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Residential Water Use: Efficiency, Affordability, and Price Elasticity

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Abstract In practice, water pricing is the main economic instrument used to discourage the wasteful use of residential water. Owing to considerations of affordability, residential water is systematically underpriced because water is essential for life. Such a low price results in water being used inefficiently. This paper proposes a system that supplements the existing price system with a cap-and-trade measure to reconcile conflicts among the goals of residential water use. It forces all people (independent of income) to be faced with reasonable price signals and to use water efficiently. The poor could, however, gain from trade and afford water. By taking advantage of the agent-based model, a simulation of this system applied to Taipei, Taiwan shows that those with lower income per capita are better off under this system even though the equilibrium price of residential water is higher. The simulated average price elasticity of market demand is −0.449.

Keywords Residential water · Efficiency · Affordability · Water pricing · Cap and trade · Price elasticity · Agent-based model

1 Introduction

Water is essential for life. The supply of water is, however, insufficient and it is becoming increasingly scarce in terms of meeting all of the demand for it (WWDR2 2006). Since the water supply for domestic use in general takes priority over other water usages, other water uses will be inefficient if residential water is not used efficiently. Thus, this paper will focus on the demand-side management and estimation in the case of residential water among all water uses.

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Around the world, water pricing is the main economic incentive instrument used to charge for residential water and to discourage its wasteful use.[1] There is a large literature that has studied the estimation of residential water demand and has mainly focused on the estimation of price elasticity. Different issues regarding the estimation have been explored, including the following topics: whether the average or the marginal price combined with the difference variable should be used as the price variable in the demand equation (see, e.g., Taylor 1975; Nordin 1976; Foster and Beattie 1979, 1981a, b; Billings and Agthe 1980; Billings 1982; Nieswiadomy and Molina 1989; Nieswiadomy 1992; Renwick and Archibald 1998; Shin 1985; Opaluch 1982, 1984; Taylor et al. 2004), model specification and functional forms of the demand equation (linear, logarithmic, Stone-Geary, or discrete/continuous choice models among others) (see, e.g., Gaudin et al. 2001; Martínez-Espiñeira and Nauges 2004; Hewitt and Hanemann 1995; Olmstead et al. 2007; Olmstead 2009), the meta-analysis of various research estimates (Espey et al. 1997; Dalhuisen et al. 2003), and country case studies (see, e.g., Martínez-Espiñeira 2003; Reynaud et al. 2005; Schleich and Hillenbrand 2009; Miyawaki et al. 2011; Dharmaratna and Harris 2012; Rinaudo et al. 2012). In comparison with the above research, the literature that is directed towards institutional reforms of residential water management is relatively small and mainly focuses on the pricing system design (see e.g., Elnaboulsi 2001; Hall 2001; Boland and Whittington 2001; Krause et al. 2003; García-Valiñas 2005; Barberán and Arbués 2009).

Charging for water serves multiple purposes regarding water use, including the user pays principle, equity and efficiency in water use, an increase in quality, the financial soundness of the water utility, and affordability for the poor. However, these purposes are not reconciled. For example, a higher price may increase the efficiency of water use and utility revenue, but it may also make water unaffordable to the poor. Owing to the consideration of affordability and the pressure from the demand side, water is "systematically underpriced by suppliers" (Griffin 2006) and the price cannot reflect all the costs of producing it. The lower price causes water to be used inefficiently and renders its production costs irrecoverable.

Differing from the above reforms in the use of pricing systems, this paper proposes a price-cum-trade incentive system (PTS hereafter) to reconcile the multiple purposes of residential water use (in particular efficiency and affordability). Nowadays, cross-subsidization is generally applied by the regulator to harmonize the dilemma. Under this measure, the water utility charges low income groups and most residences below-average rates, but charges industrial and commercial users above-average rates to make up the difference. There are, however, some problems which may arise from the cross-subsidization. First, a cross-subsidy policy sends wrong signals to both the utility and consumers. The over-consumption by subsidized customers and the loss of sales to the subsidizing customers are both inefficient and result in welfare losses to the society. Second, such a policy violates the principle of fairness. In addition, cross-subsidization frequently

[1] "Two scarcity-addressing strategies dear to water resource economists are water marketing and water pricing. *Marketing* is a management policy for natural water, whereas *pricing* pertains to partially- or fully-processed (retail) water." (Griffin 2006, p. 203). There are many existing rate systems for water utilities both in theory and practice such as flat pricing, marginal cost (MC) pricing, average cost (AC) pricing, the rate-of-return regulation, Ramsey pricing, peak-load pricing, block-rate pricing, price-cap regulation, spot market pricing, and effective water pricing. In general, if the pricing system has or tends to have the characteristic of MC pricing, it results in a higher economic efficiency. However, because the water utility is basically a natural monopoly, it will experience a loss under MC pricing and will exit the market in the long run. Instead, if the pricing system has or tends to have the characteristic of AC pricing, the natural monopoly will not experience a loss, but the economic efficiency of the society will be lower. In addition, the water utility might produce water inefficiently because its costs can be recovered anyway.

leads to serious financial losses for utility companies. Although raising tariffs is an option, it is difficult in practice to set cost recovery tariffs.

