Pricing for scarcity? An efficiency analysis of increasing block tariffs

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[1] Water pricing schedules often contain significant nonlinearities, such as the increasing block tariff (IBT) structure that is abundantly applied for residential users. The IBT is frequently supported as a good tool for achieving the goals of equity, water conservation, and revenue neutrality but seldom has been grounded on efficiency justifications. In particular, existing literature on water pricing establishes that although efficient schedules will depend on demand and supply characteristics, IBT cannot usually be recommended. In this paper, we consider whether the explicit inclusion of scarcity considerations can strengthen the appeal of IBT. Results show that when both demand and costs react to climate factors, increasing marginal prices may come about as a response to a combination of water scarcity and customer heterogeneity. We derive testable conditions and then illustrate their application through an estimation of Portuguese residential water demand. We show that the recommended tariff schedule hinges crucially on the choice of functional form for demand.

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1. Introduction

[2] In many areas where water is not abundant, water pricing schedules contain significant nonlinearities. Utilities tend to be local natural monopolies, consumers cannot choose multiple connections, and resale is tricky. Thus, it is easy, and often politically expedient, for utilities to undertake extensive price discrimination, both for distinct types of consumers (residential, industrial, agricultural, and so on) and for different levels of consumption within each consumer type. Many utilities use two-part tariffs, with fixed meter charges and a constant unit price, or multipart tariffs, which combine fixed charges and increasing or, less often, decreasing blocks. Occasionally, seasonal price variations are employed to reflect changes in water availability throughout the year. Less common is the imposition of a scarcity surcharge during drought periods, regardless of the season. In extreme droughts, water rationing is generally preferred.

[3] It seems that the two main motives for water managers to continue to defend increasing blocks are their alleged ability to benefit smaller users and their potential role in signaling scarcity. The lower prices charged for the first cubic meters of water are meant to favor lower-income consumers, who use water mainly for essential uses such as drinking, washing, bathing, or toilet flushing. The higher prices in the following blocks are set to induce water savings from other users, such as wealthier households with nonessential uses like watering gardens or filling pools. The increasing block tariff (IBT) is thus a form of cross subsidization, where access to an essential good by poorer users is paid for through the penalization of higher consumptions by richer users. However, if poorer households are larger because of either larger family size or the necessity of sharing a meter, increasing prices can end up penalizing the lower-income households that they are meant to benefit [*Komives et al.*, 2005]. A third objective that can be achieved through an IBT is revenue neutrality [*Hanemann*, 1997]. Although other tariff structures could be used to meet this goal, an IBT is one way of allowing utilities to break even in a situation of increasing marginal costs while still using efficient marginal cost pricing for the upper blocks. One last justification for an IBT given in the literature is the positive externality from a public health point of view of a minimum amount of clean water, "reducing the risks of communicable diseases throughout the community" [*Boland and Whittington*, 2000, p. 220], especially in developing countries.

[4] Highlighting the link between climate and the use of IBTs, *Hewitt* [2000, p. 275] notes that "utilities are more likely to voluntarily adopt . . . [IBT] if they are located in climates characterized by some combination of hot, dry, sunny, and lengthy growing season," which is confirmed by several recent Organisation for Economic Co-operation and Development (OECD) publications [*OECD*, 2003, 2006, 2009]. For instance, in Europe, IBTs are more common in the Mediterranean countries, such as Portugal, Spain, Italy, Greece, and Turkey. IBTs are commonly used by Portuguese water utilities to price residential water consumption, even though tariffs are independently chosen by each of the more than 300 municipalities. Portuguese residential water tariffs typically have both a meter charge and a volumetric price, and the latter almost always consists of an IBT. More surprisingly, considering the significant seasonal differences in water availability in the country, seasonal price variations are not common, and the few that do exist seem to be uncorrelated with regional climate characteristics. It should also be emphasized that many utilities incorporate a (large) number of further complications into their water rate calculations, such as the implementation of

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formulas within blocks, the existence of initial blocks with fixed rates, or the application of special contracts, so complexity is definitely the prevailing feature of water tariffs in Portugal. In an attempt to simplify matters, the Regulating Authority for Water and Waste (ERSAR) has included a four-block tariff design in its recent proposal for a tariff regime to promote efficient water pricing.

[5] In contrast, the literature on efficient tariff design does not generally recommend increasing price schedules. Only part of the abundant literature on water pricing provides efficiency results since most studies either compare the properties of different possible price schemes or estimate water demand, and many also point out the difficulties in moving toward more efficient pricing rules. Many important issues, as summarized in the extensive literature review done by *Monteiro* [2005], are not specific to the water sector: marginal cost pricing, capacity constraints, resource scarcity, revenue requirements, and nonlinear pricing are significant in the more general framework of regulated public utilities, as is clear from studies by *Brown and Sibley* [1986] and *Wilson* [1993]. However, such issues appear in this sector combined with some of its peculiarities, such as the prevalence of local natural monopolies, the seasonal and stochastic variability of the resource it aims to supply, and the essential value of the good for its consumers. Nonetheless, *Monteiro* [2005] notes that whenever justifications for increasing block rates appear, they are not directly related to scarcity concerns. Although in the presence of water scarcity the true cost of water increases because of the emergence of a scarcity cost, it is unclear whether increasing block tariffs are the best way to make consumers understand and respond to water scarcity situations, especially when the resulting tariffs are very complex. Our contribution in this paper is to investigate whether climate variables affect Ramsey price structures and, in particular, whether consideration of such variables can contribute to the choice of an IBT as an efficient pricing strategy. A recent related study in the pricing literature is the one by *Elnaboulsi* [2009], which includes a climate parameter in consumer utility and looks at the impact of demand and capacity shocks on state-contingent contracts. However, that study is purely theoretical, and it does not evaluate the properties of the derived nonlinear pricing expression, thus steering clear of the debate on IBTs.

[6] Current analysis of this issue is especially relevant considering that the Water Framework Directive [*European Union*, 2000] (article 9, number 1) required that by 2010, pricing policies in the European Union's member states not only recover the costs of the resource (including environmental and scarcity costs) but also provide adequate incentives for consumers to use water efficiently, contributing to the attainment of environmental quality targets. The problem of water scarcity in particular is now recognized by European institutions [*European Environment Agency*, 2009] as an increasingly relevant one in the face of potentially more frequent extreme weather events due to climate change, as can be seen in a recent communication issued on the topic by the *European Commission* [2007].

[7] We propose different models of efficient and second-best nonlinear prices under scarcity constraints and conclude that when both demand and costs respond to climate factors, increasing marginal prices may, indeed, come about as a response to a combination of water scarcity and customer heterogeneity under specific conditions, which we derive, although nonlinear pricing is still a consequence of consumer heterogeneity and not explicitly of water scarcity. Furthermore, we then test whether those conditions hold in Portugal by estimating the water demand function and analyzing the behavior of its price elasticity. Unlike in previous publications on water demand estimation, special attention is given here to the choice of functional form for the water demand equation, as it determines the restrictions on the price elasticity of demand. We compare the properties of the most widely used functional forms and test these for Portuguese data.

