Key stakeholders’ optimal strategy for upgrading water supply facilities in China

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Abstract

It is urgent to upgrade, replace and improve water supply facilities in China. Penalty, subsidy and water price increase are often considered the main policy tools for encouraging water supply companies to upgrade their production facilities. However, the implementation of upgrading water supply facilities is being confronted with some uncertainties because of the conflicts of involved stakeholders. This study develops a game model between municipal government and a water company to analyze their conflicts of interests and optimize the strategy for upgrading water supply facilities. Empirical analyses from three Chinese urban water companies are presented. Using theoretical and numerical analysis, the effects of penalty, subsidy and water price increase on strategies of upgrading water supply facilities were obtained. The main findings are that water price and penalty are the effective policies to optimize key stakeholders’ strategies, while subsidy policy is not useful. The conclusion has important policy implications for ensuring water supply safety and reliability.

Keywords: China; Game theory; Policy; Upgrade facilities; Water supply

1. Introduction

In recent years, China has suffered frequent drinking water supply accidents (Zhang et al., 2011). According to the Ministry of Environmental Protection Administration, there were 6,928 drinking water pollution accidents from 2000 to 2010 (China Statistic Yearbook, 2010). For example, in July 2009 more than 500 residents became ill and two died after being exposed to cadmium, a heavy metal pollutant discharged into the Liuyang River and surrounding land by the Xianghe Chemical Plant in Liuyang city in Central China’s Hunan Province (Du & Li, 2011). To ensure drinking-water safety, the new Standards for Drinking Water Quality (GB5749-2006) which demand more strict requirements for drinking water, became effective in China on 1st July 2012. All 106 items included were adopted from the World Health Organization (WHO) guidelines for drinking-water quality.

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This is the first time a developing country has implemented strict regulations on drinking-water quality, and the first time the same standards have been applied in rural and urban areas in China (Qu et al., 2012). However, many of the Chinese water companies are having difficulties in complying with the new standards due to the outdated water-processing facilities and techniques (Cosiner & Shen, 2009). Urban water supply systems in China and worldwide share a major and pressing problem: water supply facilities and infrastructures, most of which were developed by the late 1960s, are showing serious signs of aging and deterioration (Sahely et al., 2005). For urban water supply systems and management, the main task is to provide consumers with adequate drinking-water quantity at the required quality and pressure level according to current standards. Therefore, an essential challenge for China in the 21st century will be upgrading and improvement of water supply facilities to ensure water supply safety and reliability.

Safety and reliability can be identified as key parameters describing the performance of the urban water supply service. Water supply safety can be defined as ensuring adequate access and affordability of water to meet minimum livelihood standards (Biggs et al., 2013). Water supply reliability is the ability to supply a constant flow of water with specific pressure and quality to meet consumers’ demand in specific operating conditions at any or a specific time and at an acceptable price (Tchórzewska-Cieślak, 2012). However, the increased number of water supply incidents requires urban water supply stakeholders to find efficient and reactive water supply management strategies. Upgrading water supply facilities is the key to provide reliable and high-quality drinking water for consumers while minimizing the probability of urban water supply incidents.

Since water supply is one of the public utility sectors, governments tend to take a lead role in the water industry (Lee, 2010). The view of water as a public and social good made it necessary to subsidize public water supply sectors heavily (Cosiner & Shen, 2009). Due to the massive demand for water infrastructure and lack of capital, the Chinese government has opened up the water sector to domestic and foreign companies since 2002 (Lee, 2007). Since then, governments and water companies have been the most important and definitive stakeholders in urban water supply systems in China (Wang et al., 2013). Recent studies indicated that upgrading water supply facilities would be confronted with some uncertainties because of the conflicts of interests between governments and water companies (Browder et al., 2007). Municipal governments are responsible for ensuring and verifying that the water companies are capable of delivering safe water routinely. Governments would like to provide a better water service. Meanwhile, they are required to keep the water price socially acceptable (Choi et al., 2010). In addition, municipal governments in developing countries concentrate more on economic development (Dong et al., 2010). Water companies are primarily responsible for producing and delivering safe drinking water. And water companies which fail to meet the standard requirement must be charged according to the severity of the violations (Water Law of PRC, 2002). However, water companies may hesitate to upgrade water supply facilities owing to the heavy investment demands (Zhong & Mol, 2010). Many Chinese water companies have suffered from poor operating efficiency and slow technological upgrades due to current low level of water prices which can be adjusted only by China’s municipal governments (Osmo & Tapio, 2003). After all, the lack of water regulation and incentive policies are the major constraints that require serious attention. It is important to have an efficient monitoring mechanism and incentive policies to ensure water companies are able to fulfill their obligations and to upgrade their facilities.

It is useful and necessary to better understand key stakeholders’ conflicts and strategies before designing appropriate policies. Game theory can be used to predict how people behave following their own interests to deal with conflicts and to provide input for policy and planning purposes. Thus, the objective
of this study is to find the key stakeholders’ optimal strategies for upgrading water supply facilities in China using a game theory framework in order to provide implications for government policy makers.

2. Methodology

2.1. Game model development

Since von Neumann and Morgenstern (1944) published their book *The Theory of Game and Economic Behavior*, game theory has been widely used as a mathematical and logical approach applied in various research fields, such as economics, marketing and environmental management (Madani, 2010). The solutions provided by game theory are usually arrived at by considering the interaction between the ‘players’ who are involved (Choi et al., 2010).