The PTS is based on the existing price-incentive system but also allows the water users to trade the water rights to which they are entitled. In theory, price and the right market are both economic-incentive instruments and can be used individually to attain the optimality under certainty. While pricing is mainly used for residential water management, marketing is applied for natural water management. Several countries, such as the United States, Australia, Chile, and South Africa, have adopted the water market as an alternative to water allocation (Hadjigeorgalis 2009). In addition, the system of a right market is also widely applied for managing various pollutants and renewable resources.[2] However, due to the constraints, imperfections, and uncertainty in the real world and the possible multiple failures or purposes, a policy mix (the use of multiple policies) may be superior to single policies. Hybrid policies have been studied in the literature for many years. Roberts and Spence (1976) and Weitzman (1978) are, for example, two important early works. For the rationales and examples, one can see the survey of Lehmann (2012).

By combining the pricing and cap-and-trade systems, the PTS has the following positive characteristics. First, a cap design of residential water is used to take environmental sustainability into consideration.[3] Second, the allocation of initial water rights to individuals can be used to take equity into account. Third, trading forces everyone, independent of income, to face the market equilibrium price—the right price signal for water. However, the affordability problem disappears. This is because the one who uses less water than what is entitled to use can earn money by selling extra water at the market price. A poor person can either save water to sell and make money, or he can pay the existing price to use the water to which he is entitled (he is no worse off than under a pure price system). In addition, because the poor and water-saving people can earn money, the problems of resistance to a higher water price and systematic under-pricing are alleviated. Fourth, under the PTS, the market equilibrium price can adjust on its own quickly and flexibly to reflect changes in the scarcity of water. However, under the price system the regulator needs to have perfect information in order to set the optimal price system and these prices are not easily adjustable. Fifth, the water utility could benefit by drawing a share of the trade balance as its revenue.

In this paper, we also use a survey data set at the household level for Taipei to specify an agent-based model in order to study the application of the PTS system.[4] By using the agent-based model, we simulate the market equilibrium price of residential water and discuss the change of the income distribution of households. The simulated data for price and quantity are further used to estimate the price elasticity of market water demand. These research results are seldom studied in existing papers and can provide insights for residential water management.

[2] For example, the Kyoto Protocol introduced three market-based mechanisms (Emissions Trading (ET), the Clean Development Mechanism (CDM), and Joint Implementation (JI)) which created the carbon market. Many countries apply the cap-and-trade system to control their CO_2 emissions. The emissions trading markets are also implemented for SO_2 and NOx control in the US (see the Acid Rain Program and the Regional Clean Air Incentives Market (RECLAIM)). In addition, for the promotion of renewable power, a renewable portfolio standard (RPS) which specifies targets and deadlines for producing specific proportions of electricity from renewable resources coupled with transferable energy certificates (TEC) which could lower compliance costs is applied in the EU and US. There are also advocates for applying the cap-and-trade system for fishery. This could be done by first setting a strict catch limit and distributing total catch shares to fishermen. Fishermen can then buy and sell their shares.

[3] Regarding the discussion of the environmental sustainability of residential water, see Krause et al. (2003).

[4] For more information regarding the agent-based modeling, please visit this website (http://www.econ.iastate.edu/tesfatsi/).

In the next section, we shall describe the design of the price-cum-trade incentive system and analyze its characteristics of efficiency and affordability. In Section 3, the agent-based PTS model is specified. The price elasticity of residential water demand is estimated and the post-trading income distribution of households is explored. In Section 4, a further analysis on the application and viability of the PTS is discussed. Lastly, in Section 5 we provide the conclusion.

2 The Price-cum-Trade Incentive System

We design the PTS as follows:

1. Suppose that under the existing price system, the unit water price is P_0.[5]
2. The minimal level of water supply for basic life support per capita, the basic water requirement, is $\underline{q}$, which cannot be traded.
3. Suppose that the cap of residential water is $\overline{Q}$, which is converted to a corresponding amount of water rights.[6]
4. The regulator allocates $\overline{Q}$ to individual water users, who are denoted by $i=1,\ldots,n$. Suppose that each individual water user obtains $\overline{q}^i$ units of rights, $\sum_{i=1}^{n} \overline{q}^i = \overline{Q}$. It should be noted that $\overline{q}^i$ is a usufructuary right. By this we mean that $\overline{q}^i$ is not a property right. A water user should pay the unit price P_0 to enjoy the water to which he is entitled by the right.
5. Individual water users can trade $\overline{q}^i$ with each other freely. When the market equilibrium price $P^* > P_0$, the user who sells his usufructuary rights can earn a profit from the price spread $(P^* - P_0)$.
6. The compliance condition for an individual water user at the end of each period is: $\underline{q} \leq$ the amount of water he consumed $\leq$ the amount of water rights he owns.

Let us examine the PTS in detail. First, $\overline{Q}$ is the cap for residential water which is usually determined by the total amount of water rights for residential use. $\overline{Q}$ can be used to consider the environmental value and sustainable use of water as well. When water is scarcer, for example, the regulator could set a smaller amount of $\overline{Q}$. The market equilibrium price will therefore be higher and reflect the scarcity of water. In general, the existing price systems could not reflect the actual value of water appropriately and flexibly. The initial allocation of $\overline{Q}$ is related to the income distribution but unrelated to efficiency. For household water consumption, the initial quantity might be allocated equally to every person.[7] Of course, every society could apply its own appropriate approach to allocate water.

Second, water is systematically underpriced in practice regardless of the price systems adopted. The PTS can, however, help force everyone to face a higher market price while the poor are made better off. This is demonstrated in Fig. 1, which is a simple example with two water users. In Fig. 1, the demand curves for water for users 1 and 2 (D_1 and D_2) are drawn

[5] For simplification, we adopt a flat price case for ease of explanation. Different rate structures can be applied as well.

