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**INDIVIDUAL AND AGGREGATE WATER
DEMAND IN THE PRESENCE OF
HETEROGENOUS AGENTS AND TARIFF BLOCKS:
A THEORETICAL FRAMEWORK**

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Individual and aggregate water demand in the presence of heterogeneous agents and tariff blocks: A theoretical framework

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Abstract

The aim of this paper is to re-investigate water demand in the presence of tariff blocks and heterogeneous agents. The purpose is to develop a theoretical model with 'general features', which could be implemented in certain countries or cities to evaluate the impact of tariff blocks on water consumption and well-being at individual and aggregate levels.

For this purpose, we extended the "standard" utility-maximization framework set out by [Dalhuisen et al. \(2001\)](#) or [Corral et al. \(1999\)](#) to several dimensions of agent heterogeneity: wage heterogeneity (between individuals), heterogeneity in the size of the different income classes, heterogeneity in terms of preferences of individuals. We study the case of a tariff with B blocks where preferences between water and others consumption goods is captured by a constant elasticity of substitution (CES) utility, and the structure of the blocks is such that the water supplier's budget is always balanced. We also investigate problems of perception of water consumption.

Among other results, we show how balanced water supplier's budget imposes that the parameters of the block tariff (price of the 1st instalment, progressivity of the tariff, threshold levels of consumption, amount of the subscription) are dependent on agents' preferences, the distribution of income in the population and external "macro" factors.

Keywords

JEL classification D58; Q21; Q25

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1 Introduction

This paper aimed at reinvestigating water demand in the presence of tariff blocks and heterogenous agents. Its purpose is to carry a theoretical model with “general features”, which could be implementable in some countries or cities to evaluate the consequences of tariff blocks on water consumption at both individual and aggregate levels, and on well-being.

To the best of our knowledge, very few studies have specifically focused on the theoretical analysis of demand in the presence of tariff blocks when agents are heterogeneous. Recently, [Caravaggio et al. \(2024\)](#) build a theoretical game model between a household and a service provider, taking into account household size and income as well as the service provider’s consideration of consumer welfare in the presence of a 2-blocks tariff. [Neugart and Sotoudehmollahi \(2026\)](#) build an agent-based model of a water market with a 3-blocks tariff calibrated on German data. They show that different water pricing schemes have an impact on water consumption and distributive consequences as well.¹ Otherwise, most of the studies use an agent-based modeling framework, but the heterogeneity, when present, is generally at a geographical level and the agents are typically representative households (see, for example, [Sattler et al. \(2023\)](#) and [Moosavi et al. \(2023\)](#)). Our article therefore aims to address this gap by extending the ‘standard’ utility-maximisation framework set out in [Dalhuisen et al. \(2001\)](#) or [Corral et al. \(1999\)](#) to include agent heterogeneity. We have integrated several dimensions of agent heterogeneity, firstly in terms of income. Our income distribution takes into account both wage heterogeneity between individuals and heterogeneity in the size of different income classes. This has significant effects at the global level when individual consumption is aggregated. A second dimension of heterogeneity concerns individuals’ preferences, either in terms of satisfaction derived from consuming water services relative to consuming other goods or in terms of the quality of equipment associated with water consumption.

In an effort to make the model as general as possible, we extend the analysis to a form of utility that is more general than the Cobb–Douglas form, using a constant elasticity of substitution (CES) utility function between water services and the consumption of other goods. We also model a tariff with B blocks, assuming that their structure ensures the water supplier’s budget is always balanced. Furthermore, we consider variants that take important elements of water demand into account, such as individuals’ perceptions when making consumption decisions.²

Finally, the paper demonstrates how a balanced water supplier’s budget imposes constraints on the parameters of the block tariff (price of the initial installment, progressivity of the tariff, threshold levels of consumption, amount of the subscription). These constraints are contingent

¹Recently also, [Chovar Vera et al. \(2024\)](#) conduct an empirical analysis using data from a city in Chile. They evaluate how changing from a uniform price to an increasing block tariff could influence people’s behavior. Estimating the residential water demand and the price elasticity they show that people are affected by changes in tariffs and that consumers’ heterogeneity is important in the design of tariff. They show that socioeconomic determinants influence the choice of the pricing structure.