Game theory is often seen as an essential tool when dealing with water management problems with multiple agents, especially when there are conflicting objectives (Zhao et al., 2012). The application of game theory to water resources management has been discussed by a number of works, such as water or cost/benefit allocation (Dinar & Howitt, 1997; Wang et al., 2008) and water quality management (Niksohkhn et al., 2009; Schreider et al., 2010). Yet game theory applications to water supply management are still under development (Suttinon et al., 2012). Tapiero (2004) created a game theory framework to investigate governmental subsidies and penalties which can influence the possible actions of enterprises. Later, the model was modified by formulating a Stackelberg game where the polluting firm is assumed to be a follower, while the environmental agency is a leader (Tapiero, 2005). Dong et al. (2010) analyzed the effects of subsidies, penalties and other policy variables on the implementation of clear production policies by conducting a game model between a local government and a potential polluting firm. Zhao et al. (2012) used game theory to analyze the strategies selected by manufacturers to reduce environmental risk and suggested that the strategic choice of the manufactures would be influenced by government penalties or incentives. While previous studies analyzed the influence of penalty and subsidy on the strategies of governments and polluting firms, they failed to consider the adjustable price policy in the regulatory game model. In the field of water supply management, there are many researches indicating that changes in water prices affect decision-making of water companies (Hughes et al., 2009).

According to these studies, the game theoretical model developed in this paper considers adjustable price as well as penalty and subsidy. Inside the game model, municipal governments are taken as regulators who have the authority to inspect water companies, and water companies are regarded as agents. The model analysis revealed how penalty, subsidy and water price increase affect the strategies of water companies to upgrade facilities. Further, under what conditions the strategies satisfied the interests of both municipal government and water companies was discussed. In addition, the model is extended by adding some policy variables to change the payoff of municipal government or the water company, which may improve the current polices. Empirical studies were then followed to evaluate the theoretical model and to provide empirical policy implications.

2.2. Model assumptions

Three policy variables: penalty, subsidy and water price increase, and six input parameters are assumed. Explanations for each variable and parameter are illustrated in Table 1. For a particular
water company, all input parameters are fixed. Policy makers can adjust policy variables to influence the strategies of the water company and the municipal government.

The proposed models are based on the following assumptions:

1. Taking municipal government as a regulator which has the authority to inspect the water companies, give subsidy, penalty or increase water price. Any corrupt activities by municipal government are ignored during the enforcement process. Due to the limited budgets and staff, it is difficult for municipal government to inspect all water companies spontaneously. Therefore, the model assumes that municipal government may monitor the company with a specified probability and subsequently stick to it.

2. If a water company upgrades its facilities, it is considered to comply with the national drinking water standards. Then there is no penalty for it. Since municipal government could not monitor all companies, the companies that do not upgrade facilities can avoid being penalized with a fixed probability.

3. There is rigid demand for drinking water for consumers, and water is a necessary good for people to live so that water is perfectly inelastic. Thus, the model assumes that demand will not be brought down by increasing water price.

4. The extra social cost for municipal government is ignored. The social cost of this study is defined as the actual or potential public loss due to water supply accidents. It typically has two parts: the actual loss and potential risk. In general, most Chinese water facilities and techniques could comply with the national drinking water standards presently. The social cost is relatively small. Furthermore, there is no objective assessment system of urban water supply safety for municipal governments in China. As long as water companies comply with the standards, municipal governments will not focus on this part of the social cost. Thus, the model does not consider the social cost for municipal governments.

5. This research focuses on urban water supply systems and management. Because of natural monopoly and scale effect, urban water services are usually supplied by a few large-scale water companies. The annual quantity of water supply \( Q \) is fairly large.

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**Table 1. All policy variables and input parameters in the model.**

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Policy variables</strong></td>
<td></td>
</tr>
<tr>
<td>( F )</td>
<td>Penalty cost of the ‘not complying’ water company (unit: RMB)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Shared proportion of upgrading cost for municipal government (%)</td>
</tr>
<tr>
<td>( P )</td>
<td>Water price increase (unit: RMB/m(^3))</td>
</tr>
<tr>
<td><strong>Input parameters</strong></td>
<td></td>
</tr>
<tr>
<td>( C_0 )</td>
<td>Water company’s unit production cost before upgrading (unit: RMB/m(^3))</td>
</tr>
<tr>
<td>( C_U )</td>
<td>Increased unit cost of water company after upgrading (unit: RMB/m(^3))</td>
</tr>
<tr>
<td>( Q )</td>
<td>Quantity produced and consumed (unit: m(^3))</td>
</tr>
<tr>
<td>( C_R )</td>
<td>Governments’ monitoring cost (unit: RMB)</td>
</tr>
<tr>
<td>( P_0 )</td>
<td>The original water price (unit: RMB/m(^3))</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Tax rate</td>
</tr>
<tr>
<td>( r )</td>
<td>Violation risk that companies do not meet the standard requirement if they do not upgrade</td>
</tr>
</tbody>
</table>

RMB, renminbi
### 2.3. Game model and payoff matrix

In this study, the game is played by the municipal government and a water company. The interest lies on a $2 \times 2$ simultaneous-move game in Table 2. The municipal government is assumed to minimize the sum of expected subsidies and inspection costs, and the company is to maximize the profit. The municipal government has two strategies, called ‘Implement’ or ‘Not implement’. The water company has two strategies, called ‘Upgrade’ or ‘Not upgrade’.