[6] Suppose that one unit of water rights deserves one unit of water.

[7] It should be noted that residential water demand is influenced by the household size and there might be a phenomenon of scale economies in consumption. That is, the increase in water use is often less than proportional to the increase in household size (see, e.g., Arbués et al. 2003 and Arbués et al. 2010). Thus, if the scale economies exist, equal allocation would benefit people who live in large households over those in small households.

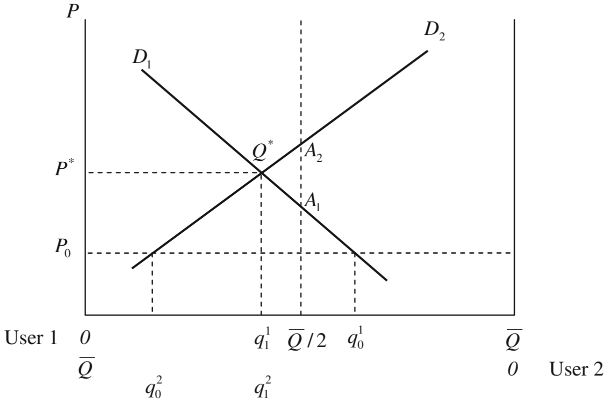

Fig. 1 The equilibrium of the water market

from the left-hand and right-hand axes, respectively. The cap of residential water is $\overline{Q}$ and the existing unit water price is P_0. At P_0, the quantities of water demanded by users 1 and 2 are q_0^1 and q_0^2, respectively. It is easily seen that $q_0^1 + q_0^2 > \overline{Q}$. Supposing that $\overline{Q}$ is an appropriate amount of water which takes into account the sustainable use, the above inequality then indicates that the price of residential water is not sufficiently high to allow the water to be used efficiently.

If the regulator somehow allocates $\overline{Q}$ equally to users 1 and 2, i.e., $\overline{q}^1 = \overline{q}^2 = \overline{Q}/2$, at the quota $\overline{Q}/2$, the marginal willingness to pay of user 2 (A_2) is higher than that of user 1 (A_1). Both users therefore have an incentive to trade. The trading would take place until the marginal willingness to pay of each user is equal. At point Q^*, the water market is in equilibrium. If user 1 is poor, we see that he could earn a profit of $\left[\left(P^* - P_0\right)\left(\overline{Q}/2 - q_1^1\right)\right]$ by saving and selling water. A very important part of the trade is that both the rich and the poor face the correct price signal and both gain from trade. A correct signal would force people to use water efficiently and save water. In addition, the regulator does not need any information to set the equilibrium price. This is, however, a difficult task under a pure price system.[8]

In the long run, because people would improve their household appliances to save water, the total amount of water used by the society will decrease. Moreover, the water industry might possibly be further developed because of the commonly active water saving behavior of people.[9]

3 The Agent-based PTS Model

In this section, we will specify an agent-based PTS model based on a survey data set at the household level. We will first describe the data set and use the Stone-Geary utility function to take into account major demand variables including the water price, income, the

[8] Existing rates are generally dependent on historical data and are very difficult to adjust to reflect the current situations because of the considerations of affordability for the poor, political commitments, and pressure from water users (the pressure is even higher when the overall economic situation is aggravated).

[9] Governments usually apply measures which encourage the renewal of water-saving facilities in government and schools to help save water and to promote the water industry. Such measures do not influence people's customs when using water, however. People are only passive when saving water and the development of the water industry heavily depends on subsidies from the government.

subsistence level of water use, and household characteristics. The estimated water demand equation is then used to calibrate the water use behavior of the household. The discussions of equilibrium, income distribution, and price elasticity follow thereafter.

3.1 Data Description

The data used in this paper consist of the original sampling data from the “Report on the Family Income and Expenditure Survey” in Taipei, Taiwan.[10] The survey is a nationwide questionnaire completed annually by Taiwan’s central and local governments and contains data on income, household characteristics, and water expenditure, etc., all at the household level. It is interesting to study the case of Taiwan because water is in fact a scarce resource in Taiwan and thus ought to be used very efficiently.[11] The price system for residential water is, however, one that is under-priced and has not been adjusted since 1994. The lower water price system not only results in inefficient water use, but the goals of financial soundness in terms of water utility, equity, and environmental sustainability can not as a result be attained.[12]

In the whole original sample, we use the data of Taipei City for the year 2005. This is mainly because, first, almost all people in Taipei are served by tap water (the percentage of population served was 99.5 % in 2005). Second, the survey in 2005 is the most newly-accessible and reliable sample for water use behavior. After 2005, the reported water expenditure includes both payments for tap water and certified trash bags so that an empirical researcher cannot distinguish between them. Since the price system for residential water has been frozen for almost two decades, behavior in terms of residential water use may have changed little in recent years.

Based on this survey, after removing missing data and outliers we have data for 1,985 households. Due to the fact that water billing accumulates bimonthly, we rescale our data into bimonthly form. Table 1 presents the descriptive statistics of average price and bimonthly disposable income, water expenditure, and water consumption.[13] It is worth noting that the expenditure-income ratio is relatively low in Taipei.

