions under which those actions are expected to be taken are discussed. A case study in Beijing is introduced as an explanation of the decision-making models as well as an example of value sharing between users and suppliers. Finally, policy implications are put forward.

PARTICIPANTS OF INDUSTRIAL WATER RECYCLING AND THEIR DECISION LOGICS

Participants of Industrial Water Recycling

There are several participants in industrial water recycling. The user, usually an industrial facility, uses tap water or other external water resource to meet its demand for water. During the industrial production process, a part of the water is evaporated, transpired, or incorporated into products. The rest of the water, of which the quality deteriorates along with the production process, is treated internally to meet the discharge standard to municipal pipeline and then discharged. The user may recycle part of water internally, thus reduces both usage of external water resource and discharge of industrial wastewater. One extreme scenario is that the user recycles all the water internally and uses external water resource as a supplement to the consumptive use of water only. In this case, the user realizes zero liquid discharge (ZLD). The main goal of the user participating in water recycling is minimizing its expenditure on water usage, though environmental and other factors may be taken into consideration.

The supplier, usually an independent company whose specialty is in water treatment or water recycling. It receives industrial wastewater discharged by an industrial user (or several industrial users in some cases), reclaims the water, and redirects the reclaimed water back to the user. The cost of the supplier to recycle the wastewater is always lower than that of the user to recycle the wastewater further-more by itself, otherwise there is no opportunity for the supplier to conduct this kind of business. Comparing to the user, cost reduction of the supplier comes from its advantages in water treatment technologies, facility constructions, equipment purchases, and operational capabilities. The goal of the supplier is maximizing its profit of water recycling business. To reach this goal, enhancing the quality of reclaimed water is a possible way, since reclaimed water with high quality may be used more wildly and be paid with a higher price. However, it also increases treatment cost. The supplier must make a tradeoff between quality and cost.

The local government can influence water recycling activities in several ways. It can lead and dominate the adjustment process of tap water tariff, which is a determining factor for water recycling. It can regulate wastewater discharging activities by revising local discharge standards or change the pattern of monitoring wastewater discharge. It can also give subsidies to either user or supplier to accelerate water recycling. The goal of local government is the sustainable development of the region.

Tap water facility (TWF) is a passive participant in water recycling. Though tap water tariff is crucial for the decisions of other participants, TWF cannot solely decide the tariff (usually regulated by local government) and cannot conduct price discrimination between different industrial users in most cases. MWRF can be regarded as a mixture of TWF and supplier. It may have more power in pricing than TWF but less than supplier, and cannot conduct price
discrimination in most cases, too. For this reason, TWF and MWRF are not discussed in decision-making models, but the role of MWRF is discussed in the case.

**Model of Single Decision Maker**

There is only one decision maker, the user, in the simplest model. The user produces different kinds of wastewater (or a mixture of them). It can determine to recycle one kind of wastewater or not (the mixture can be regarded as another single type).

The possible actions of the user include the following:

**Action 1:** Purchasing tap water and not recycling wastewater type $i$, when:

$$C_u + T_w \geq P_t + C_{di}.$$  
(1)

**Action 2:** Recycling the wastewater type $i$, when:

$$C_u + T_w < P_t + C_{di},$$  
(2)

where $C_u$ is the treatment cost of recycling water for wastewater type $i$, $T_w$ is the transportation cost of reclaimed water for wastewater type $i$, $P_t$ is the tariff of tap water, and $C_{di}$ is the treatment cost of wastewater type $i$ to meet the discharge standard to the municipal pipeline.

Overall substitution of recycled water to tap water is not possible since part of the water is consumed in the production and recycling process. In this model, the crucial factors which influence user’s decision are as follows:

**Factor 1:** $P_t$, the tariff of tap water. The higher the tariff, the higher possibility that the recycling and transportation cost ($C_u + T_w$) is lower than ($P_t + C_{di}$);

**Factor 2:** $C_u$, the recycling cost of the user for wastewater type $i$, which is determined by the quality of wastewater type $i$, overall development of technologies, and the ability of the user to apply those technologies;

**Factor 3:** $C_{di}$, the treatment cost of the user for wastewater type $i$ to meet the discharge standard to the municipal pipeline. The higher the cost, the higher possibility that the recycling and transportation cost ($C_u + T_w$) is lower than ($P_t + C_{di}$);

$T_w$, the transportation cost of reclaimed water for wastewater type $i$, is not a significant factor since the water recycling is usually within the boundary of the user.