2. Scarcity in a Simple Model

[8] A simple and intuitive view of the main aspects of efficiency in water prices is presented by *Griffin* [2001, 2006]. His model includes three pricing components: the volumetric (i.e., per unit) price, the constant meter charge, and the one-off connection charge. The latter is meant to reflect network expansion costs and will not be considered in our model since access to water supply networks is nearly universal in Portugal, with 92.3% nationwide connection rates and 100% in urban areas [*Agência Portuguesa do Ambiente*, 2008; *Instituto da Água*, 2008]. Moreover, we focus on the volumetric part of the tariff, assuming that the fixed charge, if any, is calculated so as to cover exactly the fixed costs of the water supply activity, which is the legally admissible situation in Portugal since the publication of law 12/2008. On the other hand, *Griffin* [2001] assumes a single volumetric price and does not allow for more general nonlinear prices. In fact, *Griffin* [2001, pp. 1339, 1342] stresses "the inefficiencies of block rate water pricing," most prominently the fact that multiple blocks obscure the marginal price signal. A somewhat different approach to the issue of water pricing under scarcity is presented by *Moncur and Pollock* [1988], where water is treated as a nonrenewable resource with a backstop technology. Our model is closer to that of *Griffin* [2001], although we develop it further to include nonlinear prices due to customer heterogeneity (the relevance of which is pointed out by *Krause et al.* [2003]) and also to analyze the impact of climate variables (see section 4).

[9] Considering a static model for different consumer groups, defined by their heterogeneity in relevant variables (see section 3) with a scarcity constraint, shows that the marginal cost pricing rule still holds. Define $B_j(w_j)$ as the increasing and concave monetized benefit of water consumption for consumer group j, with $j = 1, \ldots, J$ and $\mathrm{d}B_j/\mathrm{d}w_i = 0$ for $i \neq j$, and define $C(w)$ as the (convex) water supply costs, which depend on the total water supplied, i.e., $w = \sum_{j=1}^{J} w_j$. The assumption that costs are convex in w means that marginal costs increase as more water is supplied, and we also introduce a direct scarcity constraint to reflect ecosystem limits on water abstraction. In particular, we assume there is a limit to water availability, with the maximum amount denoted as W. The welfare maximization problem is

$$\begin{aligned} &\max_{\{w_j\}} \sum_{j=1}^{J} B_j(w_j) - C(w) \\ &\text{s.t.} \sum_{j=1}^{J} w_j \leq W, \end{aligned} \tag{1}$$

resulting in first-order conditions

$$\frac{\mathrm{d}B_j}{\mathrm{d}w_j} = \frac{\mathrm{d}C}{\mathrm{d}w} + \mu \qquad \forall_j, \tag{2}$$

$$\sum_{j=1}^{J} w_j \leq W, \quad \mu \geq 0, \quad \mu\left(W - \sum_{j=1}^{J} w_j\right) = 0, \tag{3}$$

where μ is the Lagrangian multiplier and it is assumed that all w_j are positive (every consumer requires a minimum amount of water). The efficiency result, expressed in equation (2), indicates that the marginal benefit of water consumption should be equal to long-run marginal costs (including scarcity costs if the constraint is binding). Also, the marginal benefit needs to be the same across consumer groups since marginal cost is the same. Finally, with a unit price p_j, the benefit maximization problem for each consumer group is

$$\max_{w_j} \; B_j(w_j) - p_j w_j, \tag{4}$$

$$\Leftrightarrow \frac{\mathrm{d}B_j}{\mathrm{d}w_j} = p_j, \tag{5}$$

so the efficient unit price must be the same for all consumer groups and is given by

$$p = \frac{\mathrm{d}C}{\mathrm{d}w} + \mu, \tag{6}$$

as given by *Griffin* [2006]. The lower W is, the tighter the constraint is, meaning that price should rise to reflect increasing scarcity. However, this rule does not ensure that the water utility's budget is balanced, namely, if there are fixed costs or if marginal cost is not constant. Several rate structure options could be employed to achieve balanced budget requirements, but for the aforementioned legal reasons, we assume fixed costs are covered by fixed rates and thus can be excluded from the pricing analysis for simplicity. We choose to obtain a second-best pricing rule through the application of a break-even constraint such as (7) on problem (1). This is known as Ramsey pricing. Naturally, the results derived here arise from this choice, supporting different volumetric prices for different customers because we seek the least inefficient way to balance the utility's accounts with volumetric rates as the only available instrument. In other conditions, alternative instruments could be explored (e.g., meter charges or revenue transfers).

$$\sum_{j=1}^{J} p_j(w_j) w_j - C(w) = 0. \tag{7}$$

[10] Note that $p_j(w_j) = \mathrm{d}B_j/\mathrm{d}w_j$ is the inverse demand of consumer j. Using equation (5), the welfare-maximizing prices with the break-even constraint will now be given by

$$\frac{p_j - \left(\frac{\mathrm{d}C}{\mathrm{d}w} + \frac{\mu}{1+\lambda}\right)}{p_j} = \frac{\lambda}{1+\lambda} \frac{1}{\xi_j\left(w_j^*\right)}, \tag{8}$$

where ξ_j is the absolute value of the price elasticity of j's demand and λ is the Lagrange multiplier of (7). This is a version of the so-called inverse elasticity rule, which states that the markup of prices over marginal cost will be inversely related to the demand elasticity, so consumer groups with lower demand elasticities will pay higher prices and vice versa. The only new term is $\mu/(1+\lambda)$, which reflects the scarcity cost. It adds the opportunity cost of using a scarce resource to the price faced by the consumer, but it does not affect the shape of the price schedule. Nonlinear prices may arise in this model because of heterogeneity in the consumers' preferences (different price elasticities) but not because of scarcity. Nonlinear prices would be increasing if the price elasticities decrease (in absolute value, getting closer to zero) with higher optimal consumption choices and decreasing otherwise.

[11] It should be noted that if the scarcity cost is recovered by a tax that the supplier collects but does not keep (along the lines of what is already done in some European countries), the model will have to be changed accordingly. In particular, if water sources are shared, the tax can be defined by a water authority that oversees several suppliers since none of them individually will provide adequately for common property (external) scarcity costs. In Portugal a new water resource charge (paid by consumers) was introduced in 2008. The resulting revenue is handed to the river basin authorities, the national water authorities, and a national tariff-balancing fund.