For identification, the formulas in the left side and right side of the semicolons are used for strategies of the municipal government and strategies for the water company, respectively (Table 2). According to the assumptions, the net benefit of the water company before upgrading facilities is $(P_0 - C_0)Q$. The inspection cost of municipal government is $CR$. The company pays tax to the municipal government at the rate of $\alpha$. If the municipal government plays ‘Not implement’, the company pays no penalty for its violation. The payoffs for the municipal government and the water company are $\alpha(P_0 - C_0)Q + (1 - \alpha)(P_0 - C_0 - C_U)Q$ and $(1 - \alpha)(P_0 - C_0 - C_U)Q$, respectively. If the municipal government plays ‘Implement’, the company has to pay penalty $F$ for its violation with risk $r$. The payoffs for the municipal government and the company are $\alpha(P_0 - C_0)Q + rF - CR$ and $(1 - \alpha)(P_0 - C_0)Q - rF$, respectively.

If the company chooses to upgrade its facilities, the unit cost for upgrading facilities is $CU$. In this case, if the municipal government plays ‘Not implement’, the payoffs for the municipal government and the company are $\alpha(P_0 - C_0 - CU)Q$ and $(1 - \alpha)(P_0 - C_0 - CU)Q$, respectively. If the municipal government plays ‘Implement’, an equipment subsidy rate of $\beta$ is provided to the water company and the water price is raised to $P_0 + P$. In the interests of the water company, it is reasonable to assume that $P + \beta CU > 0$. Then the payoffs for the municipal government and the company are $\alpha[(P_0 + P) - C_0 - (1 - \beta)CU]Q - \beta CUQ - CR$ and $(1 - \alpha)\{(P_0 + P) - C_0 - (1 - \beta)CU\}Q$, respectively.

### 3. Model analysis

#### 3.1. The Nash equilibrium

Obviously, the water company prefers not to upgrade if municipal government does not implement because $(1 - \alpha)(P_0 - C_0)Q > (1 - \alpha)(P_0 - C_0 - C_U)Q$, which means that the payoff for the company to choose ‘Not upgrade’ is higher than that to choose ‘upgrade’. In practice, the inspection cost is
usually lower than the penalty ($rF > CR$). Then, the municipal government prefers to implement if the water company does not upgrade facilities. In order for the water company to upgrade facilities, the payoffs for the water company must be satisfied:

\[
(1 - \alpha)[(P_0 + P) - C_0 - (1 - \beta)C_U]Q \geq (1 - \alpha)(P_0 - C_0)Q - rF
\]  

(1)

As assumed above, $Q$ is fairly large. In the case where the penalty ($rF$) is small relative to $Q$ or even equal to zero, Equation (1) can be rewritten as:

\[
P \geq (1 - \beta)C_U - \frac{rF}{(1 - \alpha)Q} \approx (1 - \beta)C_U
\]  

(2)

Equation (2) could be presented as an upper bound in water price in order to induce the company to upgrade, which means that the water price increase per unit of $Q$ should be at least the cost of upgrading that is not covered by the subsidy.

Notice that the Nash equilibriums vary under different policy conditions. If the municipal government tends to implement in the scenario where the water company upgrades facilities, (Implement, Upgrade) is the unique Nash equilibrium. It means that:

\[
\alpha[(P_0 + P) - C_0 - (1 - \beta)C_U]Q - \beta C_U Q - CR \geq \alpha(P_0 - C_0 - C_U)Q
\]  

(3)

In the case where the cost of auditing and controlling of the company ($CR$) is small relative to $Q$ ($CR << Q$) or even equal to zero, Equation (3) can be presented as:

\[
P \geq \frac{\beta C_U Q(1 - \alpha) + CR}{\alpha Q} \approx \frac{\beta C_U (1 - \alpha)}{\alpha}
\]  

(4)

Equation (4) shows an upper bound in water price increase in order to induce the municipal government to implement. It could be interpreted as the additional unit amount of money the municipal government receives from the increase in water price should be greater than the net subsidy provided to the company by the municipal government ($\alpha P > (1 - \alpha)\beta C_U$).

If the municipal government prefers not to implement in the scenario where the water company plays ‘Upgrade’, the Nash equilibrium of this finite game is unique and in mixed strategies. It holds that:

\[
\alpha[(P_0 + P) - C_0 - (1 - \beta)C_U]Q - \beta C_U Q - CR < \alpha(P_0 - C_0 - C_U)Q
\]  

(5)

In this case, $P$ and $\beta$ will satisfy the following expression:

\[
P < \frac{\beta C_U Q(1 - \alpha) + CR}{\alpha Q} \approx \frac{\beta C_U (1 - \alpha)}{\alpha}
\]  

(6)

