Estimating Urban Residential Water-Demand With Increasing Block Prices: The Case of Perth, Western Australia

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Abstract

This study uses panel data at suburb level to estimates the elasticity water demands in Perth, Australia from 1995 to 2005. After deriving the consumer's water demand under a non-linear budget constraint, we estimate the water demand model, which accounts for how water (and other purchased goods) is used to satisfy fundamental desires of the household. We have applied the specification of price that provided the correctly estimated marginal price from the block tariff structure, and employed a maximum likelihood estimation technique to tackle the endogeneity and heteroskedasticity issues. Our estimation of water demand price elasticities are slightly higher (more elastic) than previous study in Perth, but broadly in line with other estimates in the literature.

Key words: water demand, water pricing, block pricing, water resource management, household model
JEL classifications: Q21, Q25 and Q23

I. Introduction

The recent survey on water use by Australian Bureau of Statistics indicates that Western Australia is currently facing significant challenges in meeting its growing water needs. Following a 34 percent rise in the number of households from 449,000 in 1992 to 603,300 in 2006, the water demand for in the Perth metropolitan area has been increasing substantially (ABS, 2007). The survey also indicates that about 80 percent of households live in a detached dwelling, where outdoor-water use accounts for about half of annual water consumption (*ibid.*). Some households are able to access groundwater or use rain-water tanks (around 26 percent of households have bores and about 5 percent installed the rain-water tank in their backyard (*ibid*.)). As such, they are able to switch away from using scheme water for outdoor use. Nevertheless, per capita water consumption in Perth is higher than any other Australian capital cities (ABS, 2006).

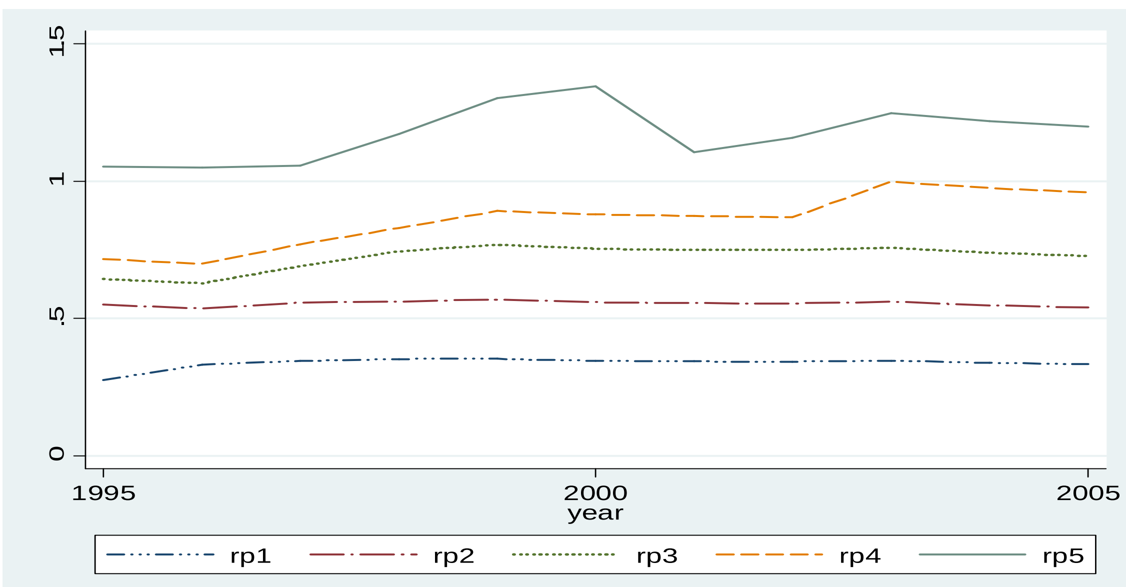
Over the past years, the government of Western Australia has adopted a number of water conservation policies.[1] The aim is to reduce per capita water consumption from the unrestricted level of 180 kilolitres a person per year to 155 kilolitres a person per year by 2012 (Government of WA, 2003). Usage restrictions in the form of a two-days-per-week-sprinkler restriction on lawn watering have been imposed since October 2001; the "Waterwise Rebate Programme" that encourages Western Australians to become more water efficient has been in operation since February 2003.[2] In tandem with these water

[1] In Western Australia (WA), the price of water is regulated by the government and water services are provided by state owned corporation: Water Coporation, Aqwest and Busselton Water The governing legislation of the state owned corporation indirectly allows the government to influence the operational efficiency of each corporation through the price and budget setting process. For further details of how the government regulate the price of water in WA see Economic Regulation Authority (2004).

[2] The rebates that are available for the approved water-saving-devices include: washing machines, showerheads, garden bores, rainwater tanks, tap timers, soil wetting agents, in-flow tap regulators, qreywater re-use systems, aerobic treatment units, swimming pool covers, subsurface irrigation pipework, rain sensors and waterwise garden assessments.

conservation policies, water tariffs with increasing prices over quantity blocks were used to encourage water saving and promoting the equity and the efficiency in the water sector.[3] However, in practice, heterogeneity in demand and the state owned corporation's requirement for cost recovery lead to efficiency and equity trade offs in the design of increasing block tariff schedules (Brennan, 2007). Instead of using water tariff setting process, the government has recently used the Community Service Obligation (CSO) payment to achieve the efficiency gains (Economic Regulation Authority, 2004).[4] By adopting this policy measure, the government relies heavily on water restriction and conservation programs for demand management, while allowing the water tariffs to increase by the inflation rate.

Figure 1. Real price of water tariffs for urban customers during 1995-2005



Source: estimated using data from Table A.1, in Appendix. rp1 to rp5 are the 1995 real price of water tariff in the first to the fifth block, respectively.

[3] These tariffs attempt to satisfy both efficiency and equity goals by providing pricing signals to influence consumption decisions at the margin, while making non-discretionary consumption available at a lower cost.