3. Scarcity With a Distribution of Consumer Types

[12] In this section a more complete model is presented, explicitly characterizing demand behavior through the definition of a continuum of consumer types. Model development is based on the work of *Brown and Sibley* [1986] and *Elnaboulsi* [2001]. A new parameter θ is introduced to reflect differences in consumer tastes, which can encompass a number of variables. For practical purposes, in the empirical estimation of section 5, θ will represent only income, but in theory, customer heterogeneity could stem from any variable that affects residential water demand differently across consumers, such as family size or housing type. A consumer with tastes given by θ will now enjoy net benefits of $B(w,\theta) - P(w)$, where $P(w)$ is the total payment for water consumption. It is assumed that $B(0,\theta) = 0$ and that high values of θ imply higher consumption benefits ($\partial B/\partial\theta > 0$, $\partial^2 B/\partial\theta\partial w > 0$). The distribution of θ throughout the consumer population is described by a distribution function $G(\theta)$ and the associated density function $g(\theta)$. Maximum and minimum values for the taste parameter are represented by $\overline{\theta}$ and $\boldsymbol{\theta}$, respectively, so $G(\overline{\theta}) = 1$ and $G(\boldsymbol{\theta}) = 0$.

[13] The first-order condition of each consumer's net benefit maximization is

$$\frac{\partial B(w,\theta)}{\partial w} = \frac{\mathrm{d}P}{\mathrm{d}w} \equiv p_m, \tag{9}$$

which is similar to condition (5) except the right-hand side represents the slope of the total payment function, i.e., the marginal price p_m. The only restriction to the shape of $P(w)$ is that if concave, it must be less so than the benefit function to ensure that the decision is, indeed, a maximizing one. Using the consumer's choice $w(\theta)$, the value function is

$$V(\theta) = B[w(\theta), \theta] - P[w(\theta)]. \tag{10}$$

[14] To find the properties of the optimal payment function with a scarcity restriction, or rather the second-best function given the break-even constraint, the following problem can be solved:

$$\begin{aligned} &\max_{w(\theta)} \int_{\boldsymbol{\theta}}^{\bar{\theta}} V(\theta)g(\theta)\mathrm{d}\theta + \int_{\boldsymbol{\theta}}^{\bar{\theta}} \{P[w(\theta)] - C[w(\theta)]\}g(\theta)\mathrm{d}\theta \\ &\text{s.t.} \quad \int_{\boldsymbol{\theta}}^{\bar{\theta}} \{P[w(\theta)] - C[w(\theta)]\}g(\theta)\mathrm{d}\theta = 0 \\ &\qquad\quad \int_{\boldsymbol{\theta}}^{\bar{\theta}} w(\theta)g(\theta)\mathrm{d}\theta \leq W, \end{aligned} \tag{11}$$

where the first component of the objective function represents consumer surplus aggregating all consumer types and the second component is profit. Some manipulations yield a more tractable version of the problem. Substituting $P[w(\theta)]$ using equation (10), noting that $G(\theta) - 1 = \int g(\theta)\mathrm{d}\theta$, and using the envelope theorem to see that $\partial V/\partial\theta = \partial B/\partial\theta$, consumer surplus can be rewritten using integration by parts as

$$\int_{\boldsymbol{\theta}}^{\bar{\theta}} V(\theta)g(\theta)\mathrm{d}\theta = V(\boldsymbol{\theta}) + \int_{\boldsymbol{\theta}}^{\bar{\theta}} \frac{\partial B}{\partial\theta}[1 - G(\theta)]\mathrm{d}\theta, \tag{12}$$

and the Lagrangian that must be maximized is

$$\begin{aligned} \mathcal{L} = &-\lambda V(\boldsymbol{\theta}) + \int_{\boldsymbol{\theta}}^{\bar{\theta}} (1+\lambda)\{B[w(\theta), \theta] - C[w(\theta)]\}g(\theta) \\ &- \lambda\frac{\partial B}{\partial\theta}[1 - G(\theta)]\mathrm{d}\theta + \mu\left(W - \int_{\boldsymbol{\theta}}^{\bar{\theta}} w(\theta)g(\theta)\mathrm{d}\theta\right). \end{aligned} \tag{13}$$

[15] For the case where $V(\boldsymbol{\theta}) = 0$, which is the most relevant, the consumer with the lowest taste parameter value has no net benefit, and the first-order condition for each θ is

$$\begin{aligned} \frac{\partial\mathcal{L}}{\partial w(\theta)} = 0 \Leftrightarrow (1+\lambda)\left(\frac{\partial B}{\partial w} - \frac{\partial C}{\partial w}\right)g(\theta) \\ - \lambda\frac{\partial^2 B}{\partial w\partial\theta}[1 - G(\theta)] - \mu g(\theta) = 0. \end{aligned} \tag{14}$$

[16] Using equation (9), a markup condition similar to the one from the previous model (equation (8)) can be derived:

$$\frac{p_m - \left(\frac{\partial C}{\partial w} + \frac{\mu}{1+\lambda}\right)}{p_m} = \frac{\lambda}{1+\lambda}\frac{1}{\xi(w, \theta)}, \tag{15}$$

where $\xi(w, \theta)$ represents the absolute value of the elasticity in each incremental market or consumer group (see Appendix A). As expected, the same conclusions as in the discrete case apply to this model regarding the role of customer heterogeneity (here represented by different θ) in generating nonlinear prices, while the scarcity cost does not affect the price schedule shape, only its level.

4. Scarcity in Demand, Cost, and Availability

[17] The sections 2 and 3 have shown that scarcity, represented as a quantity constraint, has a direct effect that can be seen as an increase in real marginal cost, so that even when coupled with a budget-balancing restriction, it cannot in itself explain a preference for increasing rates. In order to evaluate other effects of scarcity in a more general sense, this section introduces into the previous models exogenous weather factors ϕ, which affect water availability as well as consumer benefits and supply costs. It is assumed that a higher value of ϕ means hotter and drier weather, implying that $\partial B_j/\partial\phi > 0$, $\partial^2 B_j/\partial w_j\partial\phi > 0$ (water demand increases, for example, due to irrigation or swimming pools), $\partial C/\partial\phi > 0$, $\partial^2 C/\partial w\partial\phi > 0$ (supply costs are higher due to extra pumping or treatment costs), and $\mathrm{d}W/\mathrm{d}\phi < 0$ (less available water).

[18] Introducing these factors into the models from sections 2 and 3 does not change the fundamental result for the second-best price schedule, expressed by the inverse elasticity rule. The first-order conditions for the discrete and the continuous cases are very similar, so we only present results once in a general form, which is

$$\frac{p_m - \left(\frac{\partial C(w^*, \phi)}{\partial w^*} + \frac{\mu}{1+\lambda}\right)}{p_m} = \frac{\lambda}{1+\lambda}\frac{1}{\xi(w^*, \theta, \phi)}. \tag{16}$$

[19] Nonlinear pricing is still a consequence of consumer heterogeneity and not of scarcity considerations. However, the shape of the resulting price schedule may now be affected by the influence of the exogenous weather factor on the price elasticities for the different consumer types.