Contrary to Equation (4), Equation (6) establishes revenues from the water price increase which do not cover the net subsidy the municipal government has to provide to the company.
Under the condition of Equations (2) and (4), (Implement, Upgrade) is the dominant strategy for municipal government and a water company, respectively. When $P$ and $\beta$ satisfy Equations (2) and (6), the Nash equilibrium is unique and in mixed strategies. Otherwise, the municipal government will not implement and the water company prefers not to upgrade facilities. The game equilibrium under various policy conditions is shown in Figure 1. As a result, the policy goal of (Implement, Upgrade) will be achieved under the optimal conditions of $P \geq \max [(1 - \beta)C_U, \beta(1 - \alpha)C_U / \alpha]$. It means that water price increase is equal or more than the maximum between the unit upgrading cost of the water company and the upgrading cost shared by municipal government. As shown in Equation (2), if $F = 0$ (i.e. no penalty) the price increase has to be at least what the company spends in the new technology, $(1 - \alpha)C_U$. The lowest subsidy rate and the lowest water price increase can be easily shown as $\beta^* = \alpha$ and $P^* = (1 - \alpha)C_U$, respectively. Since government is required to keep the water price socially acceptable in order to satisfy the basic needs of all people, municipal government will suffer a reputational cost because of a water price increase. Hence, it would be better to minimize the water price increase. In addition, the subsidies provided by municipal government are limited because of the government’s tight budget. Therefore, the optimal subsidy is equal to the tax rate $(\beta^* = \alpha)$ while the optimal water price increase is equal to the unit cost of upgrading paid by the water company $(P^* = (1 - \alpha)C_U)$. For social welfare and equality, the maximum of the water price increase should not be higher than the increased unit upgrading cost, $C_U$. Thus, the scope of the optimal water increase is $[(1 - \alpha)C_U, C_U]$. And the scope of the optimal subsidy is $[\alpha, 1]$.

### 3.2. Impact of policy variables

According to the research by Dong et al. (2010), comparative static analysis is used to investigate how the mixed equilibrium responds to changes in variables $F$, $P$ and $\beta$, under the conditions of $P \in [(1 - \beta)C_U, \beta(1 - \alpha)C_U / \alpha]$. Let $\eta$ be the probability with which municipal government plays ‘Implement’ and $\mu$ be the probability with which a water company plays ‘Upgrade’. The equilibrium choice of $\mu^*$ is to make the municipal government indifferent between ‘Implement’ and ‘Not
implement’ so that they receive the same payoff $U$, with:

$$U = \mu [\alpha (P_0 + P) - C_0 - (1 - \beta) C_U] Q - \beta C_U Q - C_R] + (1 - \mu) [\alpha (P_0 - C_0) Q + rF - C_R]$$

$$= \mu [\alpha (P_0 - C_0 - C_U) Q] + (1 - \mu) [\alpha (P_0 - C_0) Q]$$

Similarly, the probability $\eta^*$ can be derived from:

$$\pi = \eta [(1 - \alpha) [(P_0 + P) - C_0 - (1 - \beta) C_U] Q + (1 - \eta) [(1 - \alpha) (P_0 - C_0 - C_U) Q]$$

$$= \eta [(1 - \alpha) (P_0 - C_0) Q - rF] + (1 - \eta) [(1 - \alpha) (P_0 - C_0) Q]$$

where $\pi$ is the payoff of the water company when the game reaches an equilibrium. From Equations (7) and (8), the mixed strategy equilibrium can be obtained:

$$m^* = \frac{rF - C_R}{rF + Q [(1 - \alpha) \beta C_U - \alpha P]}$$

$$\eta^* = \frac{(1 - \alpha) C_U Q}{(1 - \alpha) (P + \beta C_U) Q + rF}$$

Equations (9) and (10) suggest that the probability that the water company will upgrade facilities is $(rF - C_R) / (rF + Q [(1 - \alpha) \beta C_U - \alpha P])$ while the probability that the municipal government will implement water policies is $(1 - \alpha) C_U Q / [(1 - \alpha) (P + \beta C_U) Q + rF]$.

From Equation (9), the derivatives of $\mu^*$ with respect to $F$, $P$ and $\beta$ can be derived as Equations (11)–(13), respectively:

$$\frac{\partial \mu^*}{\partial F} = \frac{r \{C_R + Q [(1 - \alpha) \beta C_U - \alpha P] \}}{(rF + Q [(1 - \alpha) \beta C_U - \alpha P])^2} > 0$$

$$\frac{\partial \mu^*}{\partial P} = \frac{(rF - C_R) \alpha Q}{(rF + Q [(1 - \alpha) \beta C_U - \alpha P])^2} > 0$$

$$\frac{\partial \mu^*}{\partial \beta} = \frac{- (rF - C_R) (1 - \alpha) QC_U}{(rF + Q [(1 - \alpha) \beta C_U - \alpha P])^2} < 0$$

Given that $P \in [(1 - \beta) C_U, \beta (1 - \alpha) C_U / \alpha]$ and $rF > C_R$, the derivatives of $\mu^*$ with respect to $F$, $P$ and $\beta$ are positive, positive, and negative, respectively. This means that increasing the penalty (i.e. raising $F$) and water price (i.e. raising $P$) increases the probability that the water company plays ‘Upgrade’, and increasing the subsidy to the water company (i.e. raising $\beta$) reduces the probability that the water company plays ‘Upgrade’.
The derivatives of $\eta^*$ with respect to $F$, $P$ and $\beta$, respectively, can be derived from Equation (10):

$$\frac{\partial \eta^*}{\partial F} = \frac{-r(1 - \alpha)QC_U}{(1 - \alpha)(P + \beta C_U)Q + rF} < 0$$  \hspace{1cm} (14)$$

$$\frac{\partial \eta^*}{\partial P} = \frac{-(1 - \alpha)^2 Q^2 C_U}{(1 - \alpha)(P + \beta C_U)Q + rF} < 0$$  \hspace{1cm} (15)$$

$$\frac{\partial \eta^*}{\partial \beta} = \frac{-(1 - \alpha)^2 Q^2 C_U^2}{(1 - \alpha)(P + \beta C_U)Q + rF} < 0$$  \hspace{1cm} (16)$$

It is obvious that the derivatives of $\eta^*$ with respect to $F$, $P$ and $\beta$ are all negative as shown in Equations (14)–(16). This indicates that either increasing the penalty (i.e. raising $F$) or equipment subsidy (i.e. raising $\beta$) to the water company reduces the probability that municipal government plays ‘Implement’, and increasing the water price (i.e. raising $P$) also reduces the probability that municipal government plays ‘Implement’.