For each wastewater type $i$, $C_u$ and $C_{di}$ may be different. A reasonable choice of the user is recycling part of the industrial wastewater of which the recycling cost is lower enough (i.e., $C_u + T_w < P_t + C_{di}$, for industrial wastewater type $i$), and not recycling another part of the industrial wastewater of which the recycling cost is high (i.e., $C_u + T_w \geq P_t + C_{di}$, for industrial wastewater type $i$). All unrecycled wastewater is mixed up and then treated by the user itself to meet the discharge standard to the municipal pipeline.

**Model of Two Decision Makers**

A little more complex decision model is that an independent water recycling company, or supplier, is involved. In this model, there are two decision makers: a user, and a supplier.

The possible actions of the user are as follows:

**Action 1:** Purchasing tap water and not recycling water for wastewater type $i$, when:

$$C_u + T_w \geq P_t + C_{di},$$  
(3)

and

$$P_r \geq P_t.$$  
(4)

**Action 2:** Recycling the wastewater for wastewater type $i$ by itself, when:

$$C_u + T_w \leq \min(P_t + C_{di}, P_r + C_{di}).$$  
(5)

**Action 3:** Recycling the wastewater for wastewater type $i$ by the supplier, when:

$$C_u + T_w \geq P_r + C_{di},$$  
(6)

and

$$P_r < P_t,$$  
(7)

where $P_r$ is price of the recycled water provided by the supplier, whereas $C_u$, $T_u$, $P_t$, and $C_{di}$ have the same definition as in the model of single decision maker. In most cases, the user discharges a mixture of unrecycled wastewater. That means:

$$C_{um} + T_{um} > P_t,$$  
(8)

where $C_{um}$ is the recycling cost of the user for the mixture of unrecycled wastewater, and $T_{um}$ is the transportation cost of reclaimed water from the mixture of unrecycled wastewater. Then the possible actions of the user are simplified as:

**Action 1:** Purchasing tap water and not recycling the discharged mixture of wastewater by the supplier, when Equation (4) is valid;

**Action 2:** Recycling the discharged mixture of wastewater by the supplier, when Equation (7) is valid.
Obviously, the crucial factors which influence the decision logic of the user are the relationship of $P_r$ and $P_t$.

The possible actions of the supplier are as follows:

**Action 1:** Recycling water and supplying the recycled water, when:

$$C_s + T_s < P_r.$$  \hfill(9)

**Action 2:** Taking no actions, when:

$$C_s + T_s \geq P_r,$$  \hfill(10)

where $C_s$ is the treatment cost of recycling water of the supplier, and $T_s$ is the transportation cost of reclaimed water from the supplier to the user. The crucial factors which influence the decision of supplier in this model include the following factors:

**Factor 1:** Urban planning, which significantly influents $T_s$. If there is no proper land for the supplier to establish the water recycling facility within the boundaries of the user or in the neighborhood of the user, investment cost on pipelines and energy cost for water transportation may be very high.

**Factor 2:** Capability of the supplier, which determines $C_s$.

**Model of Three Decision Makers**

To promoting industrial water recycling, the local government can influent $P_t$, the tariff of tap water, or $C_{um}$, the recycling cost of the user for the mixture of unrecycled wastewater. It can also reduce $T_s$ by optimizing urban planning. Besides those indirect measures, it can also directly influent the water recycling decision model by providing subsidy to either user or supplier. The subsidy may be a compensation to the supplier for its investment and operation cost of the recycling facility, or an award to the user for its purchase and reuse of reclaimed water.

If the subsidy ($S_g$) is given to the user, the possible actions of the user are as follows:

**Action 1:** Purchasing tap water and not recycling the discharged mixture of wastewater by the supplier, when:

$$C_{um} + T_{um} \geq P_t + S_g,$$  \hfill(11)

and

$$P_r \geq P_t.$$  \hfill(12)

**Action 2:** Recycling the discharged mixture of wastewater by itself, when:

$$C_{um} + T_{um} < \min(P_t + S_g, P_r + S_g).$$  \hfill(13)

**Action 3:** Recycling the discharged mixture of wastewater by the supplier, when:

$$C_{um} + T_{um} \geq P_r + S_g,$$  \hfill(14)

while the possible choices of the supplier keep the same as they are in model of two decision makers.