3.2 The Stone-Geary Demand Function

In the literature, linear, double log, and Stone-Geary functional forms are the most commonly employed specifications of demand functions. While the linear demand function is easy to

[10] Taiwan is a newly-industrialized Asian economy with a population of 22.77 million persons and a GDP per capita based on purchasing-power-parity (PPP) of US$ 27,572.22 in 2005 (see the World Economic Outlook Database, International Monetary Fund). Taipei is its capital.

[11] Taiwan is mountainous and the distributions of rainfall and runoff are very uneven. Rivers are also relatively short and steep so that the precipitation is very hard to store for subsequent utilization. The groundwater is overused which has resulted in the problem of land subsidence in some places. Since there is a large population, the annual available water per capita (TARWR per capita 2005) in Taiwan is only 2,930 m^3/year (see Table 4.3 in WWDR2 2006).

[12] The amount of water used in Taipei is 340 l per capita per day, which is the 9th highest amount among approximately 100 cities surveyed by IWA (2010).

[13] The figures for water consumption are calculated from the data on water expenditure and the rate structure in Taipei. The rates (NT$/$M^3$, monthly per household) are 5, 5.2, 5.7, 6.5, and 7.6 for water consumption blocks of 1–20, 21–60, 61–200, 201–1000, and 1001^+ cubic meters, respectively. There are two data adjustments that should be noted. First, in practice, a sewer fee of NT$5 is charged for each cubic meter of water consumption in addition to the unit fee of water. This sewer fee is considered in this paper. Second, the magnitude of the fixed cost is related to the diameter of the water meter. Because we don’t have this data for each household, we assume that the diameter form of the meter applied by all households is 20 mm, the most popular form in Taipei.

Table 1 Descriptive statistics of variables

Variable	Description	Unit	Mean	SD	Median	Max.	Min.	Skew.
I	Disposable income	NT$	206440	119086	180554	1386616	11762	2.01
WE	Water expenditure	NT$	683.57	325.02	600	4000	150	1.99
α	Expenditure-Income ratio (=WE/I)	%	0.41	0.28	0.35	4.96	0.04	4.36
q_w	Water consumption	M^3	54.31	31.68	46.30	367.50	1.40	1.87
p_w	Average price (=WE/q_w)	NT$/$M^3$	13.76	3.92	12.96	107.14	10.88	9.72
N	Household size	person	3.15	1.32	3	9	1	0.28
H	House size	M^2	101.32	40.12	99.17	495.87	9.92	1.91

estimate and the estimated coefficients of income and price represent elasticities in double-log functional form, one of the advantages of the Stone-Geary function is that a minimum amount of water demand, irrespective of prices, can be estimated. This amount of water is viewed as the estimate of the subsistence level or the basic water requirement. Since this is a key piece of information which represents the quantity of $\underline{q}$ that is not allowed to be traded under the PTS, we will apply the Stone-Geary utility function form to derive the demand for water equation.

The Stone-Geary utility function is

$$U = (q_w - \gamma_w)^{\alpha}\left(q_y - \gamma_y\right)^{1-\alpha}, \tag{1}$$

where U denotes the level of utility, q_w and q_y are respectively the consumption of water and the composite good, α is the ratio of water expenditure to disposable income, and γ_w and γ_y represent the subsistence consumptions of water and the composite good, respectively. In considering the individual household disposable income I, water price p_w, the price of the composite good p_y, and utility function 1, we derive the following optimal consumption bundle of water:

$$q_w = \gamma_w + \frac{\alpha}{p_w}\left(I - \sum_{\forall k} p_k \gamma_k\right), \tag{2}$$

in which $k = \{w, y\}$. By assuming the composite good is the numeraire (p_y=1) and letting γ_y=0 to focus on water consumption, we can simplify the above consumption bundle 2 to

$$q_w = \gamma_w + \frac{\alpha}{p_w}(I - p_w\gamma_w) = (1-\alpha)\gamma_w + \alpha\frac{I}{p_w}. \tag{3}$$

The main advantages of the Stone-Geary specification are that the estimated elasticities are non-constant along the demand curve and it uses only two parameters which have economic meaning. Specifically, α is the marginal budget share of water and γ_w represents a threshold below which consumption may not be responsive to prices (see Gaudin et al. 2001; Martínez-Espiñeira and Nauges 2004).

In this paper, average price is treated as the price variable and is obtained as a result of dividing water expenditure by water consumption. The average price, and not the marginal price combined with the difference variable, is used because the cost of water is relatively low compared to disposable income and the price system as applied in Taipei is complicated. This price system consists of a fixed fee and five increasing block rates. It is therefore impossible for people to know exactly the marginal price level they are applying.[14] According to demand theory, it is expected that the price elasticity of demand is negative and inelastic due to the lack of substitutes for water. Household income is expected to have a positive effect on water consumption because water is a normal good. Estimates of income elasticity in the literature are commonly small and inelastic.[15]

For the empirical estimation of water demand, the explanatory variables in general include weather and seasonal factors, population and household composition, and other control variables in addition to the water price and household income in Eq. 3 (see, for example, the surveys of Worthington and Hoffman 2008 and Arbués et al. 2003). Here, we explicitly consider two household characteristics, the number of household members (*N*) and house size (*H*), as the explanatory variables for water consumption.[16] Because water is essential to life, it is expected that the coefficient of *N* is positive. That is, more family members would increase the total water consumption of the household. The coefficient of *H* is expected to be positive, too. This is because a household with a larger area may need more maintenance efforts which consume water. It should be noted that climate variables are not included because households in this area share the same climatic environment. The definitions and descriptive statistics of variables are presented in Table 1.