According to game theory, each player’s (mixed) equilibrium strategy depends upon the other player’s payoffs associated with the strategy the player has chosen. With the increase of the penalty, more water companies will play ‘Upgrade’ because of the fear of fines. With the increase of the water price, more companies will play ‘Upgrade’ for the purpose of more profits. Aware of the water companies’ strategies, the municipal government tends to reduce the probability of inspection to save expenses. However, providing subsidies will increase the government budget, which leads to negative attitudes of municipal government towards implementation. The water company realizes that the government will not implement the subsidy policy well. This may eventually lead to a lower policy efficiency. This implies that government policy makers would increase the penalty and water price to encourage water companies to upgrade their facilities while subsidy is not an efficient policy.

4. Extensions to the game model

In order to optimize the incentive policies for improving urban water supply systems, the proposed model is extended by introducing policy variables such as reputation damage of water companies, social cost of municipal government and external rewards to municipal government.

4.1. Impact of reputation damage of water companies

Recently, modern companies are paying more and more attention to their ethical responsibilities and social reputation (Alsop, 2004). Thus, the proposed model could be extended by introducing reputation damage to water companies. It is assumed that the water company that chooses to ‘Not upgrade’ will suffer a reputation damage ($D$). The new payoff matrix is shown in Table 3.

As shown in Table 3, introducing reputation damage of water companies will not change the condition of the Nash equilibrium. The new mixed equilibrium strategies of the water company and the
From Equations (17) and (18), it is found that considering reputation damage to water companies will decrease the municipal government’s probability of ‘Implement’. However, the water company’s probability of ‘Upgrade’ is not affected by reputation damage. These findings imply that if the policy makers want to affect the water company’s behavior, they should change the payoffs of municipal government.

In addition, the derivatives of $\eta_D$ with respect to $D$ is:

$$\frac{\partial \eta_D^*}{\partial D} = -\frac{1}{(1-\alpha)(P + \beta C_U)Q + rF} < 0$$

(19)

From Equation (19), increasing the reputation damage to water company reduces the probability with which municipal government plays ‘Implement’ while leaving the water company’s strategy unaltered.

### 4.2. Impact of social cost of municipal government

One limitation of the proposed model is that it does not account for the social cost of municipal government. The social cost of this study is defined as the actual or potential public loss due to water supply accidents. It is assumed that when the water company plays ‘Upgrade’, the municipal government should pay for the social cost of actual or potential public loss. The new payoff matrix is shown in Table 4.

The mixed Nash equilibrium strategy of the water company is given by:

$$\mu_S^* = \frac{rF - C_R}{rF + Q[(1-\beta)\beta C_U - \alpha P]} = \mu^*$$

(20)
Equation (20) implies that there is no change in the probability with which the water company plays 'Upgrade' by introducing the social cost of municipal government. After adding the social cost, there is no effect on the expected payoff gap of the municipal government between 'Implement' and 'Not implement'. The water company will not change its choices if it finds the equilibrium of the municipal government unchanged. This finding supports the premise assumption of the proposed model.

4.3. Impact of external reward to municipal government

In China, there is no objective assessment system of urban water supply safety for municipal governments presently. When water companies comply with the national drinking water standards, the externalities of the water supply system are indistinct and difficult to evaluate. Because of equipment subsidy, municipal government may hesitate to promote upgrading of water supply facilities. Providing external rewards for the municipal government’s subsidy, the water company’s choice may be optimized by changing the municipal government’s payoff. It is assumed that when the water company chooses to ‘Upgrade’, the municipal government will gain an external reward, $R$. The new payoff matrix is shown in Table 5.

The new Nash equilibrium of the water company is given by:

$$\mu_R^* < \frac{rF - C_R}{rF + Q[(1 - \alpha)\beta C_U - \alpha P]} - R > \mu^*$$

Equation (21) indicates that adding external motivations to the municipal government for the implementation will change the expected payoff equilibrium of the water company. The water

Table 4. The modified payoff matrix by introducing social cost ($S$).

| Water company | \begin{align*}
\text{Upgrade} & \quad \alpha \frac{(P_0 + P) - C_0 - (1 - \beta)C_U}{Q - \beta C_U} - C_R; (1 - \alpha) \\
\text{Not implement} & \quad \alpha \frac{(P_0 - C_0 - C_U) Q; (1 - \alpha) (P_0 - C_0 - C_U) Q}{Q - \beta C_U}
\end{align*} |
|---|---|
| Municipal government | Implement | \begin{align*}
\text{Upgrade} & \quad \alpha \frac{(P_0 + P) - C_0 - (1 - \beta)C_U}{Q - \beta C_U} - C_R; (1 - \alpha) \\
\text{Not implement} & \quad \alpha \frac{(P_0 - C_0 - C_U) Q; (1 - \alpha) (P_0 - C_0 - C_U) Q}{Q - \beta C_U}
\end{align*} |
| Not implement | \begin{align*}
\text{Upgrade} & \quad \alpha \frac{(P_0 - C_0 - C_U) Q; (1 - \alpha) (P_0 - C_0 - C_U) Q}{Q - \beta C_U} + rF - C_R - S; \\
\text{Not implement} & \quad \alpha \frac{(P_0 - C_0) Q - S; (1 - \alpha)}{Q - \beta C_U}
\end{align*} |