[4] The reason for not using water tariff to promote the efficiency in water sector may relate to governments' reluctance to rely heavily on price signals to ration water demand or supply due to political concern over the social implications of charging for water (see for example OECD, 1999).

As shown in Figure 1, customers of the Water Corporation in Perth face a five-block tariff structure. Over the period 1995-2005, only the real price at the upper rates has increased, while the lower rates have remained relatively constant.[5] Although setting the water tariffs in this way can be seen as a more equitable approach, it has been criticized for not reflecting the true marginal cost of water. Moreover, customers have to pay a fixed charge that takes up about 50 percent of the water bill.[6] As only half of the water bill is tied to water consumption, this price setting may offer little incentive for consumers to invest in water saving devices or to conserve water. In this regard, the prices of water in Perth have been seen as an ineffective tool for water demand management (Economic Regulation Authority, 2004). In the 2007 final report of the water price enquiry the Economic Regulation Authority has recommended that the prices of water in Perth should be increased, to reflect its marginal cost (Economic Regulation Authority, 2007).

While there has long been recognition of the roles of water prices in promoting the efficiency in the water sector, there are few studies of the effectiveness of water pricing in Perth (see for example; Thomas and Syme, 1988; Henderson, 1998; and Habibi, 2003). We address this imbalance by estimating water demand elasticities, using Perth's suburb data from 1995 to 2005. We estimate own-price demand elasticities for indoor and outdoor water use. We found that our estimation of the price elasticity of demand is slightly higher than that estimated by Thomas and Syme (1988), but our result is broadly in line with other estimates in the literature. We structure the paper as follows. Section II

[5] In this period, the average nominal price of water tariffs was increased by about 2.2 percent per year.
[6] The proportion of fixed charge to total bill is estimated for consumers who consume between 151kL to 351kL per year, using the prices of water from Table A1.

discusses the process to derive a residential water demand model and its estimation issues. Section III explains methods of data construction and their sources. The estimation results are present and discussed in Section IV. Section V concludes.

II. Methodology

The extensive body of literature on urban residential water-demand, summarised by Arbués *et al*. (2003) and Worthington and Hoffmann (2006), suggests that water demand has been determined by various factors, including, *inter alia*: water pricing structure, household income, socio-demographic factors (i.e. household size, age of household members, cultures), house characteristics (i.e. age of the house, number of bedrooms, lot size, the stock of water-using appliances and technology efficiency), and water conservation programs such as outdoor watering restrictions, public education campaigns and rebate schemes. Based on this premise, we derive a residential water demand using the basic framework of household production theory, which was originally introduced by Becker (1965) and Lancaster (1966). According to the household production theory, households purchase goods on the market to serve as inputs into a household production process, to provide the implicit goods and services which appear as arguments in the household's utility function.

Like many household services, water demands arise principally from requirements for different indoor and outdoor activities such as providing showers, car washing, watering lawns and gardens, and swimming pool. As such, we assumed that households decides to consume at a certain water-consumption level (i.e. consumption blocks from d_1 to d_5) to produce indoor and outdoor water services (g), and use the rest of their budget (y) to spend on other goods and services (o). We also assume:

(i) the production of g can be affected by climate conditions and water conservation policies (z),

(ii) households select water-using appliances to produce g and have the opportunity in the long run to adapt to price increases by purchasing more efficient water-using appliances, installing efficient plumbing fixtures and planting drought-tolerant gardens Household behaviour is captured by the technical coefficient, θ, in the production function,

(iii) demographic factors (df) and housing characters (hc) also determine household's preference, and

(iv) the price of o is used as a numeraire.

Therefore, the representative household's utility function (u) can be expressed as:

$$u = u\left\{\theta g\left[\left(d\left(d_1,...,d_5\right);z\right)\right],o;df,hc\right\} \quad (1)$$

In this framework the household's decision can be thought of as a two-stage optimisation problem (see for example Muellbauer, 1974 and Deaton and Muellbauer 1980). In the first stage, the consumer behaves as a firm, and the objective is to minimise the cost of producing g, whereas in the second stage of the optimisation problem, the consumer maximises the household's utility. The result of the optimisations yields a conditional water demand function (d) of the representative household as follows:[7]

[7] Alternatively, water demand function can be derived using discrete-continuous choice model. That is in first stage, a representative household select consumption blocks (discrete choice) by maximising utility subject to non-linear budget constraint. In the second stage, the representative household select consumption level in the selected block (continuous choice) by maximising indirect utility. See for example: Moffitt (1986, 1990), Hewitt and Hanemann (1995), and Corral et al. (1998). Also, see Appendix 2 for deriving the water demand function.

$$d = b_1 d_1^* \left(mp_1, y - s_1; \theta, z, df, hc \right) + \cdots + b_5 d_5^* \left(mp_5, y - s_5; \theta, z, df, hc \right) + c_1 D_1 + \ldots + c_5 D_5 \quad (2)$$

where k =1,…,5 denotes the water consumption levels,
$b_1 = 1$ if $d_1^*(.) < D_1$ and $b_1 = 0$ otherwise,
$b_k = 1$ if $D_{k-1} < d_k^*(.) < D_k$ and $b_k = 0$ otherwise $(k = 2,...,4)$,
$b_5 = 1$ if $d_5^*(.) > D_5$, and $b_5 = 0$ otherwise,
$c_k = 1$ if $d_k^*(.) = D_k$ and $c_k = 0$ otherwise $(k = 1,...,5)$

Following Corral et al. (1998) and Martínez-Espiñeira (2003), we obtain an aggregate water demand at different suburbs (i) and periods (t) as follows:

$$\bar{d}_{it} = \frac{1}{n} D_{it} = \sum_{n=1}^{n1} d_{1n,it}^*(.) + \ldots + \sum_{n=1}^{n5} d_{5n,it}^*(.) = \sum_{k=1}^{5} \frac{n_{k,it}}{n_{it}} \bar{d}_{k,it} \left(mp_k, y - s_k; \theta, z, df, hc \right) \quad (3)$$

where $\bar{d}_{it}$ = average water demand per household in period (t),
n_{it} = total number of households per suburbs (i) in period (t),
$n_{k,it}$ = number of households in suburbs (i) who consume in block k,
other variables defined as above.