We conduct the OLS regression. The estimate of the water demand equation yields (t-ratios in parentheses):

$$q_w = \underset{(6.962)}{14.577} + \underset{(10.840)}{0.00082}\frac{I}{p_w} + \underset{(11.926)}{6.465}\,N + \underset{(3.688)}{0.062}\,H + \varepsilon,\ \overline{R}^2 = 0.24 \tag{4}$$

According to the estimates, the subsistence level of water is calculated as $14.589\times(= 14.577/(1-0.00082))$ cubic meters per household bimonthly and, equivalently, the minimal daily water consumption per person is about 77.19 l.[17] The estimated price elasticity (η_p) and income elasticity (η_I) at the sample mean are −0.23 and 0.23, respectively. They have the same magnitude and opposite signs and can be derived by $\eta_p = -\eta_I = -\overset{\wedge}{\alpha}\,\times$

[14] One can see, e.g., Martínez-Espiñeira (2003) for the reason and comparison of applying different price specifications.

[15] Based on a review of 24 journal articles published between 1967 and 1993, Espey et al. (1997) indicated that the price elasticity estimates range from −0.02 to −3.33 in the sample, with an average of −0.51. About 90 % of the estimates are between 0 and −0.75. Dalhuisen et al. (2003) reviewed 64 studies that appeared between 1963 and 2001. The distribution of price elasticities has a sample mean of −0.41, a median of −0.35, and a standard deviation of 0.86. The minimum and maximum values are −7.47 and 7.90, respectively. The distribution of income elasticities has a mean of 0.43, a median of 0.24, and a standard deviation of 0.79. Approximately 10 % of the estimates are greater than 1. A more recent survey paper, Worthington and Hoffman (2008), indicates that price elasticity estimates are generally found in the range of zero to 0.5 in the short run and 0.5 to unity in the long run (in absolute values); income elasticity estimates are of a much smaller magnitude (usually) and positive.

[16] The candidate explanatory variables to be considered in the Taipei sample include I/p_w, *N*, *H*, the education level of the householder (*EDU*), and the number of household members above the age of 65 (*AG65*). By using the stepwise analysis in SPSS, *EDU* and *AG65* are excluded based on the criteria that the probability-of-F-to-enter is less than or equal to 0.05 and the probability-of-F-to-remove is greater than or equal to 0.1.

[17] The minimal daily water consumption per person of 77.19 l is calculated by transferring 14.589 cubic meters to 14,589 l first and then dividing 14,589 l per household bimonthly by 60 (days) and 3.15 (average number of persons per household). There are different suggestions for the basic water requirement in the literature. For example, WELL (1998) and WHO and UNICEF (2000) suggested a reasonable minimum as being 20 l per capita per day; Gleick (1996, 1998) recommended an overall basic water requirement of 50 l per capita per day. In Howard and Bartram (2003), 100 l per capita per day and above is the optimal access. In this paper, this quantity of water is defined as $\underline{q}$ which cannot be traded under the PTS. It represents a reasonable minimum of water consumption and is thus not conditional on household and house sizes.

$\left(\overline{I}/\overline{p}_w\overline{q}_w\right)$, where $\hat{\alpha}$ is the estimate of α and $\overline{I}$, $\overline{p}_w$, and $\overline{q}_w$ are the means of I, p_w, and q_w, respectively. The price elasticity shows that the water demand is not very sensitive to the water price. This finding might be due to the relatively low water price and its small variation in Taipei. In addition, small and inelastic estimates of price and income elasticities are as expected because water is a necessity and life-essential.

The number of household members has a significantly positive effect on the water consumption. The increase of one household member will result in an increase of 6.465 cubic meters of water consumption bimonthly, which is about 108 l per day. As to the house size, the bigger the house, the more significant is the amount of water consumed. Each square meter of area results in about 0.062 cubic meters of water being used bimonthly.

3.3 The Agent-based Water Rights Market and Income Distribution

Here, we simulate the scenario in which the PTS is applied in Taipei by using the agent-based model. A "household" is defined as an agent. The Stone-Geary water demand equation and bimonthly household data are used to calibrate individual household behavior. The market-clearing water price is determined when total water rights $\left(\overline{Q}\right)$ equal total water demand, which can be formulated as the following equation:

$$\overline{Q} = \sum_{i=1}^{n} \overline{q}^i = \sum_{i=1}^{n} q_w^i(p_w), \tag{5}$$

where $q_w^i(p_w)$ is the household water demand function which is represented by Eq. 4 and $\overline{q}^i$ is the water rights allocated to the i^{th} household. For simplicity in analysis, we assume that $\overline{Q}$ is rationed equally among individuals. In the status quo of the data set, the total amount of water consumed is 107,808 cubic meters. Each person is allocated 17.241 cubic meters of water rights bimonthly.[18] Households will trade water rights freely. However, the basic water requirement, 77.19 l per capita per day as estimated above, cannot be traded. We use the *Walrasian auctioneer* to determine the equilibrium water price. The simulated equilibrium price is 21.293 NT$/$M^3$. This price is notably higher than the current highest level of block rates in Taipei.

