Pricing for Scarcity?

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Abstract

In many areas where water is not abundant, water pricing schedules contain significant nonlinearities. Existing pricing literature establishes that efficient schedules will depend on demand and supply characteristics. However, most empirical studies show that actual pricing schemes have little to do with theoretical efficiency results. In particular, there are very few models recommending increasing blocks, whereas we present evidence that this type of tariff structure is abundantly used. Water managers often defend increasing blocks, both as a means to benefit smaller users and as a way to signal scarcity.

Naturally, in the presence of water scarcity the true cost of water increases due to the emergence of a scarcity cost. In this paper, we incorporate the scarcity cost associated with insufficient water availability into the optimal tariff design in several different models. We show that even when demand and costs also respond to climate factors, increasing marginal prices will not come about as a result of scarcity.

1 Introduction[1]

In many areas where water is not abundant, water pricing schedules contain significant nonlinearities. When adequate distribution networks exists, utilities are 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

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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.

This paper presents some relevant characteristics of existing water tariffs (Section 2), focusing on Portuguese tariffs for the residential sector. As expected, tariffs are usually composed by both a meter charge and a volumetric price, but the latter almost always consists of increasing block tariffs (IBT). More surprisingly, considering the well-known significant seasonal differences in water availability in the country, seasonal surcharges or seasonal price variations are not common in Portuguese water tariffs. Moreover, the few that do exist seem to be uncorrelated with regional characteristics in terms of seasonal water scarcity. It should also be emphasized that many utilities incorporate a number of further complications in their water rate calculations, enabling us to say that complexity is definitely the prevailing feature of water tariffs in Portugal. For other countries, the trend towards increasing blocks is also present, as noted in several publications. It seems that the reasons most water managers continue to defend increasing blocks are their ability to benefit smaller users and their potential role in signalling scarcity. Although, in the presence of water scarcity, the true cost of water increases due to 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.

In contrast, most results found in the literature on efficient tariff design do 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, estimate water demand, or point out the difficulties in implementing more efficient pricing rules. Section 3 summarizes the main efficiency results, indicating justifications for increasing block rates whenever they appear, and noting that none of them is directly related to scarcity.

Current analysis of this issue is specially relevant considering that the Water Framework Directive requires that by 2010 (art.9, n.1) pricing policies in the European Union's member states not only recover the costs of the resource (including enviromental and scarcity costs) but also provide adequate incentives for consumers to use water efficiently, contributing to the attainment of environmental quality targets.

Finally, the paper proposes different models of efficient and second-best nonlinear prices under scarcity constraints, and concludes that even when demand and costs also respond to climate factors, increasing marginal prices will not come about as a result of scarcity. Hence the question mark in the title.

2 Existing water tariffs

In 2005, the Portuguese National Water Institute (INAG) released results from the National Survey on Water and Waste Waster Systems for 2002. While previous inventories had focused only on the water and sewage infrastructures, this inventory began a systematic gathering of economic information. The INSAAR database contains economic data on the management model followed by water utilities, on investments for the period 1987-2002, and on costs, revenues, prices and quantities of water delivered (to customers or to other water utilities) for the years 1998, 2000 and 2002. In 2007, INAG is expected to release an update of the data for the year 2005. This update will help to improve the database significantly because the non-response rates in the years 1998 and 2000 are high and can sometimes hinder the analysis of the variables' evolution. This section provides a brief description of economic data for the year 2002.

The survey indicates that 93% of water supply tariffs in Portugal are composed of a fixed charge and a volumetric rate. The fixed charge is dependent on the diameter of the pipe. All the water utilities responsible for public water supply at the municipal level and which provided information on tariffs have volumetric rates in their tariffs. All but one of these utilities apply IBT (a few self-supplying organizations and tourist resorts practice flat rate volumetric prices). The average number of blocks is 5, but it can be as high as 27 in some extreme cases. The majority of utilities using block tariffs charges the volume within each block. Nevertheless, 18% of them use a different way to calculate the final tariff, by charging all volume at the price of the last block reached by metered consumption in the period. This causes the marginal price faced by the consumer to have significant peaks at the block limits. In this pricing system, the first cubic meter within a block can cost a consumer several times the price of the previous and the next unit, something that will hardly be clear to the average consumer from the information in the water bill.