We then derive the empirical model by replacing the generic form of the aggregate water demand function, $\bar{d}_{it} \left(mp_k, y - s_k; \theta, z, df, hc \right)$, with the following linear demand model:

$$\bar{d}_{it} = \alpha_0 + \alpha_1 \sum_{k=1}^{5} \frac{n_{k,it}}{n_{it}} mp_{k,it} + \alpha_2 \sum_{n=1}^{5} \frac{n_{k,it}}{n_{it}} \left(y_i - s_{k,it} \right) + \alpha_3 z_{it} + \alpha_4 df_{it} + \alpha_5 hc_{it} + \varepsilon_{it} \quad (4)$$

where ε_{it} = unobservable variant factors affecting water demand across suburbs.

However, one could not directly estimate the demand model at this stage, as Equation (4) could yield biased estimates. This is because endogeneity issues may arise from the demand behaviour of a utility-maximising household. As mentioned earlier, when maximising t utility households have to select the water consumption level ($\bar{d}_{it}$) that should be used to provide services for different indoor and outdoor activities. However, price varies with consumption level. As such, marginal price (mp_k), virtual income (y-s_k) and number of households consume in each block (n_k) are endogenously determined, and thus correlated with the error term.

To tackle the endogeneity issues, we have to estimate the proportion of households per blocks ($p_{k,it}$), as shown in Equation (5) below, using the Tobit regression model.

$$p_{k,it} = \frac{n_{k,it}}{n_{it}} = f\left(y, z_{it}, df_{it}, hc_{it}\right) \text{ k=1,...,5} \tag{5}$$

where $\sum_{k=1}^{5} p_{k,it} = 1,$

We then have to use the estimated proportion of water consumption per blocks to compute the weighted-mean marginal price ($m\hat{p}_{it}$), weighted-mean income difference ($\hat{s}_{it}$) and weighted-mean virtual income ($\bar{i}_{it}$), using the following Equations:

$$m\hat{p}_{it} = \sum_{k=1}^{5} \hat{p}_{k,it} mp_{k,it} \tag{6}$$

$$\hat{s}_{it} = \sum_{k=1}^{5} \hat{p}_{k,it} s_{k,it} \tag{7}$$

$$\bar{i}_{it} = \bar{y}_{it} - \hat{s}_{it} \tag{8}$$

To obtain the prices elasticity for indoor and outdoor water demands, we need the average water consumption per household for indoor and outdoor activities, or during winter and summer, to be used as the regressant ($\bar{d}_{it}$) in (4). Alternatively, we still can obtain the prices elasticity for indoor and outdoor water demands by including the interactive-price-policy-effect variables (*mpb01* and *mpa01*) in the model, to capture the potential impacts between water prices and the post-2001 water conservation policies on water demand. By substituting Equations (6) to (8) into Equation (4), then including the policy and the price-policy interaction variables, we obtained the empirical regression model as follows:

$$\bar{d}_{it} = \beta_0 + \beta_1 d0105 + \beta_2 mpb01_{it} + \beta_3 mpa01_{it} + \beta_4 i_{it} + \sum_{l=1}^{L} \beta_l z_{it} + \sum_{m=1}^{M} \beta_m df_{it} + \sum_{n=1}^{N} \beta_6 hc_{it} + \varepsilon_{it} \quad (9)$$

Where $mpb01 = m\hat{p} * (1\text{-}d0105)$ captures the pre-2001-interactive-price-policy effects, $mpa01 = m\hat{p} * d0105$ captures the post-2001-interactive-price-policy effects, *d0105* singles out the potential impacts of conservative policies, *d0105* =1 if year=2001 to 2005, =0 otherwise.

From Equation (9) we can compute the prices elasticity for indoor and outdoor water demand from the estimate coefficients of the price-policy interaction effect variables (*mpb01* and *mpa01*). This is because the two-days-per-week-sprinkler restrictions that were imposed after 2001 has limited water use for the most of outdoor activities and may have restricted water consumption to the point where there is little opportunity for a response to price changes (i.e. the restriction has shifted consumers to a corner solution wrt price changes and external use, and only extreme price changes would cause further change). The coefficient of *mpa01* variable should capture how households adjust using the indoor-water-using appliances in response to change in water prices. Therefore, we can use the estimate of β_3 to compute the value of price elasticity demand for indoor activities. Likewise, the *mpb01* variable should capture how households respond for both indoor and outdoor water use, and thus the estimate of β_2 were used to compute total price elasticity. The pre-restriction outdoor price-elasticity demand can be computed using the total price elasticity and the indoor price-elasticity demands (see Appendix 3 for deriving the outdoor price-elasticity formula).

Theoretically, the water demand in Equation (9) can be estimated using pooled OLS techniques, but many studies suggest that the process of constructing the instrumental variables, similar to that we employed in Equations (6) to (8), may not solve completely the endogeneity errors (see a discussion for this issue in Arbués *et al.*, 2003, pp. 92-95). Billings (1982) suggest estimating the water demand model using the maximum likelihood technique. In addition, although the use of various explanatory variables to control for the heterogeneous water consumption patterns across suburbs in Equation (9), we need to account for unobserved factors affecting the average of water consumption per household. We deal with this issue by adding the random effect component into the error term of Equation (9) as follows:

$$\varepsilon_{it} = u_i + e_{it} \tag{10}$$

where u_{it} = a random variable representing unobservable factors accounting for the deviation of water consumption per household across suburbs,

e_{it} = a classical error term with zero mean and a homoscedastic covariance matrix.