The average statistics of water consumption, water expenditure and its change, and the expenditure-income ratio per household after trading by quintile are shown in Table 2. Note that a negative figure of "Net expenditure from trading WR" shows that the household sells its rights. Because a household with lower disposable income per capita indicates that on average the economic condition of that household is relatively poor, we sort the trading results by the disposable income per capita quintile to check the change in the income distribution after trading. In the columns of "Sorted by PC I", we see that the net expenditures from trading WR for households with lower income per capita are negative. Thus, the average poorer households play the role of seller and gain from trade.[19] The income distribution situation is thus improved. In addition, the water share is around 20 % for each quintile.

[18] There are 6,253 persons in the sample and 17.241 = 107,808/6253.

[19] However, it should be noted that two households with the same income per capita but of different sizes will benefit differently from trade. Because of the phenomenon of scale economies in water consumption, the individuals in the larger household will enjoy a greater level of satisfaction than those in the smaller household.

Table 2 Changes in water expenditure after trading

	Lowest 20 %		Fourth 20 %		Third 20 %		Second 20 %		Highest 20 %	
Average statistics per household	Sorted by PC *I*	Sorted by PC WC	Sorted by PC *I*	Sorted by PC WC	Sorted by PC *I*	Sorted by PC WC	Sorted by PC *I*	Sorted by PC WC	Sorted by PC *I*	Sorted by PC WC
q_w (M^3) (water share)	54.31 (21 %)	42.30 (16 %)	52.41 (20 %)	48.64 (18 %)	55.04 (21 %)	52.48 (20 %)	53.21 (20 %)	58.39 (22 %)	48.71 (18 %)	61.88 (23 %)
WE for initial WR$^{(1)}$	753	749	703	722	696	684	640	655	543	524
Net expenditure from trading WR$^{(2)}$	−147	−395	−83	−203	−12	−41	66	144	174	495
Post-trading WE$^{(3)}$	606	354	620	519	684	643	706	799	717	1019
Status quo WE$^{(4)}$	685	422	666	566	713	667	701	803	653	961
ΔWE$^{(5)}$	−79	−68	−46	−47	−29	−24	+5	−4	+64	+58
WE-Income ratio$^{(6)}$	0.51 %	0.17 %	0.39 %	0.24 %	0.34 %	0.30 %	0.30 %	0.37 %	0.23 %	0.55 %

WE water expenditure, *WR* water right, Δ change, *PC* per capita, *WC* water consumption

In the first column, the item with superscript (3) = (1) + (2); (5) = (3) – (4); and (6) = (3)/*I*

There are 397 households in each quintile

We then sort the trading results by water consumption per capita. In the columns for "Sorted by PC WC", households with lower water consumption per capita can earn more from selling water rights and households with higher water consumption per capita should pay more to buy water rights. This outcome is compatible with the user pays principle.

3.4 The Simulated Market Price Elasticity

One of the advantages of the agent-based model is that it can be used to simulate different scenarios but is based on the water-use behavior of households. In this subsection, we further discuss the price elasticity under the scenario of changing the total quantity of water supply.[20]

Suppose that there are 41 different scenarios where total water supply varies and water rights allocated for individual persons vary correspondingly from 7.241 to 27.241 cubic meters with an increment of 0.5 cubic meters.[21] The *Walrasian auctioneer* is used to determine the equilibrium water prices under these various levels of water supply cases. The simulation results of the market equilibrium are graphically displayed in Fig. 2. Since the equilibrium water prices are determined when total water demand equals total water supply, the curve in the upper panel of Fig. 2 is in essence the market water demand curve.

We further transfer the levels of price and quantity to the logarithmic scale and present it in the lower panel of Fig. 2 (note that $\ln p_w$ is presented on the horizontal axis and $\ln Q$ is presented on the vertical axis). By so doing, the slope of the curve is the price elasticity of market water demand which varies along the demand curve. It is observed that, the lower the total water supply, the smaller the water demand elasticity. When the total water supply approaches the minimum water requirement, the absolute value of the elasticity will approach zero. On the other hand, if water is supplied very abundantly, its elasticity will asymptotically go to −1. This is because when $\overline{Q}$ goes to infinity, p_w will go to zero. Equation 3 will simply become the Cobb-Douglas demand function.

In addition, since the simulations have generated 41 data points, we can use these data to run a double-log regression to obtain an average estimate of market price elasticity. The estimated equation is presented as follows (t-ratios are in parentheses):

$$\ln Q = \underset{(223.21)}{12.982} - \underset{(-25.887)}{0.449} \ln p_w + u, \overline{R}^2 = 0.94.^{22} \tag{6}$$

The coefficient of $\ln p_w$, -0.449, represents the price elasticity of market water demand for the above-mentioned varying range of total water supply. Moreover, a rough estimate of the price elasticity for the status quo total water supply is −0.644.[23] It shows that when the

[20] Note that in practice the total water supply might change due to different weather conditions and the consideration of environmental and ecological purposes.

[21] As mentioned above, each person is allocated 17.241 cubic meters of water rights bimonthly. We take a range of 20 cubic meters around this number to specify the simulation scenario. The number of 41 is arrived at by the calculation: $41 = (27.241 - 7.241)/0.5 + 1$. Correspondingly, the total quantity of water supply varies from 45,278 to 170,338 cubic meters.

[22] It should be noted that the data points applied here are obtained from the 41 market simulation scenarios. They describe the relationship between the price and quantity of a market. Thus, the water demand equation is estimated for a market and not for a household. As a result, the household characteristics, such as household and house sizes, should not be included as the explanatory variables in Eq. 6.