Table 5. The modified payoff matrix by introducing external reward ($R$).

| Water company | \begin{align*}
\text{Upgrade} & \quad \alpha \frac{(P_0 + P) - C_0 - (1 - \beta)C_U}{Q - \beta C_U} - C_R; (1 - \alpha) \\
\text{Not implement} & \quad \alpha \frac{(P_0 - C_0 - C_U) Q; (1 - \alpha) (P_0 - C_0 - C_U) Q}{Q - \beta C_U}
\end{align*} |
|---|---|
| Municipal government | Implement | \begin{align*}
\text{Upgrade} & \quad \alpha \frac{(P_0 + P) - C_0 - (1 - \beta)C_U}{Q - \beta C_U} - C_R; (1 - \alpha) \\
\text{Not implement} & \quad \alpha \frac{(P_0 - C_0 - C_U) Q; (1 - \alpha) (P_0 - C_0 - C_U) Q}{Q - \beta C_U}
\end{align*} |
| Not implement | \begin{align*}
\text{Upgrade} & \quad \alpha \frac{(P_0 - C_0 - C_U) Q; (1 - \alpha) (P_0 - C_0 - C_U) Q}{Q - \beta C_U} + rF - C_R - S; \\
\text{Not implement} & \quad \alpha \frac{(P_0 - C_0) Q - S; (1 - \alpha)}{Q - \beta C_U}
\end{align*} |
company’s probability of ‘Upgrade’ is increased by introducing external rewards to municipal government. And it is helpful to achieve the optimal policy condition as shown in Equation (3).

The derivatives of $\mu_R$ with $R$ is:

$$\frac{\partial \mu_R}{\partial R} = \frac{rF - C_R}{\{rF + Q(1 - \alpha)\beta C_U - \alpha P\} - R} > 0$$  \hspace{1cm} (22)

From Equation (22), it can be determined that increasing the reward to the municipal government’s investment in incentive policies increases the probability that the water company upgrades its water supply facilities. Therefore, it is effective to provide external rewards to municipal government for encouraging the upgrading of water supply facilities.

5. Empirical analysis

In this section, empirical analyses from three Chinese urban water companies are presented. The purpose is to analyze the actual conditions of water policies using the models established in previous sections within a realistic, numerical framework. As typical Chinese cities, Guangzhou, Wuhan and Shanghai are applicable for the proposed model. The data on municipal government are obtained from the official website of the national and regional water affairs sectors. And the data on water companies come from Guangzhou City Water Supply Cost Auditing Report (2012), Wuhan City Water Supply Cost Auditing Report (2012) and Shanghai Water Supply Cost Auditing Report (2012), respectively. The collected data are presented in Table 6.

Take Guangzhou, for example: the current payoff matrix between a municipal government and a water company is presented in Table 7. Under the current policy conditions, the unique and stable Nash equilibrium is (Implement, Upgrade). Water companies will upgrade facilities actively and municipal government will implement the penalty and price policies. However, it is necessary to discuss whether the optimal combination of policies has been achieved. The impact of the policy variables ($F$, $P$ and $\beta$) on the equilibrium of the model is discussed in detail below.

Table 6. The collected data from empirical studies.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Guangzhou</th>
<th>Wuhan</th>
<th>Shanghai</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$ (m³)</td>
<td>$1.19 \times 10^9$</td>
<td>$6.01 \times 10^9$</td>
<td>$1.72 \times 10^8$</td>
</tr>
<tr>
<td>$C_0$ (Yuan/m³)</td>
<td>1.57</td>
<td>1.02</td>
<td>1.51</td>
</tr>
<tr>
<td>$C_U$ (Yuan/m³)</td>
<td>0.45</td>
<td>0.30</td>
<td>0.62</td>
</tr>
<tr>
<td>$P_0$ (Yuan/m³)</td>
<td>1.78</td>
<td>1.10</td>
<td>1.63</td>
</tr>
<tr>
<td>$P$ (Yuan/m³)</td>
<td>0.89</td>
<td>0.45</td>
<td>0.85</td>
</tr>
<tr>
<td>$C_R$ (Million Yuan)</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F$ (Million Yuan)</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta$ (%)</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$ (%)</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r$ (%)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.1. Policy impact of penalty

The effects of the penalty for water companies on $\mu^*$ and $\eta^*$ are presented in Figure 2. The impact of the penalty for water companies in Guangzhou, Wuhan and Shanghai are presented in Figures 2(a), 2(b) and 2(c), respectively.

As shown in Figure 2, the water company’s probability of ‘Upgrade’ ($\mu^*$) increases with increased penalty. The municipal government’s probability of ‘Implement’ decreases as the penalty increases. Take Guangzhou for example: at the range of 0.1 to 20 million Yuan, the increase of the penalty will rapidly increase the probability of ‘Upgrade’. Thus, a penalty within this range is a useful and efficient policy to encourage upgrading of water supply facilities. When the penalty reaches 20 million Yuan, the impact of the penalty on the water company’s probability of upgrading is weaker and weaker. However, even with the presence of a heavy penalty, it cannot be assured that all water companies will upgrade their facilities. As shown in Figure 2(a), the current penalty level (0.3 million Yuan) is too low. Figure 2(a) suggests that the current penalty level for the Guangzhou’s water company should be raised to 20 million Yuan. This result is consistent with the other two analyses in Figures 2(b) and 2(c). Due to the different scales of water supply, the optimal penalty is different for each water company. For the water company in Wuhan, the penalty should be raised to 50 million Yuan. However, the optimal penalty for the water companies in Shanghai is about 4 million Yuan.