The final form of the water demand model depends on the availability of data, which we discuss in detail in the following section.

III. Data and variables

Annual data on water consumption at the suburb level is provided by Water Corporation. With this information, we constructed the proportion of water consumption (by suburb) per block ($\frac{d_{k,it}}{d_{it}}$), and water demand ($\bar{d}_{it}$). The data covers the period 1994/95-2004/05 with the consumption year starting from July and ending at June. The weighted-mean marginal price (mp_{it}), and the weighted-mean income difference (s_{it}) were also constructed using the prices of water provided by the Water Corporation. The Perth consumer price index downloaded from the Australian Bureau of Statistic's website was used to compute the real water prices.

Monthly climatic data (z_{it}) stemming from five weather stations (Jandakot, Gosnells, Perth, Medina, and Swanborne) are obtained from the Bureau of Meteorology. We then converted the data into season variables: summer precipitation (*precipitations*) and summer cooling-degree-day (*cddays*), by making the season periods compatible with the water consumption-year periods. That is we considered the summer period starts from November and ends in April of a consecutive year, while the winter period from July-October and end in May-June of a consecutive year. To construct the climatic data at suburb level, we used the urban map number published in the 2007 Perth and Surrounds Street Directory to determine the locations between the suburbs and the weather stations. We then assigned the climatic data to each suburb according to its closest location to the weather stations.

Demographic factors (df_{it}) at suburb level are sourced from the census data of the Australian Bureau of Statistic. We extracted the following groups of data: age and population distribution, house ownership, housing characters and household earning. We used the data to construct household income (*y*), the number of households owning their house (*ownhouse*), the number of households renting the house (*renthouse*), the number of people who is over 65 years old (*ageover65*), the number of people who is under 19 years old (*ageunder19*), and household sizes (*hhsize*). Since the census data are only available for 1996, 2001 and 2006, we used linear-interpolation technique to estimate the missing observations in other years.

The housing characteristics (hc_{it}) at suburb level are provided by CSIRO. The data contains number of bores per 100 accounts (*bores*) and the average lot size (*lotsize*). However, the number of bores per 100 accounts is available for only 2001. We did not attempt to estimate the missing data, as the information about the history of bore installation is limited. To be able to estimate the models in panel data, we set the numbers of bores for other years equals to the number of bore installed in 2001. This means that the impacts of bores on water consumption could be under-estimated. Summary statistics of variables used in the estimation of water demand models are provided in the Table 1.

Table 1. Summary statistics

Variable	units	Obs	Mean	Std. Dev.	Min	Max
d	kL / Househouse	2419	363.3	124.3	102.7	1684.8
mp	1995 Dollars / kL	2390	0.72	0.05	0.59	0.89
s	1995 Dollars	2390	-120.0	21.4	-242.0	-63.1
i	1995 Dollars	2390	40506.2	12045.5	16062.4	96257.2
y	1995 Dollars	2419	40229.7	12081.3	15914.2	96173.8
ownhouse	% of total detached house	2419	75.5	9.3	33.6	95.1
renthouse	% of total detached house	2419	17.3	7.8	2.4	56.9
ageover65	% of total population	2419	11.9	6.1	0.0	44.3
ageunder19	% of total population	2419	29.3	6.2	12.4	49.2
hhsize	Persons	2419	2.7	0.4	1.5	3.6
lotsize	square metres	2419	737.7	105.7	411.0	1187.5
bores	bores/100 accounts	2419	23.4	20.5	0.2	83.5
precipitations	milimetres	2419	110.5	53.4	33.1	251.6
cddays	Celsius-days	2419	120.4	43.5	25.5	214.4

Notes: *d*: water consumption per household, *mp*: weighted-mean marginal price, *s*: weighted-mean income difference per household, *i*: household's weighted-mean virtual income, *y*: household's real income, *ownhouse*: number of households owning the house, *renthouse*: number of households renting the house, *ageover65*: number of people who is over 65 yrs, *ageunder19*: number of people who is under 19 yrs, *hhsize*: household sizes, *lotsize*: lot size, *bores*: number of bores per 100 accounts, *precipitations*: summer precipitation, *cddays*: summer cooling degree days.

IV. Results and discussions

For the estimation of Equations (5) and (9), we considered the observations with the water consumption per household less than 100 kL per annum and the lot size bigger than

1200 square meter, as the outliers, and were dropped. Therefore, we have an unbalanced panel data of 234 Perth's suburbs observed over 11 years (1995-2005) with 2390 observations. We estimated the proportions of household per blocks (Equation (5)) using climate data, demographic factors and housing characters as the explanatory variables. As suggested by Schefter and David (1985), we used the observed proportion of water consumption per block ($\frac{d_{k,it}}{d_{it}}$) as a proxy of the proportion of households per block ($\frac{n_{k,it}}{n_{it}}$). We then compared the predicted proportions of water-consumption per block with their original observations, as shown in Figure 2. The bar graphs suggest that the predictions are reasonably close to the originally observed values.