The popularity of increasing block tariffs is not a Portuguese peculiarity. (Hoffmann, Worthington & Higgs 2006) mentions "the trend in most OECD economies towards metering, increasing block prices and reduced subsidies for residential water supply", as reported by (Dalhuisen, Groot & Nijkamp 2001) to the European Commission in 2001. The OECD itself not only reports the growing use of IBT by stating that "there is evidence that the use of such tariffs [IBT] is increasing" (OECD 2003*a*), but also seems to support their use by saying that "there seem to be clear potential benefits from increasing block tariff structure" (OECD 2003*a*). (Bartoszczuk & Nakamori 2004) point out that "the strong tradition of low tariffs for households and increasing block rates is present in Belgium, Italy, Greece, Portugal, Spain and US". With the Belgian exception, we find very similar climate conditions in these countries (or parts of them, given the size of the US). The use of IBT in these and other countries is also well documented in several OECD reports ((OECD 2006), (OECD 2003*a*), (OECD 2003*b*) , (OECD 1999*a*), (OECD 1999*b*) or (OECD 1999*c*)). One of the advantages of IBT pointed out by the OECD reports is related with affordability for poorer households. Nonetheless, in Portugal water expenses fall below 1% of average disposable income (Monteiro, Meireles, Mestre, Roseta-Palma & Sugahara 2006), and affordability cannot explain the use of a large number of blocks.

One feature we would expect to see in Portuguese water tariffs given the variable weather conditions (significant seasonal weather differences, namely in rainfall; existence of drought-prone regions) is seasonal surcharges. However, no more than 3% of the water utilities use such tools in their water tariffs. Moreover, their location seems unrelated to the water availability problems in the country, with most of them being located in the wetter regions of the coastal northwest of the country. The few seasonal surcharges we do find are in place during the summer months and raise the price of the higher blocks between 30%-50% on average.

Simplicity is not a prevalent feature of Portuguese water tariffs. The calculation process of the IBT (volume charged within each block or at the price of the last block) can be mixed in some utilities, depending on the consumption block. Tariffs can combine blocks with flat (nonvolumetric) fees within some blocks with volumetric rates for others. Specific formulas are sometimes applied within the blocks to find the unit price. Water availability charges that are fixed within each block, but variable among blocks, are sometimes levied and added to the price. Some utilities practice social tariffs for disadvantaged households or propose special contracts with different prices.

Finally, it should be noted that the national cost recovery level for water supply is close to 100% (considering only financial costs), but falls well below that level, to 54%, for wastewater drainage and treatment services (INAG 2005). This can be explained by the fact that some utilities do not charge for wastewater at all, while others make the payment dependent of variables such as apartment area; number of inhabitants, real estate value of the house or building or taxable income. The majority of wastewater utilities levy at least some of their charges based on water consumption levels, so that both payments are part of the water bill.

3 Efficient water pricing literature

In this section, we review the literature on water pricing, focusing on the results dealing with nonlinear pricing, scarcity and seasonal rates. Several important issues are not specific to the water sector: marginal cost pricing, capacity constraints, resource scarcity, revenue requirements or nonlinear pricing are significant in the more general framework of regulated public utilities, as is clear from books like (Brown & Sibley 1986) and (**?**). However, such issues appear in this sector combined with some of its peculiarities, such as the large capital investments which turn suppliers into 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.

The first question to be addressed in the water pricing literature was the incompatibility between the marginal pricing recommendation from microeconomics and the average cost pricing practice in the water industry. Although cost recovery is an important goal, so that average costs are clearly paramount in utilities' actual rate setting, the idea, stressed many times by economists, is that more attention needs to be paid to marginal costs. A water user will decide whether or not to consume an additional unit by comparing the benefit associated to that unit with its price (which may or may not be the same as average price, depending on the rate structure). Therefore, in the absence of external effects, social net benefits should be maximized when the price per unit is equal to the marginal cost of supplying the water.This literature dates back to the 60's (Hirshleifer, de Haven & Milliman 1960), but despite the overwhelming evidence in favour of marginal cost pricing as a more efficient pricing tool, the discussion has not fully subsided. (Briand 2006), for example, uses a dynamic computable general equilibrium model to question the application of average cost pricing in Senegal. Moreover, there are other more efficient ways of achieving a balanced budget than average cost pricing. For example, two-part tariffs can separate the recovery of fixed and variable costs through fixed charges and volumetric rates on water consumption. Second-best Ramsey pricing can, as shown in the following sections, differentiate price according to the customers' price-elasticities of demand, charging higher tariffs to types of customers which respond less to price changes. This technique allows the utility to recover costs while sacrificing as little welfare as possible.