[20] As noted, the marginal unit price and the markup for each consumer type or market increment depend inversely on its price elasticity of demand. Nonlinear prices would be increasing if demand becomes less price elastic with higher optimal consumption choices and decreasing otherwise. We can investigate the conditions under which the resulting price schedule is increasing, constant, or decreasing and how they are affected by the weather parameter. The partial derivative of elasticity with respect to the optimal level of water consumption is

$$\begin{aligned} &\frac{\partial\xi(w^*, \theta, \phi)}{\partial w^*} = \\ &-\frac{\left[\frac{\partial^2 B(w^*, \theta, \phi)}{\partial w^{*2}}\right]^2 w^* - \frac{\partial B(w^*, \theta, \phi)}{\partial w^*}\left[\frac{\mathrm{d}^3 B(w^*, \theta, \phi)}{\mathrm{d}w^{*3}}w^* + \frac{\partial^2 B(w^*, \theta, \phi)}{\partial w^{*2}}\right]}{\left[\frac{\mathrm{d}^2 B(w^*, \theta, \phi)}{\mathrm{d}w^{*2}}w^*\right]^2}. \end{aligned} \tag{17}$$

[21] The price schedule will be increasing, constant, or decreasing according to whether $\partial\xi/\partial w^*$ is negative, null, or positive. In order for elasticity to stay the same regardless of consumption, implying that the efficient unit price is

constant, the following condition is necessary and sufficient:

$$\frac{\partial \xi(w^*, p_m)}{\partial w^*} = 0 \Leftrightarrow \frac{\frac{\partial B}{\partial w^*}\left[\frac{\partial^3 B}{\partial w^{*3}} w^* + \frac{\partial^2 B}{\partial w^{*2}}\right]}{\left[\frac{\partial^2 B}{\partial w^{*2}}\right]^2 w^*} = 1. \tag{18}$$

[22] Likewise, for $\partial \xi / \partial w^* < 0$, the expression on the right-hand side of equation (18) must be smaller than 1, and for $\partial \xi / \partial w^* > 0$, it must be greater than 1. It can be seen that the sign of $\partial^3 B / \partial w^{*3}$, which reflects the curvature of the demand function, plays a very important role in determining the shape of the resulting price schedule. In particular, given an increasing and concave benefit $B(w)$, $\partial^3 B / \partial w^{*3} \leq 0$ is a sufficient condition for an IBT to be efficient. This condition means the demand (marginal benefit) function is concave, which is related to an accelerating decrease in the marginal benefit as consumption grows larger.

[23] Additionally, we can analyze the impact of the weather parameter on the price schedule by differentiating expression (18) in relation to ϕ. We omit the lengthy resulting expression and present only sufficient conditions for the result to be negative, i.e., for the influence of the weather variable on the price schedule to reinforce the case for an IBT:

$$\frac{\partial^3 B}{\partial w^{*3}} \leq 0, \tag{19}$$

$$\frac{\partial^3 B}{\partial w^{*2} \partial \phi} \geq 0, \tag{20}$$

$$\frac{\partial^4 B}{\partial w^{*3} \partial \phi} \leq 0. \tag{21}$$

[24] Condition (19) requires concavity of the demand function, so that an IBT would be efficient in the first place. Condition (20) implies that the demand function's negative slope would have to be constant or to become less steep as temperature and dryness increase. Finally, condition (21) requires the demand function's curvature to be constant or to become more concave as temperature and dryness increase. Why do these conditions favor the adoption of IBTs in hotter and drier regions or time periods? They seem to create a framework where willingness to pay for water consumption increases more with temperature for high-demand consumers than for those with low-demand profiles, decreasing the difference in marginal valuation of the initial consumptions and the more extravagant ones. This is consistent with the fact that low-demand residential consumers have a mainly indoor water use, which does not vary much with weather conditions, whereas high-demand residential consumers include those with gardens to water or swimming pools to fill in the summer, therefore showing a demand pattern that varies more with weather.

[25] High-demand residential consumers are also usually associated with higher income levels (reflected in θ in our model), which means that water expenses may weigh very little on their budget. In this context, relative water demand rigidity between high- and low-demand users may increase, with high-income, high-demand users being more willing and able to afford the ever-scarcer water as temperature increases. The fact that high-income residential consumers tend to have more rigid water demands has been empirically demonstrated, for example, by *Agthe and Billings* [1987], *Renwick and Archibald* [1998], and *Mylopoulos et al.* [2004]. In the presence of a Ramsey pricing policy (with price levels inversely related with price elasticities of demand) this would mean that the tariff schedule would tend toward an IBT as temperature increases and a bigger share of the water utility's revenues would be generated by high-demand consumers, which may be an explanation for the fact that IBTs are more frequent in countries with hotter and drier climates.

[26] *Roseta-Palma and Monteiro* [2008] provide some additional results for the model. In particular, when marginal cost pricing is followed, if the marginal benefit functions and the way they respond to weather conditions $(\partial^2 B_j / \partial w_j \partial \phi)$ differ enough among consumer types, it may be efficient for some consumers (those whose willingness to pay increases more with temperature increases and the resulting scarcity) to increase their water consumption in drier periods, while those whose marginal benefits change less will save more water. This is not the case in the context of a Ramsey pricing policy, where the greater willingness to pay from such consumer types will be reflected in less elastic water demand, so that the water utility will assign them a higher price and they will also consume less water. It can also be shown that the scarcity cost will not necessarily increase with ϕ because of the effect on supply costs. The intuitive result that drier and hotter weather will increase scarcity cost arises if the marginal benefit of water consumption increases more with drier weather conditions than the marginal cost of water supply. This is confirmed by a dynamic model of water supply enhancement, where the same condition is necessary for optimal investments in water supply to increase with an expected permanent increase in ϕ (such as the one that would occur for Mediterranean areas in the context of global warming).

5. Estimation of Portuguese Residential Water Demand

[27] In section 4 we included climate variables in a pricing model and analyzed the impact of such variables on the price structure. From the inverse-elasticity rule (16) we know that a necessary and sufficient condition for nonlinear increasing tariffs is for demand to become less price elastic with higher levels of water consumption. Therefore, we now estimate water demand and check whether this condition holds, implying that nonlinear increasing tariffs would be justified.

5.1. Importance of the Choice of Functional Form

[28] The water demand function can be written as

$$w = w(p, \theta, \phi, z), \tag{22}$$

where w is the quantity of water demanded and p is the water price. As previously defined, θ stands for income and ϕ represents weather variables such as temperature and precipitation. The vector z can include other household attributes related to water consumption such as garden or household size, age and education of household members, or the number of water-using appliances, just to name a few. Here $w(\ldots)$ is a parametric function that can take one of several available functional forms.

[29] The choice of the functional form for the equation to be estimated is one of the important decisions to be made by the empirical analyst. Five types of functional forms are most commonly used in the estimation of residential water demand: linear, double-log, semilogarithmic (lin-log or log-lin), and Stone-Geary. The choice of one of these options is not neutral and can have an impact on the results. For instance, *Espey et al.* [1997] and *Dalhuisen et al.* [2003] include a dummy variable for log linear specifications in their meta-analysis of the price elasticities of water demand estimated in the literature and find positive coefficients, meaning that, with all else being equal, a log linear specification may result in a less elastic estimate. This fact is known to empirical researchers, despite the fact that it has received less attention than other aspects of the estimation process, such as the choice of the estimation technique [*Renzetti*, 2002].