[23] It is estimated by using three data points: the status quo ($\ln p_w$, $\ln Q$) and its two contiguous data points.

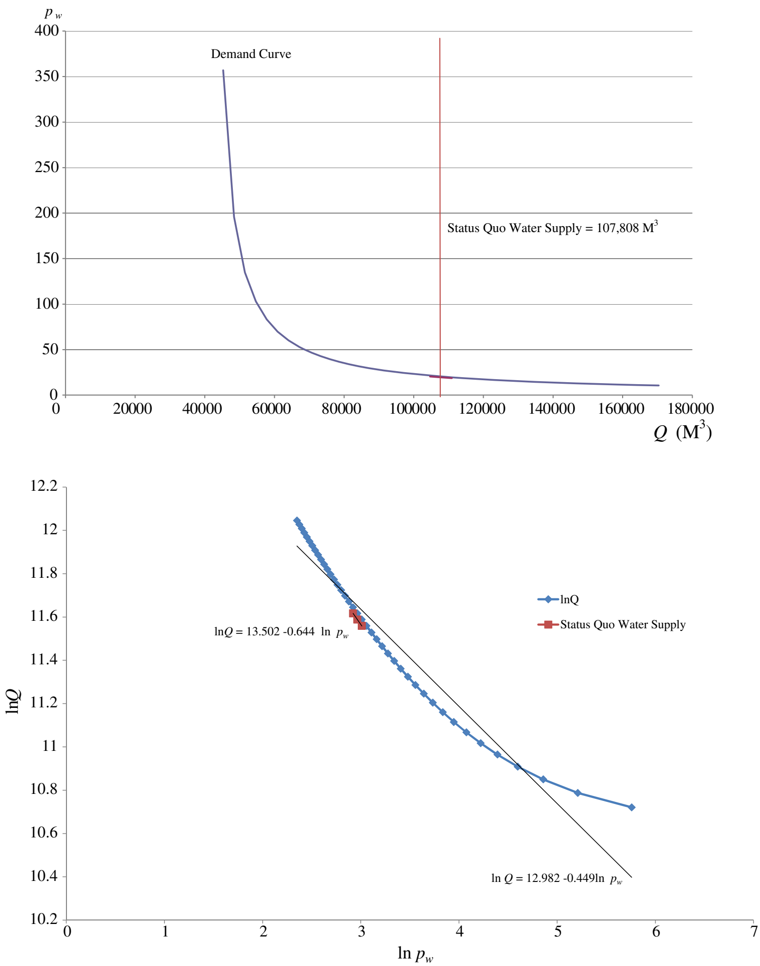

Fig. 2 The market water demand curve

market price rises by 1 %, the aggregate demand for water will be reduced by 0.644 %, which is higher than that for individual households in absolute value terms.

4 A Further Discussion on the Application of PTS

In Section 2, we have described the basic institutional design of the PTS. Here, we will further discuss its application and viability. We propose two possible trading mechanisms for application: the centralized market and the ex-post market. Overall, the transaction costs of the latter are lower than those of the former. In what follows, we will first introduce the basics of these two mechanisms and then analyze the issue of transaction costs.

(1) The centralized market

Because the market participants are numerous households, the right market might be designed as a centralized market where all of the trading is done over a computer network. The whole trading procedure could be separated into trading and implementation periods. In the trading period, the buyers (sellers) report the amount of water that they would like to buy (sell) and the price they are willing to pay (accept). The demand orders are electronically ranked by price from high to low to shape a demand curve and the supplies are ranked by price from low to high to shape a supply curve. Then the market equilibrium price and quantity are derived electronically. The buyers (sellers) that bid higher (requested lower) than the equilibrium price buy (sell) the amount of rights they reported at the equilibrium price.

In the implementation period, all households consume water according to the amount of water rights they own. The total expenditure on the water bill is calculated by summing up the net expenditure from trading (positive or negative) and the expenditure from the existing pricing system for the rights allocated.

The compliance condition of the PTS is that households should not consume more water than the amount of water rights they own. As water is an essential resource in people's lives, what then happens if the household consumes too much water? One of the compliance measures is to design a "safety valve" which is commonly applied in the cap-and-trade system of emission regulation. The safety valve is a pre-set price that the regulator offers to sell rights in unlimited amounts at this price. When the price is set high enough, it is similar to a per-unit penalty (see, e.g., Jacoby and Ellerman 2004).[24] Therefore, under the PTS, the violators should pay this high penalty price for the amount of over-consumption. In addition, to mitigate the uncertainty in trading for households, some degree of over-consumption might be allowable. The banking and forfeiture of rights should be considered as well.

(2) The ex-post market

Under this mechanism, the market equilibrium price (P*) is determined by the water supply curve (S) of water utility and the actual total water demand of households (Q_a) (see Fig. 3 for a simple two-user illustration). When $Q_a \geq \overline{Q}$, the cap of total water supply, a household pays the water expenditure for the right allocation $\overline{q}$ at P_0 (the existing price system). In addition, a household whose actual water consumption is greater (less) than $\overline{q}$ pays (earns) for the over- (lower-) consumption at the equilibrium price. When $Q_a < \overline{Q}$, which means that total water is abundant, no trading is needed and the household pays for its actual water consumption at the existing price. The PTS becomes a pure pricing system at this time. In order to mitigate the uncertainty of P* (being too high or too volatile), the regulator could set a safety valve as an upper limit $\left(\overline{P}\right)$. If $P^* > \overline{P}$, the monetary amounts for over-consumption and lower-consumption are calculated at $\overline{P}$.