Figure 2: Proportions of the water consumption per blocks and its estimations

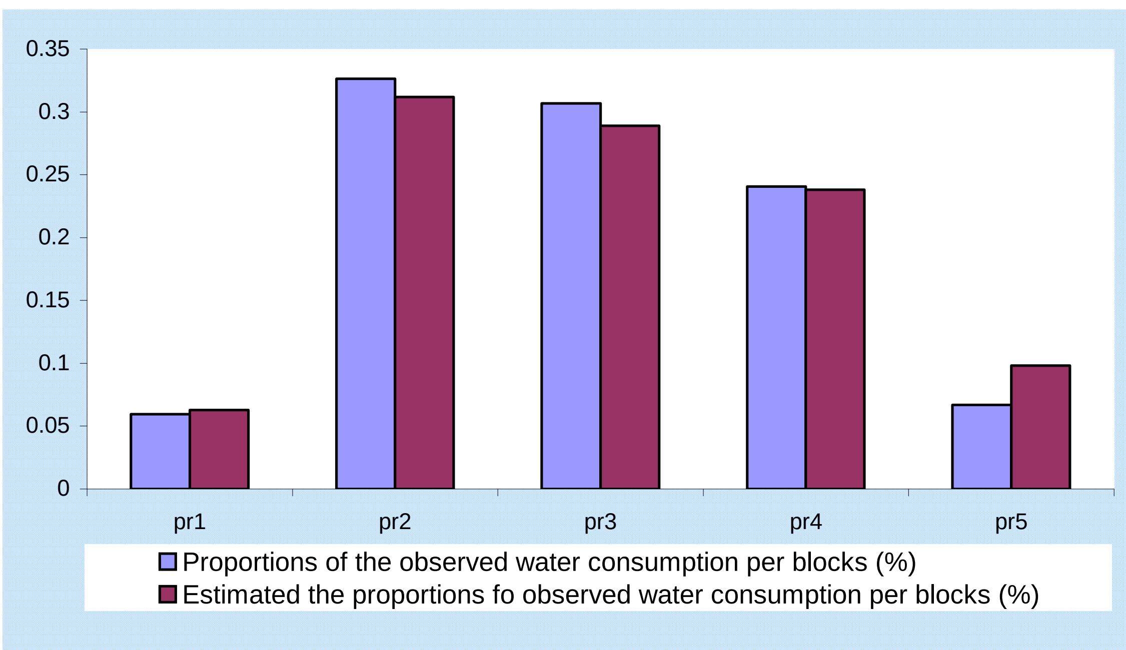
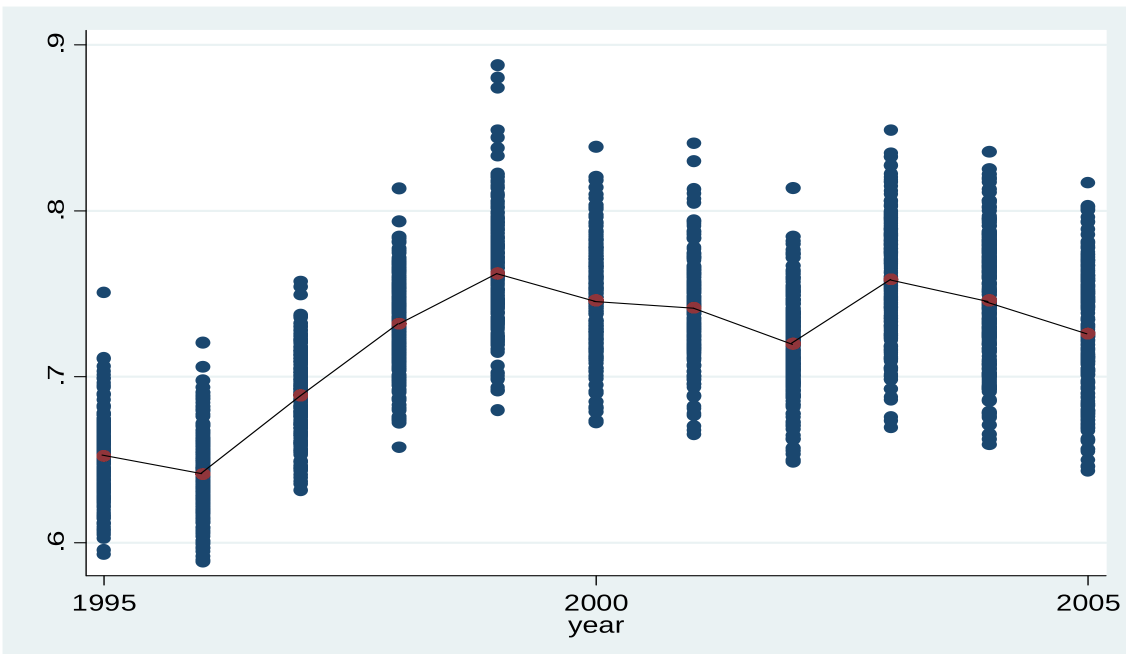


Figure 3 below shows the variation of the weighted-mean real marginal price ($m\hat{p}_{it}$) across suburbs. Notice that the trend of weighted marginal price (solid line) increased from about $0.65 in 1995 to about $0.75 in 2005, despite some water tariffs have been set to change in line with the inflation rate (see the discussion earlier). The reason is that more households consumed in the upper blocks (pr2 to pr5 in Figure 2) where the price tariffs were increased in real terms. Therefore, we expected that households should have reduced water consumption in response to the increase in prices of water over the year under-investigation.

Figure 3: Weighted-mean real marginal price during 1995-2005



We estimated the water demand in Equation (9) as random effect model using the maximum likelihood estimation technique. Apart from marginal price income and dummy for to capture the effect of water conservation policies, we also included climate data, demographic factors and housing characters employed in Equation (5) as explanatory variables. Since the correlations among the demographic variables are high, we estimated the water demand model in various specifications, and reported the estimation results in Table 2 below.