[30] To see whether demand becomes less price elastic with higher levels of water consumption, we can look directly at the implications of each functional form on the behavior of the price elasticity of demand. Note that equations (20) and (21) are zero for these functional forms. Table 1 presents the price elasticities for the aforementioned functional forms, where w, p, θ, ϕ, and z are defined as above and a, b, c, d, f, g, and h are parameters. In the Stone-Geary specification, g stands for the fixed proportion of the supernumerary income spent on water (the residual income after the essential needs of water and other goods have been satisfied), and h stands for the fixed component of water consumption (unresponsive to prices). See *Martínez-Espiñeira and Nauges* [2004] for more details on the Stone-Geary functional form. The signs for the parameters given in Table 1 are those we expect from the theoretical model. Weather variables with a negative impact on water consumption can be included in vector ϕ with a minus sign or with an inverse transformation so that $c > 0$.

[31] We can see that demand becomes less elastic (price elasticity becomes less negative) with higher consumption for most functional forms. Only the double-log case is associated with constant elasticity (this is, in fact, one of the reasons it is so appealing), whereas the Stone-Geary specification has an undetermined result, dependent on the actual values taken by the variables and the associated parameters. Therefore, under the assumptions of our model, an IBT will be a natural consequence of demand characteristics for all cases except these two.

5.2. Model and Data

[32] Annual data on water consumption and water and wastewater tariffs were provided by the Portuguese National Water Institute (INAG) for the years 1998, 2000, 2002, and 2005 (annual consumption was divided by 12 to get average monthly water consumption). The data consist of aggregate data for all 278 municipalities in mainland Portugal, excluding the Azores and Madeira archipelagos for which no information was available. The data have been combined with information on income, weather, water quality, and household characteristics from the Ministry of Finance and Public Administration, the National Weather Institute, ERSAR, and the National Statistics Institute, respectively. Because of the presence of missing data concerning consumption levels the data constitute an unbalanced panel for the study period. The missing data problem was minimized through direct collection of additional information on consumption and tariffs from the water and wastewater utilities of each municipality.

[33] The estimated model is

$$\begin{aligned} w_{it} &= f(p_{it}, D_{it}, F_{it}, \theta_{it}, \phi_{1it}, \phi_{2it}, \mathrm{qual}_{it}, \mathrm{nobath}_i, \mathrm{elder}_i, \mathrm{seasonal}_i) \\ &\quad + \alpha_i + \varepsilon_{it}, \alpha_i \sim IID\left(0, \sigma_\alpha^2\right), \quad \varepsilon_{it} = \varepsilon_{it-1} + v_{it}, \\ &\quad v_{it} \sim IID\left(0, \sigma_v^2\right). \end{aligned} \tag{23}$$

[34] The formulation of the error variable as the sum of a municipality effect and an autoregressive component is not assumed from the outset but is instead the result of the preliminary analysis.

[35] Tables 2 and 3 show the definition of the main variables used and some summary statistics. The inclusion of a "difference variable," defined by the difference between the variable part of the water and sewage bill and the value it would have had if all the volume had been charged at the marginal price, is standard in the literature and is meant to capture the income effect of the block subsidy implied by the IBT structure. The fixed part of the bill is included as well because, in theory, it can also have an income effect on consumption.

[36] Note that residential water tariffs in Portugal are very diverse. For water supply, almost all utilities charge both fixed and variable rates (97.5%), and in the latter, 98.6% use IBTs. The average number of blocks is 5, although some utilities define as many as 30. The majority of utilities apply the price of each block to the consumption within that block, although 18% bill consumers for the full volume at the price of the highest block, giving rise to marginal price "peaks" at the blocks' lower limit. Wastewater services are not universally charged, with a zero price in 21% of utilities. Around one third include fixed and

Table 1. Price Elasticities of Demand for Several Functional Forms[a]

Type	Functional Form	Price Elasticity $\xi_p = \frac{\partial w}{\partial p}\frac{p}{w}$	$\frac{\partial \xi_p}{\partial w}$
Linear	$w = ap + b\theta + c\phi' + \mathrm{d}z' + f$	$a\frac{p}{w} = 1 - \frac{(b\theta + c\phi' + \mathrm{d}z' + f)}{w}$	>0
Double-log	$\ln w = a \ln p + b \ln \theta + c \ln \phi' + \mathrm{d}z' + f$	a	$=0$
Semilogarithmic (log-lin)	$\ln w = ap + b\theta + c\phi' + \mathrm{d}z' + f$	$ap = \ln w - (b\theta + c\phi' + \mathrm{d}z' + f)$	>0
Semilogarithmic (lin-log)	$w = a \ln p + b \ln \theta + c \ln \phi' + \mathrm{d}z' + f$	$\frac{a}{w}$	>0
Stone-Geary	$w = (1-g)h + g\frac{\theta}{p} + c\phi' + \mathrm{d}z'$	$-\frac{g\theta}{wp} = -1 + \frac{[(1-g)h + c\phi' + \mathrm{d}z' + f]}{w}$	Undetermined

[a]Assumptions are as follows: $a < 0; b, c, g > 0; b\theta + c\phi + \mathrm{d}z' + f > 0$; $\ln w - (b\theta + c\phi + \mathrm{d}z' + f) > 0$.

Table 2. Definition of Variables

Variable	Definition
w	Average monthly water consumption (m^3/month)
p	Marginal price of water supply and sewage disposal (per m^3)
D	Difference variable/variable part of the water and sewage bill − (MP*Water) (per month)
F	Fixed part of the water and sewage bill (per month)
θ	Per capita available income (10^3 per person per year)
ϕ_1	Total annual precipitation (mm)
ϕ_2	Average annual temperature (°C)
qual	Percent of delivered water analysis failing to comply with mandatory parameters
nobath	Percent of regularly inhabited dwellings without shower or bathtub
elder	Percent of population with 65 or more years of age
seasonal	Percent of dwellings with seasonal use

variable charges, and another third have only variable rates. In the absence of sewage meters, these are typically based on water consumption, although they can also be a proportion of the water supply bill (see *Monteiro* [2009] for a more detailed description).

5.3. Methodology and Estimation

[37] We deal with the known endogeneity problem in the price-related variables p and D by creating instrumental variables from the tariff unit prices for specific volumes of consumption. We look at unit prices for monthly consumptions of 1, 5, 10, 15, and 20 m^3 (this procedure is also followed by *Reynaud et al.* [2005]), the utility's calculation procedure (whether each unit is charged at the price of its block or all are charged at the unit price of the last block reached), and the type of water utility (municipality, private company, and others). The instruments for p are dummy variables for the type of utility, the utility's calculation procedure, and the tariff prices at 5, 10, and 15 m^3. The instruments for the difference variable are the utility's calculation procedure and the tariff prices at 1, 10, and 20 m^3. The Anderson, Sargan, and difference-in-Sargan tests are performed to check on instrument relevance and validity (the xtivreg2 procedure for Stata [*Schaffer*, 2007] is used). Regarding the instruments for p, the Anderson underidentification test rejected the null hypothesis of the instruments' irrelevance (test statistic of 16.076, p value for $\chi^2(7)$ of 0.024), while the Sargan test of instrument validity did not reject the null of the instruments' validity (test statistic of 6.333, p value for $\chi^2(6)$ of 0.387). Regarding the instruments for the difference variable, the Anderson test rejected the instruments' irrelevance (test statistic of 16.368, p value for $\chi^2(4)$ of 0.003), while the Sargan test of instrument validity did not (test statistic of 1.877, p value for $\chi^2(3)$ of 0.598). Difference-in-Sargan tests for each instrument (for either p or D) did not reject the null hypothesis of individual instrument validity for any of them.