Because the equilibrium price is determined after the actual consumption occurred, households understand the allocation amount of water $(\overline{q})$, the rate structure (the lower limit), and the safety valve (the upper limit), but do not know the equilibrium price ex ante. To help households make better water consumption decisions, the regulator should provide ex-ante and real-time information regarding the supply curve, climate data and weather forecasts, water consumption history, and equilibrium price prediction.

(3) Transaction costs

[24] The safety valve in practice also plays the role of an upper limit to the market price.

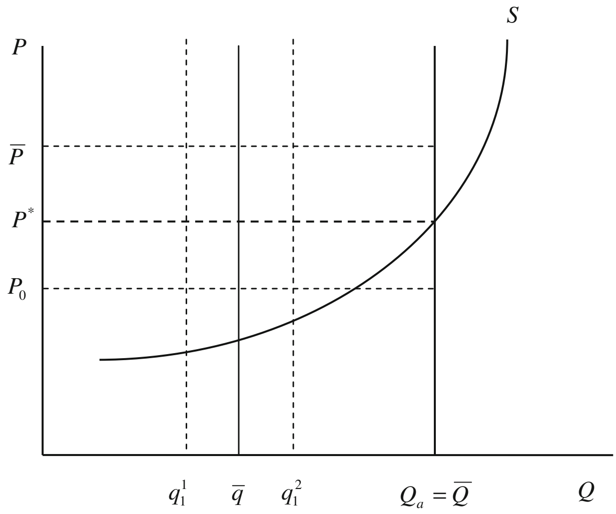

Fig. 3 The ex-post market and the equilibrium

By comparing the above two mechanisms, it is obvious that the transaction costs of the ex-post market are lower than those of the centralized one. In a centralized market, because households cannot normally know their actual consumption levels exactly ex ante or in real time, this would usually lead households to make conservative decisions when selling water rights. The consequence would be a very narrow and inefficient market. Under the ex-post market mechanism, households use the predetermined information of lower and upper price limits (P_0 and $\overline{P}$), quota $(\overline{q})$, and the predicted equilibrium price to make their water consumption decisions. They pay water fees on water bills as usual and do not need to proceed with physical trades, and thus the trading burden on both the households and the regulator is largely reduced.

In fact, in comparison with other commodities such as irrigated water, SO_2 and CO_2 that have been practically traded under the cap-and-trade system, the transaction costs for residential water market should be lower.[25] In the residential water market, participants are numerous small buyers and sellers who hold no market power, the product is homogeneous, and the geographic domain of trading is smaller as well. Finally, if the water is really scarce, the costs of resource-using inefficiency under the existing systematically-underpriced system should be taken into consideration and be compared with the transaction costs.

5 Conclusion

Because some of the goals of residential water use are mutually conflicting, existing pure price systems are, in practice, systematically underpriced. In this paper, we first propose a

[25] For the transfers of irrigated water, there are two broad groups of externalities associated: return flow effects and instream flow effects (Griffin and Boadu 1992 and Lee and Jouravlev 1998). In addition, changes in water quality after trading contribute another trading barrier. For the SO_2 trading, because SO_2 is a non-uniformly mixed assimilative pollutant, a simple one-to-one trading will result in the problem of hot spots. CO_2 is a uniformly mixed accumulative pollutant. However, trading globally, strategic behaviors, and the consideration of equity between generations and countries make the transaction costs very high.

price-cum-trade incentive system, the PTS, which supplements the existing price system with a cap-and-trade measure to reconcile these problems. One of the PTS's advantages is that it forces everyone to face the correct price signal. Under the existing pure price systems, the interests of all water users are the same—they do not prefer a higher water price. Under the PTS, however, these common interests could be broken. Because the poor could save water to sell and earn money, they do not need to protest against a higher price, while major water users are now forced to face higher prices.

The cap on residential water use can be used in considering other values of water use, such as environmental and ecological values among others. The market then works by itself to reach the equilibrium. The government does not need to set the optimal price. Two possible trading mechanisms, the centralized and ex-post markets, are proposed for the actual application of PTS. Although some transaction costs will result from trades, the price information provided by the trades is very important. It will induce people to use water with a more conscious attitude. It also reflects the true value of a natural resource. Experiments based on true trading deserve further research to help explore the PTS and reduce the transaction costs.

Second, by applying the agent-based model and a survey data set at the household level for Taipei, we empirically estimate the Stone-Geary water demand equation to calibrate the water use behavior of the household. The estimated results show that household and house sizes have significantly positive effects on the household water consumption. The estimated price and income elasticities are −0.23 and 0.23, respectively, which indicate that water demand is not sensitive to the water price and household income. The simulated market equilibrium price at the status quo total water supply is 21.293 NT$/$M^3$. This price is notably higher than the current highest level of block rates in Taipei. In addition, the market demand elasticity is higher than that for the household level and decreases as the total water supply is reduced.

Third, the simulation results show that households with lower disposable income per capita do gain from trade and the income distribution is improved after trading. On the other hand, households with lower water consumption per capita earn more from selling water rights and households with higher water consumption per capita pay more for buying water rights. This outcome is compatible with the user pays principle.

Finally, when the water market works well, some derivatives such as options and futures for water might be derived. These instruments could help reduce the uncertainty of water availability. These topics and experiments based on true trading should be interesting for future studies.

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