If the subsidy ($S_g$) is given to the supplier, the possible actions of the supplier are as follows:

**Action 1:** Recycling water and supplying the recycled water, when:

$$C_s + T_s < P_r + S_g.$$  \hfill(16)

**Action 2:** Taking no actions, when:

$$C_s + T_s \geq P_r + S_g,$$  \hfill(17)

while possible choices of the user keep the same as they are in model of two decision makers. In both scenarios, the subsidies will increase the recycling rate of water and push $P_r$ to a new equilibrium, which depends on the bargaining power of user and supplier.

The possible actions of the local government are as follows:

**Action 1:** Giving subsidies is an option but not a must, when:

$$S_g < B_g,$$  \hfill(18)

especially when Equation (18) is valid and

$$P_r > P_t,$$  \hfill(19)

and

$$P_r < P_t + S_g.$$  \hfill(20)

**Action 2:** Taking no actions, when:

$$S_g \geq B_g,$$  \hfill(21)

where $S_g$ is the subsidy given by the local government and $B_g$ is beneficial of the local area from water saving, environmental protection, and industrial development due to water recycling.
CASE STUDY

Stage 1: The User Used Tap Water

The user is an electronic manufacturer located in Beijing, a city with severe water scarcity. At the beginning, its total water consumption was about 10,000 m³/day. It used tap water as an external water source. 500 m³/day of water was consumed in its production processes, and 9,500 m³/day of wastewater, which was a mixture of four types of wastewater, was treated by the user itself to meet the discharge standards and then discharged to municipal pipeline. The discharged wastewater was transported to a downstream municipal Wastewater Treatment Facility about 3 km away from the user, where the transported wastewater, together with wastewater discharged by other domestic and industrial users in the neighborhood, is treated. The whole process is shown as Figure 1.

The model of single decision maker can be applied. $P_t$ is RMB 9 Yuan/m³ at the present level. $C_u$ and $T_u$ cannot be clearly quantified since the user does not disclose such information, but it can be disserted that it is valid for $C_u + T_u \geq P_t$.

Stage 2: An MWRF in the Upstream Was Introduced

An MWRF in the upstream, which collects and reclaims municipal wastewater discharged by upstream domestic users, latterly started providing reclaimed water to the user via a pipeline of 10 km. The user still used a part of tap water because the reclaimed water cannot fully meet its requirement for water quality and quantity, though the price of reclaimed water (RMB 7 Yuan/m³ at the present level) is much cheaper than tap water (RMB 9 Yuan/m³ at the present level). Since $C_{um} + T_{um}$ is higher than $P_t$ and $P_t$ is higher than the price of reclaimed water supplied by the MWRF in the upstream, it is expected that the user did not deviate from its action in the initial situation — part of tap water is substituted by reclaimed water, but the total amount of discharged wastewater is the same, or 9,500 m³/day. The whole process is shown as Figure 2.

Stage 3: An Supplier was Introduced

A supplier, which is specialized in water recycling, was introduced later. The supplier invested a water recycling facility adjacent (as shown in Figure 3) to the user, which completely intersects and reclaims the wastewater discharged by the user so that there is no wastewater discharged to the municipal pipeline anymore.

In the whole water cycle, the water loss is 740 m³/day, among which 500 m³/day is evaporation.
and other loss in the production processes of the user and another 240 m³/day is evaporation and other loss in the water treatment process of the supplier. That means external water resources can be recycled by 13.5 times (10,000/740) in this water recycling system.

For the user, \( P_t \) is still RMB 9 Yuan/m³, and \( P_r \) is RMB 6.79 Yuan/m³, which was written on a contract between the user and the supplier. \( P_r \) is not only less than \( P_t \), but also slightly less than the price of reclaimed water from MWRF in the upstream to maintain price advantage. It is valid for \( P_r < P_t \), and it is also valid for \( C_{um} + T_{um} \geq P_t \) and \( C_u + T_u \geq P_r \) apparently, since the user does not recycle any more water internally.

For the supplier, its specialty in water recycling ensures that \( C_s \) is lower enough to make \( C_s < P_r < P_t \). The reclaimed water is transported back to the user via a very short pipeline since the user and supplier are adjacent to each other, which makes \( C_t \), the transportation cost can be ignored. That means \( C_u + T_u < P_r < P_t < C_{um} + T_{um} \), under which the supplier chooses to supply reclaimed water. The whole process is shown as Figure 4.

The local government encourages such cooperation in water recycling between the user and supplier. It gives a subsidy to the supplier for investing water recycling facility, which slightly reduces the total cost of the water recycling by RMB 0.36 Yuan/m³ (supposing internal rate of return [IRR] = 8% and the calculation period = 10 years).