Because marginal cost pricing does not ensure that the water utility will break even, as average-cost pricing does, the harmonisation of efficiency with the balancing of the utility's budget has been the subject of much attention. (Collinge 1992), (Kim 1995), (Griffin 2001) and (Schuck & Green 2002) have all dealt with this question. While (Collinge 1992) works out a way to return excess profit to consumers through tradable discount coupons (arguing his method does not require the utility to gather information on water demand), (Kim 1995) relies on Ramsey second-best pricing to ensure a two product utility producing residential and non-residential water collects enough revenue to meet its costs. (Schuck & Green 2002) also base their analysis on a Ramsey pricing rule, while (Griffin 2001) proposes a threshold on water consumption to be added to a two-part tariff, generating credits to the consumer below the threshold (as in (Collinge 1992), the aim is to return excess profits).

The importance of price differentiation, according to the type of customer or the season of the year, is another question dealt with in the literature. Temporal price variation in particular has been analysed by several authors, who have pointed out the advantages of having intra-annual price changes to reflect differences in marginal costs, with the aim of enhancing efficiency (an early example is (Gysi & Loucks 1971)). A more recent paper is (Schuck & Green 2002), which presents a supply-based water pricing model (where price changes with water availability). It uses a conjunctive use system for farming with stochastic surface water flows and combines it with second-best (Ramsey) water pricing. It considers the possibility of recharging the aquifer with excessive surface water in bountiful years, although not without a cost. The authors use simulation techniques to test their model on a Californian water district using land, water and energy, and conclude that a supply-based pricing policy reduces the use of these three resources in periods of drought.

The analysis of capacity constraints on water supply and the related issued of optimal timing for system expansion is another subject that dates back to the 60's and 70's, when the problem of supplying enough water to meet the needs was mostly seen as a problem of increasing capacity ((Riordan 1971), (Riley & Scherer 1979), or (Manning & Gallagher 1982), are examples of authors dealing with these issues). The problem of water storage is related to the problem of resource variability, resulting either from regular seasonal rainfall variability or from the more uncertain occurrence of longer periods of drought, which can alternate with plentiful rain or even floods.

The scarcity of the resource itself is a more recent concern in the literature. It has accompanied a change in water managers' concerns, from water supply increase to water demand management. (Moncur & Pollock 1988) deal with the problem of determining the scarcity rent of water. They consider the case of a water utility with groundwater as its only source, and use a nonrenewable resource efficient extraction model to determine the scarcity value and the efficient path of price in the future. They calculate the scarcity value through the consideration of the future increase in costs originated by the necessity to use costly backstop technologies (such as desalination or trans-basin diversions) to satisfy water demand. They apply their model to Honolulu and find the scarcity value to be approximately twice the current water charge. (Elnaboulsi 2001) includes a constraint on the water available which, when binding, allows the determination of the shadow value of water resources to be included in the price. (Griffin 2001) demonstrates that price should include opportunity costs such as the marginal user cost of water (for renewable or non-renewable sources) and the marginal capacity cost. This issue will be developed in the following sections.

Finally, in relation to nonlinear prices, while we can find examples of authors who support the use of increasing block tariffs for water ((Gysi & Loucks 1971) is an early example), such support is based on distributional considerations and not on the basis of efficiency. (Cardadeiro 2005) is a partial exception. He introduces a social benefit of universal access, through the consideration of a positive externality for the first few liters/person/day, due to public health improvements. The existence of only two blocks in the tariff is imposed on the model, as it is argued that the externality refers only to those first few liters. The result, as expected, is that social welfare can be maximized by setting the first block price lower than the second. In another of the rare water pricing models applying nonlinear pricing, (Elnaboulsi 2001) develops a model of optimal nonlinear pricing of water and wastewater services, considering the issues of temporal variation, capacity constraints, scarcity and consumer heterogeneity. He concludes that the marginal price should be constant or decreasing, in which case a menu of two-part tariffs can be constructed in such a way that it would be equivalent to offering consumers quantity discounts.