Table 2. Estimated water demand models

Dependent variable (d)	Model1	Model2	Model3	Model4	Model5	Model6
d0105	-304.305***	-301.658***	-335.753***	-336.376***	-314.167***	-313.404***
	(55.586)	(56.162)	(56.906)	(56.893)	(56.154)	(55.848)
ampp	-533.109***	-578.260***	-559.081***	-558.108***	-557.155***	-551.504***
	(49.494)	(48.872)	(49.860)	(49.527)	(48.813)	(48.601)
amp0105	-178.685**	-218.340***	-162.654**	-161.117**	-187.181***	-183.504**
	(72.702)	(73.026)	(74.241)	(73.822)	(72.836)	(72.424)
y	0.004***	0.004***	0.005***	0.005***	0.004***	0.004***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ownhouse	-2.966***		0.076			
	(0.924)		(0.448)			
renthouse	-1.129			0.006		
	(0.989)			(0.517)		
ageover65	-1.244				-4.514***	
	(1.013)				(0.813)	
ageunder19	3.037***					5.314***
	(0.962)					(0.729)
hhsize	66.861***	81.590***				
	(16.285)	(10.778)				
lotsize	0.081***	0.069**	0.078***	0.078***	0.090***	0.074***
	(0.029)	(0.029)	(0.029)	(0.029)	(0.029)	(0.029)
bores	-1.820***	-2.164***	-2.495***	-2.498***	-1.955***	-1.943***
	(0.268)	(0.238)	(0.232)	(0.233)	(0.265)	(0.255)
precipitations	-0.125***	-0.137***	-0.123***	-0.123***	-0.128***	-0.126***
	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)	(0.023)
cddays	0.077*	0.118***	0.065	0.064	0.084*	0.080*
	(0.044)	(0.044)	(0.045)	(0.044)	(0.044)	(0.043)
year	18.454***	15.750***	15.978***	16.018***	16.938***	17.180***
	(1.303)	(1.136)	(1.175)	(1.153)	(1.147)	(1.141)
_cons	-36358***	-31111***	-31391***	-31467***	-33255***	-33942***
	(2546.540)	(2241.138)	(2316.107)	(2274.535)	(2264.222)	(2255.785)
Number of observations	2397	2397	2397	2397	2397	2397
Number of suburbs	234	234	234	234	234	234
Sigma_u	70.868	67.546	66.605	66.595	71.343	70.477
	(3.972)	(3.491)	(3.378)	(3.377)	(3.902)	(3.812)
Sigma_e	55.921	56.596	57.443	57.444	56.602	56.347
	(0.864)	(0.865)	(0.876)	(0.876)	(0.872)	(0.867)
Likelihood-ratio test for Ho: Sigma_u=0	1314***	1336***	1325***	1328***	1366***	1364***
Income elasticity	0.51	0.50	0.59	0.60	0.53	0.54
total price elasticity	-1.06	-1.15	-1.11	-1.11	-1.10	-1.09
indoor price elasticity	-0.77	-0.94	-0.70	-0.70	-0.81	-0.79
outdoor price elasticity	-1.30	-1.32	-1.45	-1.45	-1.36	-1.35

Notes: * significant at 10%, ** significant at 5%, *** significant at 1%, figures in the brackets are standard error. Price and income elasticities were estimated at the sample mean. Outdoor price elasticity was computed using the formula in Appendix 3, and the proportion of outdoor demand, α=54.1 percent (taken from McFarlane et al., 2006).

In the maximum likelihood estimation, the distribution of water consumption across suburbs is assumed to be normal. We performed a bootstrap estimation, as there is no pre-assumption about the distribution shape for this estimation technique. The standard error for all coefficients estimated using the bootstrap estimation are similar to that reported in Table 2. The bootstrap standard error is not report here but available on request.

Overall, the selected econometric technique seem to be appropriate for all models, as the likelihood-ratio test for the null hypothesis stating that the average water consumption per household are homogenous across suburbs is rejected. All estimated coefficients are statistically significant and have the expected signs; excepted the coefficients on the number of households owning the houses are not significant in model (2) and the sign should be positive in model (1); the coefficients on the number of households renting the houses are not significant but have only the right sign in model (1); the coefficients on number of people who is over 65 years old have the expected sign but is not significant in model (1).

The estimated coefficients for *d0105*, *mpb01*, and *mpa01* have a negative sign suggests that the water conservation policies and water prices adopted by the water authority of Western Australia have contributed to the decrease in water consumption by households in detached houses in Perth metropolitan. The magnitude of *mpa01* coefficient being smaller in absolute term than that of *mpb01* suggest that the impact of water prices on consumption is more inelastic after the post-2001 periods. Other variables such as *renthouse*, *ageover65*, *bores*, and *precipitations* have a negative estimated coefficient, while *ownhouse*, *ageunder19*, *hhsize*, *lotsize* and *ccdays* have a positive estimated coefficient. This result is consistent with the findings in the water demand literature; for example, Arbués et al. (2003) and Nauges and Thomas (2000) argued that demand for water in areas with a higher proportion of younger persons is likely to be higher, as more frequent laundering and use of water-intensive outdoor leisure activities. Other examples can be found in Arbués *et al.* (2003) and Worthington and Hoffmann (2006).

We computed the elasticity demands at the sample mean and found the income elasticity to be in a range between 0.50 and 0.60, while the pre-2001 price elasticity (total price elasticity) ranges between -1.05 to -1.14 and the post-2001 price elasticity (indoor price elasticity) between -0.70 to -0.94. To compute outdoor price elasticity, we assumed that water demand for outdoor activity accounts for 54.1 percent of total consumption (this figure taken from McFarlane et al., 2006). The estimated outdoor-price elasticity is in a range between -1.30 to -1.45.

Table 3 compares our estimation of price elasticity demand with other studies. Notice that the price elasticity demands during winter is similar to that of indoor demand, while the price elasticity demand during summer is similar to that of outdoor demand.