Value Creating and Sharing

The user and supplier signed a value-sharing contract (as shown in Figure 5) before the investment of the water recycling facility. The supplier committed to invest and operate the facility, and provide reclaimed water to the use at a floating price that is equal to 80% of the tap water tariff. If tap water tariff varies, the price of reclaimed water should be adjusted accordingly. When the contract was signed, the price of tap water for industrial use is RMB 6.21 Yuan/m³ and now increase to RMB 9 Yuan/m³. That is, \( P_r \) is RMB 7.2 Yuan/m³ at the present level. However, to compete with the reclaimed water from the MWRF in the upstream, the supplier agreed to add a clause to the contract that \( P_r \) should be slightly lower than the price of reclaimed water from the MWFR in the upstream (RMB 7 Yuan/m³ at the present level). Under that clause, \( P_r \) is adjusted to RMB 6.79 Yuan/m³. As a guarantee, the user committed that it will supply wastewater which meets the discharge standard to the supplier by free.

By recycling the wastewater discharged by the user, the supplier creates a financial value that equals to \( (P_r - C_s - T_s) \), which is shared by the user and supplier. The supplier also creates an economic value that is not shared by the user and supplier but by the local community. First, the external water resource needed by the user largely declines from 10,000 to 740 m³/day. That means 9,260 m³/day of external water resource now can be used by other industrial users. Since Beijing is a water-scarce city, some industrial activities may be restricted if there is no additional water resource released by the water recycling cooperation mentioned above. In this case, after the supplier started to supply reclaimed water to the user, the reclaimed water supplied by MWRF in the upstream to the user declined. However, the usage rate of the MWRF in the upstream does not decline since the reclaimed water was shift to other users immediately. Second, ZLD is realized for the user (also for the supplier). It will largely reduce the omission of pollutants. The benefits of increasing industrial activities and decreasing pollutant...
omissions can be calculated by appropriate models (Fan et al. 2015), and local government can make a policy decision of subsidy of such water recycling cooperation based on the calculation result.

The supplier does not disclose its cost of water recycling. However, when the value-sharing contract was signed, the tap water tariff was RMB 6.21 Yuan/m$^3$ and the corresponding $P_r$ is RMB 4.97 Yuan/m$^3$. The government subsidy was not assured at that time. Therefore, it can be deducted that $C_s + T_s < $ RMB 4.97 Yuan/m$^3$ by applying decision model of the supplier. Value creating and sharing in the Water Recycling Process is shown in Figure 6.

**Further Cooperation between the User and Supplier**

This case only shows a start of water recycling cooperation between the user and supplier. In the next step, the user may outsource pretreatment and posttreatment of the industrial water to the supplier, or introduce the supplier to treat some types of industrial wastewater before they are mixed with other types to save treatment cost and furtherly enhance the water recycling rate.

**POLICY IMPLICATIONS**

Based on the analysis of decision models for industrial water recycling and the case study, there are some policy implications: (1) Companies which are specialized in water recycling, or suppliers, are necessary for industrial water recycling. Industrial water that cannot be internally recycled by the user itself can be externally recycled by a supplier, since the supplier may have cost advantages. Therefore, the establishment of such suppliers and their cooperation with users should be encouraged. (2) Tap water tariff, or $P_t$, plays a very important role in the decision logics. It is the upper limit of the price of recycled water provided by the supplier, or $P_r$. The increase in tap water tariff will accelerate either internal or external water recycling. Tap water tariff in water-scarce region should be adjusted to a reasonable level to reflect the real value of water resource and to stimulate water recycling; (3) $C_d$, the treatment cost of the user for wastewater to meet the discharge standard to municipal pipeline, also plays a very important role in the decision logics. The local government can regulate wastewater discharging activities of the user.
by revising local discharge standards or change the pattern of monitoring wastewater discharge. (4) Urban planning is crucial to external water recycling since the transportation cost of recycling water, or \( T_s \), may be very high if there is no suitable land to established the recycling facility or no proper route for the transportation of recycling water. Water recycling cooperation, as the case shows, will significantly reduce the need of user for external water resources. When local governments make industrial and urban planning, this factor should be incorporated into consideration. (5) Government subsidy is helpful but not necessary. It depends on the economic value created by the supplier and how the local government measures it.

AUTHORS’ CONTRIBUTIONS

Zhihua Liu: Formal analysis; investigation; methodology; writing-original draft. Shaofeng Jia: Conceptualization; funding acquisition; methodology; supervision; writing-review & editing.

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