Table 3. Summary Statistics

Variable	N	Mean	Standard Deviation	Minimum	Maximum
w	884	7.46	2.21	2.46	19.50
p	871	0.62	0.39	0.05	4.59
D	875	−0.73	1.24	−14.35	2.50
F	864	2.09	1.35	0.00	10.49
θ	1112	3.48	3.27	0.67	29.80
ϕ_1	1112	877.53	435.65	205.47	2807.75
ϕ_2	1112	15.27	1.34	10.93	18.15
qual	1106	4.06	4.40	0.00	40.09
nobath	1112	9.75	5.54	7.91	33.76
elder	1112	20.83	6.33	7.52	42.02
seasonal	1112	23.98	11.13	4.54	54.10

[38] Heteroskedasticity and autocorrelation are detected in the data. We use a generalized least squares (GLS) estimator with first-order autoregression (AR(1)) disturbances to account for them. The Breusch-Pagan Lagrangian multiplier test confirms the presence of municipal specific effects, and the Hausman test does not reject the null hypothesis of independence between the municipal effects and the exogenous regressors (this procedure is also followed by *Dalmas and Reynaud* [2005]). Therefore, the GLS estimator (random effects) is not only efficient but also consistent, so we choose to use it.

[39] Finally, a price perception test [*Nieswiadomy and Molina*, 1991] was performed and confirmed that consumers respond to the marginal rather than the average price. The test procedure starts by considering a "price perception variable" (P^*), where k is the price perception parameter to be estimated, p is the marginal price of water services, and AP is the average price:

$$P^* = p\left(\frac{\mathrm{AP}}{p}\right)^k. \quad (24)$$

[40] A value of 0 for k would mean that consumers were responding to marginal price, rather than average price, while a value of 1 would have the opposite meaning. We adapt the test to our panel data framework by including the ratio AP/p in an estimation of a double-log functional form for water demand together with the marginal price and all other regressors unrelated to the tariffs with an error structure similar to the one described above. The k can be recovered after the estimation by dividing the coefficients associated with ln(AP/p) and ln p. Because the endogeneity suspicions apply to the average price as well as the marginal price, we start by instrumenting it also. The instruments for the AP are the fixed component of the tariff, the tariff price at 10 m^3, and the utility's calculation procedure. The Anderson underidentification test rejected the instrument's irrelevance (test statistic of 348.31, p value for $\chi^2(4)$ of 0.00), while the Sargan test of instrument validity did not (test statistic of 4.356, p value for $\chi^2(3)$ of 0.23). Difference-in-Sargan tests for each instrument did not reject the null hypothesis of individual instrument validity for any of them. The coefficients estimated for ln(AP/p) and ln p are 0.0208 and −0.1110, respectively, and the value for k is −0.188. After the model was estimated, the following nonlinear hypothesis were tested: $k = 0$ and $k = 1$. The test statistics were 0.23 for $k = 0$ (p value for $\chi^2(1)$ of 0.6347) and 9.04 for $k = 1$ (p value for $\chi^2(1)$ of 0.0026), so $k = 0$ is not rejected, while $k = 1$ is, meaning that Portuguese consumers do respond to the marginal price and not to the average price of water.

5.4. Results

[41] Table 4 presents the estimation results for the functional forms considered in Table 1, including the values

Table 4. Estimation Results[a]

Variable	Functional Form				
	Linear	Double-log	Log-lin	Lin-log	Stone-Geary
p	−1.515*** (0.453)	−0.121*** (0.036)	−0.180*** (0.057)	−0.993*** (0.280)	-
D	−0.212 (0.185)	−0.003 (0.023)	0.013 (0.023)	−0.130 (0.184)	−0.022 (0.161)
F	−0.048 (0.068)	0.002 (0.021)	−0.001 (0.008)	−0.082 (0.163)	−0.082 (0.067)
θ	0.077*** (0.030)	0.087*** (0.025)	0.009** (0.004)	0.565*** (0.198)	-
$(\theta \times 10^3)/p$	-	-	-	-	0.0008*** (0.0002)
ϕ_1	−0.0002 (0.0002)	−0.030† (0.019)	−0.00002 (0.00002)	−0.267* (0.151)	−0.0002 (0.0002)
ϕ_2	0.285*** (0.083)	0.573*** (0.160)	0.043*** (0.011)	3.217*** (1.241)	0.274*** (0.084)
seasonal	−3.989*** (1.094)	−0.123*** (0.030)	−0.651*** (0.141)	−0.870*** (0.233)	−3.401*** (1.066)
nobath	−5.705 (2.127)	−0.042 (0.028)	−0.852*** (0.274)	−0.381* (0.214)	−4.551** (2.091)
elder	−8.286*** (1.913)	−0.238*** (0.055)	−1.125*** (0.244)	−1.672*** (0.423)	−8.249*** (1.928)
qual	−3.250** (1.568)	−0.012* (0.007)	−0.416** (0.189)	−0.091† (0.056)	−2.569† (1.572)
intercept	7.260*** (1.547)	−0.287 (0.491)	1.889*** (0.195)	−6.119 † (3.849)	6.284*** (1.536)
N	850	804	850	804	850
Wald $\chi^2(7)$	192.44***	258.49***	247.74***	209.32***	185.08***
Price elasticity	−0.124	−0.121	−0.110	−0.133	−0.051
Income elasticity	0.036	0.087	0.032	0.076	0.051

[a]Significance levels are indicated as follows: ***, significance at the 0.01 level; **, significance at the 0.05 level; *, significance at the 0.10 level; †, significance at the 0.15 level. Standard errors are given in parentheses.

derived for price and income elasticities in each case. The fact that the coefficients for the variables, which together compose the usual "difference" variable in the Taylor-Nordin price specification, are not significantly different from zero may be a demonstration that consumers are not aware of the block subsidy effect or simply do not react to it since it is small in comparison to their household income.

[42] All coefficients have the expected signs and most of them are significant at the 1% level. The value at the sample variable means for the price elasticity of demand varies between −0.133 and −0.051, a relatively small value, but in line with the established result that water demand is price inelastic. The estimated values are significantly lower than the value of −0.558 estimated by *Martins and Fortunato* [2007] for five Portuguese municipalities with monthly aggregate data but are similar to the values estimated by *Martínez-Espiñeira and Nauges* [2004] and *Martínez-Espiñeira* [2002] for Seville and Galicia in Spain, respectively.