4 Scarcity in a simple model

A simple view of the main aspects of efficiency in water prices is presented by (Griffin 2001),(Griffin 2006). His model includes three pricing components: the volumetric (ie. 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.[2] On the other hand, he assumes a single volumetric price and does not allow for more general nonlinear prices, as neither consumer heterogeneity nor purchase size cost dependency are taken into account. In fact, (Griffin 2001) stresses "the inefficiencies of block rate water pricing".(pp.1339 and1342).

A static model for different consumer (identified) groups, with a scarcity constraint, shows that the marginal cost pricing rule still holds. Ignoring meter charges for the moment, define $B_j(w_j)$ as the increasing and concave monetized benefit of water consumption for consumer group j, with $j = 1, ...J$, and $C(w)$ as the (convex) water supply costs, which depend on the total water supplied, ie. $w = \sum_j w_j$. Water availability is limited, with the maximum amount denoted as W. The welfare maximization problem is

$$\begin{aligned} \underset{\{w_j\}}{Max} \quad & \sum_j B_j(w_j) - C(w) \\ & s.t. \sum_j w_j \leq W \end{aligned} \tag{1}$$

resulting in first order conditions[3]

$$\frac{dB_j}{dw_j} = \frac{dC}{dw} + \mu \qquad \forall_j \tag{2}$$

$$\sum_j w_j \leq W, \quad \mu \geq 0, \quad \mu(W - \sum_j w_j) = 0 \tag{3}$$

where μ is the Lagrangean 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 marginal costs (including scarcity costs if the constraint is binding). Also, the marginal benefit needs to be the same across consumers, since marginal cost is the same. Finally, with a unit price p_j the benefit maximization problem for each consumer is

$$\underset{w_j}{Max} \quad B_j(w_j) - p_j w_j \tag{4}$$

$$\Leftrightarrow \quad \frac{dB_j}{dw_j} = p_j \tag{5}$$

[2] Access to water supply networks is nearly universal in Portugal by now, with 92% average connection rates and 100% in urban areas.

[3] There are no cross effects in demand, ie. $\frac{dB_j}{dw_i} = 0$ for $i \neq j$.

so that the efficient unit price must be the same for all consumers and is given by

$$p = \frac{dC}{dw} + \mu \tag{6}$$

as in (Griffin 2006).[4] The lower W the tighter the constraint, 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. Although a fixed meter component could be adjusted to reflect such concerns, the second-best pricing rule is obtained by imposing a break-even constraint such as (7) on problem (1). This is known as Ramsey pricing. Note that $p_j(w_j)$ is now the inverted demand of consumer j.

$$\sum_j p_j(w_j)w_j - C(w) = 0 \tag{7}$$

Using equation (5), the welfare maximizing prices will now be given by

$$\frac{p_j - \left(\frac{dC}{dw} + \frac{\mu}{1+\lambda}\right)}{p_j} = \frac{\lambda}{1+\lambda}\frac{1}{\varepsilon_j} \tag{8}$$

where ε_j is 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 mark-up of prices over marginal cost will be inversely related to the demand elasticity, so that consumers with lower demand elasticities will pay higher prices and vice-versa. The only new term is $\frac{\mu}{1+\lambda}$, which reflects the scarcity cost. It should be noted that if the scarcity cost is defined as a tax which 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. This is particularly important when several suppliers share available water, since none of them will adequately provide for external scarcity costs.