5.2. Policy impact of subsidy

Under the conditions of $P \in [(1 - \beta)C_U, \beta(1 - \alpha)C_U/\alpha]$, $\beta$ must be higher than 0.25. The dependence of $\mu^*$ and $\eta^*$ on the subsidy is shown in Figure 3. The impacts of subsidy for water companies in Guangzhou,
Wuhan and Shanghai are presented in Figures 3(a), 3(b) and 3(c), respectively. From Figure 3, both $\eta^*$ and $\mu^*$ decrease with the increase of equipment subsidy. Thus subsidy policy is not useful for encouraging upgrading of water supply facilities. Municipal governments could share the upgrading cost by offering a subsidy to reduce the water price increase, while the rate of equipment subsidy should be less than 30%.

5.3. Policy impact of water price adjustment

The influence of water price increase ($P$) on $\mu^*$ and $\eta^*$ under different scenarios shown is analyzed in Figure 4. The impacts of a water price increase for water companies in Guangzhou, Wuhan and Shanghai are presented in Figures 4(a), 4(b) and 4(c), respectively. Figures 4(a)–4(c) all indicate that increasing water price will increase the water company’s probability of ‘Upgrade’ ($\mu^*$) and decrease the municipal government’s probability of ‘Implement’ ($\eta^*$). Thus, water price adjustment is an efficient and necessary policy to encourage water companies to upgrade equipment.

The impact of both water price increase and subsidy is discussed in the case of the water company in Guangzhou. Under the conditions of $P \in [(1 - \beta)C_U, \beta(1 - \alpha)C_U/\alpha]$ and $F = 20$ million Yuan, the
impact of water price increase ($P$) and subsidy ($\beta$) on the water company’s probability of ‘Upgrade’ ($\mu^*$) are shown in Figure 5. Given a small scale of subsidy (close to 25%), the water company’s probability of ‘Upgrade’ would be up to 90% by increasing water price modestly (about 0.4 Yuan). However, the influence of water price increase on the probability of upgrading declines as the subsidy increases. The more subsidy municipal government provides to water companies, the higher level of water price increase is needed and the lower the probability of ‘Upgrade’ is. Therefore, water price adjustment is an efficient policy to encourage equipment upgrading, and the effectiveness of water price policy is affected by subsidy.

5.4. Policy impact of external reward to municipal government

The dependence of $\mu^*$ and $\eta^*$ on the external reward to municipal government is presented in Figure 6. The impact of external reward to the municipal governments of Guangzhou, Wuhan and Shanghai are shown in Figures 6(a), 6(b) and 6(c), respectively.

As shown in Figures 6(a)–6(c), the water company’s probability of ‘Upgrade’ is increased with the external reward to municipal government. However, the municipal government’s probability of ‘Implement’ is independent of the reward for it. Thus, it is useful to provide external reward to municipal government for implementation. Moreover, once the municipal government is given enough reward for its implementation, it will choose to implement regardless of the choice of the water company. Take Guangzhou for example: if the reward exceeds 112 million Yuan, the Nash equilibrium becomes (Implement, Upgrade).

6. Discussion and policy implication

Penalty, subsidy and adjustable water price are always considered as three common policy instruments to ensure urban water supply safety and reliability. However, this research provides interesting implications of these policies for governments and for water companies to choose different strategies regarding water supply facilities based on a game theoretical model.
In agreement with other authors (Tapiero, 2004, 2005; Zhao et al., 2012), this study confirms that penalty is a useful incentive measure to promote upgrading of water supply facilities. This implies that all water companies are obliged to internalize the costs of treatment required to fulfill the standards for drinking-water quality under the threat of suffering sanctions that range from fines to judicial penalties (at the limit, forbidding activities and arresting the responsible people). Doubtlessly, from the standpoint of complying with the standards, the penalty policy may be effective, in direct proportion with the efficiency of the inspection apparatuses and the flexibility of the judiciary power. However, it presents a low economic efficiency, since there is no mechanism that takes investment demands into account. In addition to the difficulties in implementation and operation, there are problems when the cost–benefit relations of this policy are taken into account.

Urban water supply activities are currently subsidized directly by government spending programs and indirectly by deductions, allowances and credits in China and many other countries. Previous studies indicated that subsidy provides economic incentives for agents to apply new technologies or participation in environmental programs (Zekri, 2008; McGilligan et al., 2010). Heumesser et al. (2012) applied a stochastic dynamic programming model to analyze a farmer’s optimal investment strategy to adopt water-saving irrigation technologies. They found that investment is unlikely unless subsidies for equipment cost are granted. Finger & Lehmann (2012) analyzed policy effects on water-saving irrigation technologies in Switzerland. This study found that subsidies may have crowding-out effects and the implementation of increased water prices would lead to a sustainable increase in the share of water-saving technologies. From previous studies, the incentive effect of subsidy is ambiguous and complicated. In this research, an agent’s behavior depends on both its own interests and its interactions with other stakeholders and the environment under the constraints of market prices and economic incentives (penalty/subsidy). The analysis revealed that subsidy itself is not a useful policy to promote water facility upgrading. This result is similar to the research by Dong et al. (2010). Therefore, it is suggested that municipal governments could share the upgrading costs by offering a subsidy to minimize the water price increase. However, the lower the subsidy the better. In addition, the limitation of subsidy policy can be made up by providing external rewards for municipal government’s implementation from the national government.