[43] The weather-related variables have the expected signs; that is, water demand increases with temperature and decreases with precipitation, although only temperature has a significant coefficient for all functional forms. It would be interesting to consider more general functional forms by allowing interaction terms between weather-related variables and price. Thus, a household's response to price could vary directly with weather conditions. This approach was tried, but the interaction terms turned out to be nonsignificant, and a substantial amount of multicollinearity was introduced in the estimation, which is probably the consequence of using aggregate data. Further tests, using household data, would be needed to allow more general conclusions. Nevertheless, Table 1 shows that for some functional forms the price elasticity of demand does depend on the values of these variables.

[44] As expected, the percentage of seasonally inhabited dwellings has a significant negative effect on water consumption, as does the percentage of houses without a bathtub or a shower. The negative coefficient for the percentage of people 65 or older also confirms previous findings by *Nauges and Thomas* [2000], *Nauges and Reynaud* [2001], *Martínez-Espiñeira* [2002, 2003], and *Martins and Fortunato* [2007], who have all convincingly shown that older people use less water. Finally, the negative (and significant for some functional forms) coefficient for qual supports the view that consumers are aware of tap water quality and do decrease their consumption when they consider it inadequate, perhaps turning to bottled water, private boreholes and wells, or public fountains for their drinking and cooking water needs. This finding adds to the evidence of *Ford and Ziegler* [1981], who presented the only other study we are aware of that included delivered water quality as an explanatory factor for residential water demand.

[45] To choose between the functional forms presented in Tables 1 and 4, we now focus on three different methods: an encompassing approach [*Mizon and Richard*, 1986], a comprehensive approach, i.e., the J test [*Davidson and MacKinnon*, 1981], and the extended projection (PE) test [*MacKinnon et al.*, 1983]. The first two approaches (see Table 5) are used to compare nonnested models with the same dependent variable, while the PE test is used to compare models where consumption is defined in natural logarithms with models where it is introduced without that transformation [*Greene*, 2003]. The encompassing approach assumes one of the models being compared as the base model. Then, it proceeds to create and estimate a model where the variables from the alternative model not included in the base model are added to it. The null hypothesis of the test is that the coefficients of these additional variables are all zero. A t test or a Waldman F test, depending on whether one or more additional regressors were added to the base model, is performed to test the null hypothesis and the validity of the base model. The role of each model can be reversed, and the test can be performed again to test the validity of the alternative model. The comprehensive approach or J test consists of adding to the base model the fitted values of the alternative model and testing whether or not they are significantly different from zero by means of a t test. The null hypothesis of a zero coefficient corresponds to a valid base model. Finally, the PE test for

Table 5. Specification Tests Results and Resulting Preferred Functional Form[a]

	Functional Form			
	Double-log	Log-lin	Lin-log	Stone-Geary
Linear	Undetermined	Linear	Lin-log	Linear
Encompassing			H_0: linear; F test: 0.178 H_0: lin-log; F test: 0.862	H_0: linear; t test: 0.393 H_0: SG; F test: 0.095
Comprehensive	H_0: linear; t test: 0.013 H_0: d-log; t test: 0.001	H_0: linear; t test: 0.570 H_0: log-lin; t test: 0.000	H_0: linear; t test: 0.003 H_0: lin-log; t test: 0.343	H_0: linear; t test: 0.393 H_0: SG; t test: 0.037
Double-log		Double-log	Undetermined	Undetermined
Encompassing		H_0: d-log; F test: 0.448 H_0: log-lin; F test: 0.051		
Comprehensive		H_0: d-log; t test: 0.166 H_0: lin-log; t test: 0.001	H_0: d-log; t test: 0.000 H_0: lin-log; t test: 0.004	H_0: d-log; t test: 0.001 H_0: SG; t test: 0.008
Log-lin			Lin-log	Stone-Geary
Comprehensive			H_0: log-lin; t test: 0.000 H_0: lin-log; t test: 0.719	H_0: log-lin; t test: 0.002 H_0: SG; t test: 0.303
Lin-log				Lin-log
Encompassing				H_0: lin-log; F test: 0.847 H_0: SG; F test: 0.072
Comprehensive				H_0: lin-log; t test: 0.455 H_0: SG; t test: 0.000

[a]Comprehensive is J test or PE test. Here d-log is double-log, SG is Stone-Geary, and H_0 is null hypothesis.

the validity of the model with the linear specification of the dependent variable (base model) involves adding to this base model the difference between the natural logarithm of the fitted values for the base model and the fitted values for the alternative model (the one with the dependent variable in logarithms). The null hypothesis that the coefficient of this additional regressor is zero supports the linear model if it is not rejected and invalidates it against the alternative otherwise. To test the validity of the model with the dependent variable in logarithms, we must add to the log linear model the difference between fitted values of the linear model and the exponential function of the fitted values of the log linear model. The null hypothesis for this second model states that the coefficient of this additional regressor is zero. If rejected, it invalidates the log linear model, but if not rejected, then it may be preferable. The PE test is an adaptation of the J test for different dependent variables.

[46] Summing up the results, the Davidson-MacKinnon PE test fails to decide between a semilogarithmic functional form (lin-log) and a double-log functional form. All other specifications (Stone-Geary form, linear, or the log-lin semilogarithmic form) are rejected against at least one of the two previous alternatives. Recall that while a lin-log specification would lead to a recommendation of an IBT, the double-log functional form favors a uniform volumetric rate (either of them coupled with a fixed charge, leading to a multipart tariff for the former and a two-part tariff for the latter). Hence, our analysis of the Portuguese residential water demand does not enable us to conclude if the IBT typically applied by water utilities for residential water supply, and to a lesser extent to the wastewater component of the water bill, can be grounded on efficiency reasons.

6. Conclusion

[47] We set out to write this paper because of a puzzling question: if increasing block tariffs for water are not recommended in theoretical economic models, why are they so popular in practice? Clearly, having one block where water is charged at a low price (or even a small free allocation) can be justified by the need to ensure universal access to such a vital good. Yet the IBT schemes we found were much more complex than that. Water managers often mention that increasing rates signal scarcity and, as such, is a useful tool in reducing resource use. Yet after scanning the literature and developing our own models, a relatively strong conclusion stands out: the best way to allocate water when scarcity occurs is to raise its price in accordance with its true marginal cost, which includes the scarcity cost. Nonlinear pricing is a consequence of consumer heterogeneity and not specifically of scarcity considerations.

[48] However, we do show that the shape of the resulting price schedule may, in certain circumstances, be affected by the influence of the exogenous weather factor on the price elasticities of the demands for the different consumer types. If high-demand consumers' willingness to pay for water rises more with temperature increases relative to that of low-demand consumers, then an IBT may be more appropriate in countries with hotter and drier climates. This is consistent with the fact that Mediterranean European countries are often mentioned in OECD reports as making extensive use of IBTs.