5 Scarcity with a distribution of consumer types

In this section a more complete model is presented, explicitly characterizing demand behavior through the definition of consumer types. Model devel-

[4] The same result can be obtained with the more complicated pricing formula from (Griffin 2001). In that case the bill paid by each consumer is given by $Bill_j = M + p(w_j - \overline{w})$, where M is the meter charge and $\overline{w}$ is a budget-balancing parameter.

opment is based on (Brown & Sibley 1986) as well as (Elnaboulsi 2001). A new parameter, θ, is introduced to reflect differences in consumer tastes, which can encompass a number of variables, including income, family size, or housing. A consumer with tastes given by θ will now enjoy net benefits of $B(w, \theta, \phi) - P(w)$, where ϕ represents exogenous influences such as the weather and $P(w)$ is the total payment for water consumption. It is assumed that $B(0, \theta, \phi) = 0$ and that high values of θ imply higher consumption benefits $\frac{\partial B}{\partial \theta} > 0$, $\frac{\partial^2 B}{\partial \theta \partial w} > 0$. The distribution of θ throughout the consumer population is described by a distribution funtion $G(\theta)$ and the associated density function $g(\theta)$. Maximum and minimum values for the taste parameter are represented by $\overline{\theta}$ and $\underline{\theta}$, respectively, so that $G(\overline{\theta}) = 1$ and $G(\underline{\theta}) = 0$.

The first order condition of each consumer's net benefit maximization is

$$\frac{\partial B(w, \theta, \phi)}{\partial w} = \frac{dP}{dw} \equiv p_m \tag{9}$$

which is similar to condition (5) except the right-hand side represents the slope of the total payment function, ie. 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, $w(\theta, \phi)$, the value function is

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

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

$$\begin{aligned} & \underset{w(\theta,\phi)}{Max} \quad \int_{\underline{\theta}}^{\overline{\theta}} V(\theta) g(\theta) d\theta + \int_{\underline{\theta}}^{\overline{\theta}} \left[P(w(\theta, \phi) - C(w(\theta, \phi))\right] g(\theta) d\theta \\ & s.t. \quad \begin{array}{c} \int_{\underline{\theta}}^{\overline{\theta}} \left[P(w(\theta, \phi) - C(w(\theta, \phi))\right] g(\theta) d\theta = 0 \\ \int_{\underline{\theta}}^{\overline{\theta}} w(\theta, \phi) g(\theta) d\theta \leq W \end{array} \end{aligned} \tag{11}$$

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. Substituing $P(w(\theta, \phi)$ using equation (10), noting that $G(\theta) - 1 = \int g(\theta) d\theta$ and using the envelope theorem to see that $\frac{\partial V}{\partial \theta} = \frac{\partial B}{\partial \theta}$, consumer surplus can be rewritten using integration by parts

$$\int_{\underline{\theta}}^{\overline{\theta}} V(\theta)g(\theta)d\theta = V(\underline{\theta}) + \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial B}{\partial \theta}(1 - G(\theta))d\theta \tag{12}$$

and the Lagrangean that must be maximized is

$$\begin{aligned}
\mathcal{L} &= V(\underline{\theta}) + \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial B}{\partial \theta}(1 - G(\theta))d\theta + (1+\lambda)\int_{\underline{\theta}}^{\overline{\theta}} \left(B(w(\theta,\phi) - V(\theta) - C(w(\theta,\phi))\right) g(\theta)d\theta \\
&\quad +\mu \left(W - \int_{\underline{\theta}}^{\overline{\theta}} w(\theta,\phi)g(\theta)d\theta \right) \qquad (13) \\
&= -\lambda V(\underline{\theta}) + \int_{\underline{\theta}}^{\overline{\theta}} (1+\lambda)\left(B(w(\theta,\phi) - C(w(\theta,\phi))\right) g(\theta) - \lambda \frac{\partial B}{\partial \theta}(1 - G(\theta))d\theta \\
&\quad +\mu \left(W - \int_{\underline{\theta}}^{\overline{\theta}} w(\theta,\phi)g(\theta)d\theta \right) \qquad (14)
\end{aligned}$$

For the case where $V(\underline{\theta}) = 0$, 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

$$\begin{aligned}
\frac{\partial L}{\partial w(.)} &= 0 \qquad (15) \\
&= (1+\lambda)\left(\frac{\partial B}{\partial w} - \frac{\partial C}{\partial w}\right) g(\theta) - \lambda \frac{\partial^2 B}{\partial w \partial \theta}(1 - G(\theta)) - \mu g(\theta) = 0
\end{aligned}$$

Using equation (9), a mark-up condition similar to the one from the previous model (equation (8)) can de derived:

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

where $\xi(w, p_m)$ represents the elasticity in each incremental market. (see Appendix)

6 Scarcity in demand, cost, and availability

The previous sections have shown that scarcity, represented as a quantity constraint, has a direct effect that can be seen as an increase on 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 develops a model where exogenous weather factors, ϕ, 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 $\frac{\partial B_j}{\partial \phi} > 0$, $\frac{\partial^2 B_j}{\partial w_j \partial \phi} > 0$ (water demand increases, for example due to irrigation or swimming pools), $\frac{\partial C}{\partial \phi} > 0$, $\frac{\partial^2 C}{\partial w \partial \phi} > 0$ (supply costs are higher due to extra pumping or treatment costs), and $\frac{dW}{d\phi} < 0$ (less available water).

Introducing these factors into the model from section 4, the welfare maximization problem becomes:

$$\begin{array}{cc} \underset{\{w_j\}}{Max} & \sum_j B_j(w_j, \phi) - C(w, \phi) \\ & s.t. \sum_j w_j \leq W(\phi) \end{array} \tag{17}$$

resulting in first order conditions

$$\frac{dB_j}{dw_j}(w_j, \phi) = \frac{dC}{dw}(w, \phi) + \mu \qquad \forall_j \tag{18}$$

$$\sum_j w_j \leq W, \quad \mu \geq 0, \quad \mu(W - \sum_j w_j) = 0 \tag{19}$$

It should be stressed that, once again, condition (18) implies that marginal benefit must be equal for all consumers, so that the marginal price must be the same. The effects of the weather on costs and on scarcity aren't consumer-specific, so there still is no scarcity related reason to use increasing marginal prices. Nonetheless, if the scarcity constraint is binding, these conditions provide a solution for $w_j^*(\phi)$, $j = 1...J$ and $\mu^*(\phi)$, which can be used for comparative static analysis of ϕ. The relevant system is

$$\begin{bmatrix} 0 & -1 & \cdots & -1 \\ -1 & H_{11} & & H_{1J} \\ \vdots & & \ddots & \\ -1 & H_{1J} & & H_{JJ} \end{bmatrix} \begin{bmatrix} \frac{\partial \mu^*}{\partial \phi} \\ \frac{\partial w_1^*}{\partial \phi} \\ \vdots \\ \frac{\partial w_J^*}{\partial \phi} \end{bmatrix} = \begin{bmatrix} -\frac{dW}{d\phi} \\ -H_{1\phi} \\ \vdots \\ -H_{J\phi} \end{bmatrix}$$

where $H_{jj} = \left(\frac{\partial^2 B_j}{\partial w_j^2} - \frac{\partial^2 C}{\partial w^2} \right)$, $H_{ij} = -\frac{\partial^2 C}{\partial w^2}$ for $i \neq j$, so that the first matrix, denoted $\overline{H}$, is the bordered Hessian of the maximization problem, and where $H_{j\phi} = \left(\frac{\partial^2 B_j}{\partial w_j \partial \phi} - \frac{\partial^2 C}{\partial w \partial \phi} \right)$. Using Cramer's rule, we know that

$$
\begin{aligned}
\frac{\partial \mu^*}{\partial \phi} &= \frac{1}{|\overline{H}|} \begin{vmatrix} -\frac{dW}{d\phi} & -1 & \cdots & -1 \\ -H_{1\phi} & H_{11} & & H_{1J} \\ \vdots & & \ddots & \\ -H_{J\phi} & H_{1J} & & H_{JJ} \end{vmatrix} \\
\frac{\partial w_j^*}{\partial \phi} &= \frac{1}{|\overline{H}|} \begin{vmatrix} 0 & -1 & \cdots & -\frac{dW}{d\phi} & \cdots & -1 \\ -1 & H_{11} & & -H_{1\phi} & & H_{1J} \\ \vdots & & \ddots & \vdots & & \\ -1 & H_{1J} & & -H_{J\phi} & \cdots & H_{JJ} \end{vmatrix} \qquad \forall j
\end{aligned}
$$

While the sign for $\frac{\partial \mu^*}{\partial \phi}$ is undetermined, $\frac{\partial w_j^*}{\partial \phi}$ should be negative for all consumers, as expected.