Table 3. Comparison price elasticity demands

Authors	Year	Location	Price elasticity	
NRA (1993) cited in Houston et al (2001)	various	USA & Canada	Winter	-0.06 to -0.3
			Summer	-0.43 to -1.5
			All year	-0.25 to -0.9
Veck and Bill	2000	South Africa	Indoor	-0.13 to -0.14
			Outdoor	-0.19 to -0.47
			Total	-0.14 to -0.18
Ran Water study (2000) cited in van Zyl et al (2003)	2000	South Africa	Indoor	-0.24 to -0.67
			Outdoor	-0.39 to -0.79
			Total	-0.29 to -0.69
Thomas and Syme	1988	Perth, Australia	Indoor	-0.04
			Outdoor	-0.31
			Total	-0.18
NRA (1993) cited in Houston et al (2001)	various	Australia	Winter	-0.04 to -0.36
			Summer	-0.30 to -1.20
Dandy *et al.*	2001	Adelaide, Australia	Winter	-0.29 to-0.45
			Summer	-0.69 to -0.86
			All year	-0.63 to -0.77
this study		Perth, Australia	Indoor	-0.70 to -0.94
			Outdoor	-1.30 to -1.45
			Total	-1.05 to -1.14

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Comparing our results with other studies in Australia suggests that our estimation for indoor price elasticity demands are slightly higher (more elastic), while outdoor and total price elasticities are broadly in line with those studies (except for Thomas and Syme,1988 where our estimation for all price elasticities are higher). It is not surprising that our estimation for indoor price elasticity is high. This is because the demand for water during the two-days-per-week-sprinkler restriction may include water use for outdoor activities such as providing car washing, hosing lawns and gardens, and swimming pool.

V. Conclusion

This study has provided new insights into the importance of water price in promoting water conservation in Perth. Over the past years, water price have been seen as an ineffective tool for water demand management, as the empirical evidence suggested that the price elasticity of demand for residential water in Perth was relatively inelastic. However, we argue that the water use in Perth has been dominated by discretionary outdoor demands, and that we expected the greater responsiveness in water use to changes in the prices of water. To support this hypothesis, we have estimated the water demand model by applying the price specification that provided the correctly estimated marginal price from the block tariff structure, and employed the maximum likelihood estimation technique to deal with the heterogeneity and endogeneity issues.

Our key findings can be summarised as follows. The empirical results suggest that the price elasticity of demand for residential water in Perth is relatively more elastic than previous estimates. The non-price control such as the sprinkler restriction and the "Waterwise Rebate Programme" and bores have been worked well in promoting water conservation. Other factors beyond the control of water authority that have influenced water use are housing characters, demographic factors, and climate conditions. Some of these factors have significantly influenced the increase in water demand: income, household size, lot size of the house, and the warm temperature which measured by cooling degree days (the extent of the temperature in the house that needs to be cool down).

While this finding suggests that the price-based policy instrument may be important as a demand driver, more empirical work is needed to estimate the price elasticity for indoor and outdoor demands. For example, the price elasticity demands could be estimated using the observed water consumption for indoor and outdoor activities if that is available or during winter and summer.

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Appendix 1: Tables

Table A1: Residential water tariff and consumer price index for Perth

Year	Fix_Charge Per Dollars	P0_150 Cents / kL	P150_350 Cents / kL	P350_550 Cents / kL	P550_750 Cents / kL	P750_950 Cents / kL	P950_1150 Cents / kL	P1150_1950 Cents / kL	P1950plus Cents / kL	cpi95
1995	121.45	27.5	55	64.4	70.3	74.7	83.3	83.3	102.8	100
1996	121.45	34	55	64.4	70.3	74.7	83.3	83.3	102.8	102.58
1997	126.3	35.4	57.2	70.8	77.3	82.2	91.6	91.6	113.1	102.51
1998	130.1	36.5	58.2	77.2	84.3	89.6	99.8	99.8	123.3	103.67
1999	132.7	37.2	60.1	81.1	92.7	98.6	109.8	109.8	135.6	105.52
2000	135.4	37.94	61.3	82.72	94.55	100.57	112	112	138.31	109.72
2001	140.1	39.2	63.4	85.6	97.9	104.1	104.1	115.9	143.1	114.2
2002	144.2	40.3	65.2	88.1	100.7	107.1	107.1	119.3	147.2	117.55
2003	149	41.6	67.4	91	120	120	150	150	150	120.18
2004	149	41.6	67.4	91	120	120	150	150	150	123.07
2005	152.3	42.5	68.9	93	122.6	122.6	153.3	153.3	153.3	127.77
2006	154.6	49.3	73.2	95	126.8	126.8	158.8	158.8	158.8	133.07
2007	162.6	56.9	78.4	98	132.4	132.4	166.1	166.1	166.1	

Sources: Water tariff are sourced from Water Corp. The figures attached to a letter P is the lower to upper bound of water consumption volume for each block. Cpi95 is 1995 based consumer price index for Perth.

Table A2. Correlation matrix of explanatory variables

	amp	*s*	*i*	*y*	*ownhouse*	*renthouse*	*ageover65*	*ageunder19*	*hhsize*	*lotsize*	*bores*	*precipitations*	*cddays*
amp	1.00												
s	-0.92	1.00											
i	-0.03	0.16	1.00										
y	-0.04	0.16	1.00	1.00									
ownhouse	0.22	-0.16	0.57	0.57	1.00								
renthouse	-0.05	0.02	-0.49	-0.49	-0.93	1.00							
ageover65	-0.23	0.23	-0.29	-0.29	-0.45	0.38	1.00						
ageunder19	0.25	-0.27	0.26	0.26	0.46	-0.42	-0.67	1.00					
hhsize	0.31	-0.29	0.48	0.48	0.72	-0.64	-0.73	0.83	1.00				
lotsize	-0.09	0.05	-0.04	-0.04	0.16	-0.20	0.16	0.01	0.04	1.00			
bores	-0.38	0.37	-0.04	-0.04	-0.11	0.10	0.42	-0.34	-0.26	0.23	1.00		
precipitations	0.16	-0.07	-0.02	-0.02	0.03	0.00	-0.01	0.00	0.02	-0.01	-0.01	1.00	
cddays	0.14	-0.11	0.04	0.04	-0.04	0.05	0.07	-0.05	-0.06	0.03	0.12	0.19	1.00