[49] In a context where volumetric rates are the only available instrument for variable cost recovery, we tested the condition for an IBT to be efficient, derived from our model, through the estimation of Portuguese residential water demand and showed that the choice of functional form is crucial. After the appropriate specification tests, we are left with an inconclusive choice between a semilogarithmic lin-log functional form and a double-log specification: the former favors IBT, while the latter favors two-part tariffs. Thus, we have not been able to prove that the use of IBTs can be grounded in efficiency, but such a possibility could not be dismissed either. Therefore, it is possible that the widespread use of IBTs in Portugal is actually efficient, although decision makers may see it mainly as an issue of equity or perceived water conservation effects. Moreover, given that results depend on the specific demand function, additional research with nonparametric (or semiparametric) techniques should be carried out.

[50] Our demand estimation also produced some results that are relevant in themselves. In addition to the usual positive impacts of income, temperature, and water-using appliances and the negative impact of price and the proportion of elderly people, we also show that the proportion of seasonally inhabited dwellings and reduced water quality on delivery can have a significant negative influence on the amount of water that households consume.

[51] Further research should focus on gathering household-level data to increase data variability and improve the choice of the functional form. A database with enough detail would allow the use of discrete continuous choice models and to estimate the unconditional (on the block choice) price elasticity of demand. If intra-annual data are available, seasonal effects of weather variables and seasonal house occupancy on water demand could be ascertained. Finally, the current demand analysis could be combined with water supply information, taking into consideration the reduction in water availability that is expected for Portugal due to climate change. Such work is relevant for an assessment of climate change impacts in the residential water sector.

Appendix A: Derivation of Equation (15)

[52] This appendix contains the derivation of equation (15) [see also *Brown and Sibley*, 1986].

$$(1+\lambda)\left(\tfrac{\partial B}{\partial w} - \tfrac{\partial C}{\partial w}\right)g(\theta) - \lambda\tfrac{\partial^2 B}{\partial w \partial \theta}[1 - G(\theta)] - \mu g(\theta) = 0$$

since

$$\tfrac{\partial B(w,\theta,\phi)}{\partial w} = \tfrac{\mathrm{d}P}{\mathrm{d}w} \equiv p_m,$$

$$\Leftrightarrow (1+\lambda)\left(p_m - \tfrac{\partial C}{\partial w}\right)g(\theta) - \mu g(\theta) = \lambda\tfrac{\partial^2 B}{\partial w \partial \theta}[1 - G(\theta)] \Leftrightarrow,$$

$$\Leftrightarrow \frac{p_m - \left(\frac{\partial C}{\partial w} + \frac{\mu}{1+\lambda}\right)}{p_m} = \tfrac{\lambda}{1+\lambda}\tfrac{1}{p_m}\tfrac{\partial^2 B}{\partial w \partial \theta}\tfrac{[1-G(\theta)]}{g(\theta)} \Leftrightarrow,$$

$$\Leftrightarrow \frac{p_m - \left(\frac{\partial C}{\partial w} + \frac{\mu}{1+\lambda}\right)}{p_m} = \frac{\lambda}{1+\lambda}\frac{1}{p_m}\frac{1}{\dfrac{\partial \boldsymbol{\theta}}{\partial p_m}}\tfrac{[1-G(\theta)]}{g(\theta)} \Leftrightarrow,$$

where $\boldsymbol{\theta}$ indicates the marginal consumer group ($\boldsymbol{\theta} = \boldsymbol{\theta}[Q, P(Q)]$).

[53] Defining marginal willingness to pay $\rho(w,\theta)$, the self-selection condition is $\rho(w,\boldsymbol{\theta}) = p_m$, so

$$\frac{\mathrm{d}\rho}{\mathrm{d}p_m} = 1 \Leftrightarrow \frac{\partial \rho}{\partial \boldsymbol{\theta}}\frac{\partial \boldsymbol{\theta}}{\partial p_m} = 1 \Leftrightarrow \frac{\partial \boldsymbol{\theta}}{\partial p_m}\rho_\theta = 1 \Leftrightarrow \frac{\partial \boldsymbol{\theta}}{\partial p_m} = \frac{1}{\rho_\theta} > 0\,.$$

[54] Since

$$B_{w\theta} \equiv \frac{\partial^2 B(w,\theta)}{\partial w \partial \theta} \equiv \rho_\theta \equiv \frac{\partial \rho(w,\theta)}{\partial \theta}\,, \frac{\partial \boldsymbol{\theta}}{\partial p_m} = \frac{1}{B_{\theta w}}\,.$$

[55] Finally,

$$\Leftrightarrow \frac{p_m - \left(\frac{\partial C}{\partial w} + \frac{\mu}{1+\lambda}\right)}{p_m} = \tfrac{\lambda}{1+\lambda}\frac{1}{p_m\dfrac{\partial \boldsymbol{\theta}}{\partial p_m}\dfrac{g(\theta)}{[1-G(\theta)]}} \Leftrightarrow,$$

$$\Leftrightarrow \frac{p_m - \left(\frac{\partial C}{\partial w} + \frac{\mu}{1+\lambda}\right)}{p_m} = \tfrac{\lambda}{1+\lambda}\frac{1}{\xi(w,p_m)}\,,$$

which is the condition in the text. Then $\xi(w,p_m)$ emerges through the following manipulations:

$$\frac{\partial \ln p_m(w)}{\partial p_m(w)} = \frac{1}{p_m(w)}\,,$$

$$\frac{\mathrm{d}\ln[1 - G(\boldsymbol{\theta})]}{\mathrm{d}p_m(w)} = \frac{\partial \ln[1 - G(\boldsymbol{\theta})]}{\partial \ln p_m(w)}\frac{\partial \ln p_m(w)}{\partial p_m(w)} \Leftrightarrow,$$

$$\Leftrightarrow \frac{1}{[1 - G(\boldsymbol{\theta})]}\left(-g(\boldsymbol{\theta})\frac{\partial \boldsymbol{\theta}}{\partial p_m}\right) = \frac{\partial \ln[1 - G(\boldsymbol{\theta})]}{\partial \ln p_m(w)}\frac{1}{p_m(w)} \Leftrightarrow,$$

$$\Leftrightarrow \frac{\mathrm{d}\ln[1 - G(\boldsymbol{\theta})]}{\mathrm{d}\ln p_m(w)} = \frac{-g(\boldsymbol{\theta})\dfrac{\partial \boldsymbol{\theta}}{\partial p_m}p_m(w)}{[1 - G(\boldsymbol{\theta})]}$$

$$\Leftrightarrow -\frac{\partial \ln[1 - G(\boldsymbol{\theta})]}{\partial \ln p_m(w)} = \frac{g(\boldsymbol{\theta})\dfrac{\partial \boldsymbol{\theta}}{\partial p_m}p_m(w)}{[1 - G(\boldsymbol{\theta})]}\,.$$

[56] Note that, in general,

$$\xi_x f(x) = \frac{\partial f(x)}{\partial x}\frac{x}{f(x)} = \frac{\partial \ln f(x)}{\partial \ln x}\,.$$

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