7 Conclusion

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 IB schemes we found were much more complex than that. Water managers often mention that increasing rates signal scarcity and as such are a useful tool in reducing resource use. But after a thorough revision of the literature and an experimentation with several different 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. This is not to say that the use of IB.cannot be justified on other grounds, only that scarcity does not appear to play a role in such a justification.

There are many avenues for further research which must now be followed. One is the introduction of dynamic water variability explicitly into the model. The temporal variability of supply may originate from a regular and expected seasonality or from a more uncertain inter-annual irregularity of water inflows. Optimal coping strategies might be different, which can lead us to reconsider the role of capital investments like dam construction in the stabilization of water supply and in the prevention of floods and droughts.

In order to assess the potential of nonlinear prices to promote efficiency in the use of water, to reduce overall water demand, and to recover the costs of water supply, it is also important to consider real water demand.profiles. Further work in this area could be directed at testing the assertion that IBT are, per se, scarcity signals with the potential to influence consumer behavior even when price elasticities are very low (as they tend to be for water).

8 Appendix

This Appendix contains the derivation of equation (16). See also ((Brown & Sibley 1986, pp.205-6)).

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

since $\frac{\partial B(w,\theta,\phi)}{\partial w}=\frac{dP}{dw}\equiv p_m$

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

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

$$\Leftrightarrow \frac{p_m-\left(\frac{\partial C}{\partial w}+\frac{\mu}{1+\lambda}\right)}{p_m}=\frac{\lambda}{1+\lambda}\frac{1}{p_m}\frac{1}{\frac{\partial\underline{\theta}}{\partial p_m}}\frac{(1-G(\theta))}{g(\theta)}\Leftrightarrow$$

where $\underline{\theta}$ indicates the marginal consumer group $(\underline{\theta}=\underline{\theta}(Q,P(Q)))$

Defining marginal willingness to pay, $\rho(w,\theta)$, the self-selection condition is $\rho(w,\underline{\theta})=p_m$,so that $\frac{d\rho}{dp_m}=1\Leftrightarrow\frac{\partial\rho}{\partial\underline{\theta}}\frac{\partial\underline{\theta}}{\partial p_m}=1\Leftrightarrow\frac{\partial\underline{\theta}}{\partial p_m}\rho_\theta=1\Leftrightarrow\frac{\partial\underline{\theta}}{\partial p_m}=\frac{1}{\rho_\theta}>0$

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

Finally,

$$\Leftrightarrow \frac{p_m-\left(\frac{\partial C}{\partial w}+\frac{\mu}{1+\lambda}\right)}{p_m}=\frac{\lambda}{1+\lambda}\frac{1}{p_m\frac{\partial\underline{\theta}}{\partial p_m}\frac{g(\theta)}{(1-G(\theta))}}\Leftrightarrow$$

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

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

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

$$\frac{d \ln\left[1 - G(\underline{\theta})\right]}{dp_m(w)} = \frac{\partial \ln\left[1 - G(\underline{\theta})\right]}{\partial \ln p_m(w)} \frac{\partial \ln p_m(w)}{\partial p_m(w)} \Longleftrightarrow$$

$$\Longleftrightarrow \frac{1}{\left[1 - G(\underline{\theta})\right]} \left(-g(\underline{\theta}) \frac{\partial \underline{\theta}}{\partial p_m}\right) = \frac{\partial \ln\left[1 - G(\underline{\theta})\right]}{\partial \ln p_m(w)} * \frac{1}{p_m(w)} \Longleftrightarrow$$

$$\Longleftrightarrow \frac{d \ln\left[1 - G(\underline{\theta})\right]}{d \ln p_m(w)} = \frac{-g(\underline{\theta}) \frac{\partial \underline{\theta}}{\partial p_m} p_m(w)}{\left[1 - G(\underline{\theta})\right]} \Longleftrightarrow -\frac{\partial \ln\left[1 - G(\underline{\theta})\right]}{\partial \ln p_m(w)} = \frac{g(\underline{\theta}) \frac{\partial \underline{\theta}}{\partial p_m} p_m(w)}{\left[1 - G(\underline{\theta})\right]}]$$

[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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