Appendix 2: Deriving water demand function

Define variables:

let k =1,…,5 denotes the water consumption levels,
s_k = Taylor-Nordin difference variable (income difference),
D_k = the upper limit of each consumption block,
$C[.]$ = cost function,
$g[.]$ = production function,
$d[.]$ =conditional water demand function,
$mp[.]$ = water tariff (marginal price),
z = climate conditions and water conservation policies,
θ = the technical coefficient,
df = demographic factors and
hc = housing characters

Optimisation process:

In the first stage, the consumer behaves as a firm, and the objective is to minimise the cost of producing water services. This amount is equal to solving the problem:

$$\begin{aligned} &\underset{d(.)}{\text{Minimise}}\ C\left[d\left(d_1,...,d_5\right);mp\left(mp_1,...,mp_5\right)\right]+o \\ &\qquad\text{subject to } g=\theta g\left[d\left(d_1,...,d_5\right);z\right] \end{aligned} \tag{2.1}$$

Solving this optimisation problem gives the following expenditure function:

$$E=E\left[mp\left(mp_1,...,mp_5\right),g;\theta,z\right] \tag{2.2}$$

Applying Shephard's lemma gives the conditional water demand function as follows:

$$d\left[mp\left(mp_1,...,mp_5\right),g;\theta,z\right]=\frac{\partial E\left[mp\left(mp_1,...,mp_5\right),g;\theta,z\right]}{\partial mp} \tag{2.3}$$

In the second stage of the optimisation problem, the consumer maximises the utility. This amount is equal to solving the problem:

$$\begin{aligned} &\underset{g,o}{\text{Maximise}}\ u\left(g,o;df,hc\right) \\ &\qquad\text{subject to } y-s\left(s_1,...,s_5\right)=E\left[mp\left(mp_1,...,mp_5\right),g;\theta,z\right]+o \end{aligned} \tag{2.4}$$

The result of this optimisation procedure gives the demand function for outdoor water services (*G*) as follows:

$$g = g\left[mp\left(mp_1,...,mp_5 \right), y - s\left(s_1,...,s_5 \right); \theta, z, df, hc \right] \tag{2.5}$$

Finally, the outdoor water demand function can then be found by substituting Equation (2.5) into Equations (2.3) yields:

$$d = d\left[mp\left(mp_1,...,mp_5 \right), g\left(mp\left(mp_1,...,mp_5 \right), y - s\left(s_1,...,s_5 \right); \theta, z, df, hc \right); \theta, z \right]$$

or (2.6)

$$d = d\left[mp\left(mp_1,...,mp_5 \right), y - s\left(s_1,...,s_5 \right); \theta, z, df, hc \right]$$

Since consumers select the optimal consumption level at certain block, the water demand function can be expressed as follows:

$$d = b_1 d_1^* \left(mp_1, y - s_1; \theta, z, df, hc \right) + \cdots + b_5 d_5^* \left(mp_5, y - s_5; \theta, z, df, hc \right) + c_1 D_1 + ... + c_5 D_5 \tag{2.7}$$

where

$b_1 = 1$ if $d_1^*(.) < D_1$ and $b_1 = 0$ otherwise,

$b_k = 1$ if $D_{k-1} < d_k^*(.) < D_k$ and $b_k = 0$ otherwise$(k = 2,...,4)$,

$b_5 = 1$ if $d_5^*(.) > D_5$, and $b_5 = 0$ otherwise,

$c_k = 1$ if $d_k^*(.) = D_k$ and $c_k = 0$ otherwise$(k = 1,...,5)$

Appendix 3: Deriving the Outdoor Price-Elasticity Formula.

Let:

$\varepsilon_t = \frac{p}{q_t}\frac{\partial q}{\partial p}$ be the own price elasticity for total water demand

$\varepsilon_i = \frac{p}{q_i}\frac{\partial q_i}{\partial p}$ be the own price elasticity for indoor water demand

$\varepsilon_o = \frac{p}{q_o}\frac{\partial q_o}{\partial p}$ be the own price elasticity for outdoor water demand

We know that:

$$q_t = q_i + q_o \tag{3.1}$$

$$\beta_2 = \frac{\partial q_t}{\partial p} \Rightarrow \varepsilon_t = \beta_2 \frac{\bar{p}}{\bar{q}_t} \tag{3.2}$$

$$\beta_3 = \frac{\partial q_i}{\partial p} \Rightarrow \varepsilon_i = \beta_3 \frac{\bar{p}}{\bar{q}_i} \tag{3.3}$$

Take partial derivative of (3.1) with respect to p and multiply $\frac{p}{q}$ on both side of the equation yields:

$$\frac{p}{q}\frac{\partial q}{\partial p} = \left(\frac{\partial q_i}{\partial p} + \frac{\partial q_o}{\partial p}\right)\frac{p}{q} = \frac{p}{q}\frac{\partial q_i}{\partial p} + \frac{p}{q}\frac{\partial q_o}{\partial p} \tag{3.4}$$

Assume that:

$$q_i = (1-\alpha)q \Leftrightarrow q = \frac{q_i}{(1-\alpha)} \tag{3.5}$$

$$q_o = \alpha q \Leftrightarrow q = \frac{q_o}{\alpha} \tag{3.6}$$

Substitute (3.5) and (3.6) into (3.4) yields:

$$\frac{p}{q}\frac{\partial q}{\partial p} = (1-\alpha)\frac{p}{q_i}\frac{\partial q_i}{\partial p} + \alpha\frac{p}{q_o}\frac{\partial q_o}{\partial p} \tag{3.7}$$

$$\varepsilon_t = (1-\alpha)\varepsilon_i + \alpha\varepsilon_o \tag{3.8}$$

Therefore, the outdoor elasticity demand can be expressed as follows:

$$\varepsilon_o = \frac{1}{\alpha}\left[\varepsilon_t - (1-\alpha)\varepsilon_i\right] \tag{3.9}$$