Water pricing is an important management tool that can be used to assist with the management of urban water supply systems (Whittington, 2003). However, there is little consensus on municipal...
water price issues because of the disagreement over the objectives of water pricing and tariff design. Water pricing decisions affect several different objectives or goals of stakeholders, often in conflicting ways. Water companies expect a higher water price for profit-seeking, while consumers wish to keep a low-level water price. And governments should balance the interests of water companies and consumers to maximize social welfare. To our knowledge, previous studies failed to consider the adjustable price policy in the regulatory game model. However, water price is a key factor which affects strategies of water supply stakeholders. In this study, it is proved that water price adjustment is an efficient policy to encourage upgrading of water supply facilities and to improve urban water supply safety. The traditional debate in water pricing that focuses on keeping a low price would have to shift to how to distribute ‘excess costs’ generated by upgrading water supply facilities. Nevertheless, the water prices in China are still too low to provide a significant boost in revenue and to cover the investment and operation costs of urban water supply systems. There exists a huge gap between the costs required to maintain the operation of existing water supply systems and the revenues generated through the existing water pricing system and other sources to match the growing demand for more reliable and safe urban water supply. Therefore, a series of reforms would be required to attempt to define administered water prices to improve water supply safety. It is imperative to overcome the technical and political obstacles to marginal cost-based pricing.

With the goal of reducing costs, municipal government could encourage upgrading of water supply facilities by increasing the penalty or raising the water price. The subsidy provided by municipal government should be kept at a low level. However, in order to maximize social welfare, municipal government is required to keep the water price socially acceptable. Therefore, municipal government could offer a small scale of subsidy (close to the tax rate) to share the upgrading cost. Water price increase is a useful policy to encourage water companies to upgrade their facilities. But the water price increase could not be higher than the unit cost of upgrading that is not covered by the subsidy. In addition, providing external rewards for municipal government’s subsidy is a useful policy. Overall, in order to promote upgrading of water supply facilities, it is efficient to increase the penalty and raise the water price while a subsidy is not used.

7. Conclusion

Regarding urban water supply safety and reliability, upgrading of water supply facilities should be paid more and more attention. Essentially, substantial financial efforts are needed to repair, rebuild and adapt the existing water supply facilities to new standards. However, the water companies’ profit-seeking motive seems difficult to reconcile with upgrading water supply facilities actively. This implies that government has both the capacity and the duty to guide water companies’ behavior and ensure water supply safety. It is suggested that the key role of regulatory mechanisms and efficient policies could coordinate the interests of key stakeholders and further affect their strategies.

In this paper, a game model between municipal government and a water company has been developed to analyze their conflicts of interests and to optimize the strategy for upgrading water supply facilities. The optimal combination of policies based on penalty, subsidy and water price increase is achieved. A mixed-strategy game-theoretic model is used to analyze how the regulation and incentive policies would affect the strategies for water companies to upgrade water supply facilities. In addition, the model is extended by adding some policy variables, such as reputation damage of water companies, social
cost of municipal government and external rewards to municipal government, to change the strategies of municipal government or the water company.

It is concluded that raising the water price or increasing the penalty could encourage water companies to upgrade their facilities, but decrease the probability of ‘Implement’ by municipal government. The increase of subsidy will both decrease the probability of implementation and the probability of upgrading facilities. It is suggested that penalty is an effective measure to promote upgrading of water facilities. Yet it cannot ensure that all water companies will upgrade their facilities. Water price increase is a necessary policy to ensure water companies upgrade their facilities efficiently. However, subsidy policy is not useful to encourage upgrading of water supply facilities.

In order to achieve the policy goals that the municipal government implements fully and for water companies to upgrade actively, the water price increase should be equal or more than the maximum between the unit upgrading cost of the water company and the unit upgrading cost shared by municipal government. At this point, the municipal government’s optimal strategy is ‘Implement’. And regarding water companies, upgrading water supply facilities is their optimal strategy. Under the optimal policy conditions, the optimal subsidy rate is equal to the tax rate while the optimal water price rise is equal to the unit cost of upgrading paid by water companies. In order to minimize the water price increase, municipal governments share the upgrading cost by offering subsidy. Yet subsidy policy is not useful to promote water companies upgrading their facilities.

By extending the proposed model, it is found that the strategy of water supply facilities upgrading is not affected by reputation damage of water companies and social cost of municipal government. It is suggested that providing external rewards for the municipal government’s subsidy is useful and effective to encourage upgrading of water supply facilities. If the municipal government is given enough reward for its implementation, ‘Implement’ is the optimal strategy for municipal government. And water companies’ optimal strategy is upgrading their facilities.

The empirical analysis shows that the current policies can encourage water companies to upgrade their facilities. However, the current penalty level is too low. And the optimal penalty is different for each water company. Water price adjustment is an efficient policy to encourage equipment upgrading, and the effectiveness of water price policy is affected by subsidy. If municipal government provides a small scale of subsidy (less than 30% of upgrading cost), the increase of the water price could be lower.

This research focuses on the strategies of key stakeholders for urban water supply systems and management. One limitation of this study is that the proposed model is applicable to the Chinese urban area which has been covered by centralized water supply systems. The applications of the model to rural water supply and other countries could be investigated in further research. Second, the game model for encouraging water companies to upgrade facilities is played only once by a municipal government and a single potentially unqualified water company whose water supply quality is below the standard requirement. However, municipal government is typically involved in sequences of the inspection game, either with the same or with different companies. These should be discussed in further studies.

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