²Thus, we obtain a theoretical framework that can be simulated using data on a country’s or city’s income distribution and individual demand characteristics. Such a numerical exercise is done in the second part of this paper ([Maslianskaia-Pautrel et al., 2023](#)).

on agents' preferences, the distribution of income in the population, and external "macro" factors. In this way, our modeling and result differ from [Caravaggio et al. \(2024\)](#) and [Neugart and Sotoudehmollashahi \(2026\)](#), and offer a complementary contribution to the investigation of water demand in the presence of tariff blocks and heterogeneous agents.

2 The heterogeneous agent model with a 3-blocks tariff

We take up the approach used, among others by [Dalhuisen et al. \(2001, p.5\)](#), for the derivation of the demand for water, as a result of the maximisation of the utility of an individual under a budget constraint, by considering the consumption of other goods in the decision-making process.

2.1 The framework

Compared to [Dalhuisen et al. \(2001\)](#) and other theoretical works on water demand, we introduce several important modifications.

1. We consider that there is a set of individuals who are heterogeneous, both in terms of income, but also in terms of their utility, the efficiency of the equipment linked to water consumption, etc. Then it makes possible to characterize specific individual demands for water (for example, as a function of income bracket) and an overall demand for water that will be linked to the distribution of the population. Furthermore it enables to introduce a “*disconnection*” between individual demand and overall demand and to study the “*redistributive*” effects of water-pricing.
2. We have chosen a more general utility function than the Cobb-Douglas function used by these aforementioned authors. The choice of a CES utility was motivated by the fact that most theoretical contributions make the assumption of a Cobb-Douglas utility between water services and other consumer goods, i.e. a unitary elasticity of substitution between water services and other consumer goods. One possible justification for the use of the Cobb-Douglas form, apart from its ease of handling, is that demand for water with a Cobb-Douglas utility is independent of the price of other goods, which is in line with the low elasticity between water consumption and the price of other goods that emerges from a number of empirical studies (see [Dalhuisen et al., 2003](#); [Sebri, 2014](#); [Reynaud and Romano, 2018](#); [Puri and Maas, 2020](#), among others). Nevertheless, as highlighted in [Maslianskaia-Pautrel et al. \(2023\)](#), relaxing the assumption of a Cobb-Douglas utility function could have strong implications for individual consumption, aggregate consumption by income group, the financial equilibrium of the water supplier, and the affordability of the tariff. Furthermore, the relaxation of the Cobb-Douglas hypothesis modifies the reactions of water consumers to a variation in their environment (an improvement in the efficiency of equipment associated with water consumption, an increase in the price of consumer goods, a switch from binary pricing to block pricing, a rebalancing of the water

provider's budget, etc.). That the reason why we have chosen the general CES form of utility.

3. We first develop a 3-block pricing version before extending it to a general framework of a B -block pricing. This enables us to account for more complex tariff systems, for example the super-progressive block pricing existing in Spain, to compare the effects with the progressive block pricing.
4. We assume that the water supplier's budget is always balanced, which is rarely taken into account in water demand modeling. The major implication of this assumption is that, for a given subscription amount, the tariff structure must adjust to changes in the environment so that the prices set by the operator take account of this budget balancing constraint. If a shock occurs in the economy, leading for example to a fall in the operator's income, the operator will have to increase its resources (by increasing prices or the subscription), which will have additional implications for the demand for water.

2.2 The assumptions

We make the following assumptions:

1. There is a population of heterogeneous agents of size n . The population is divided according to income. Agents in the same income bracket i are indexed by i and are n^i in number, so that $n = \sum_i n^i$. If the individual i has an individual consumption of q^i , then the consumption of the income bracket i is $n^i q^i$ and the global consumption is the sum of all the income brackets $\sum_i n^i q^i$.
2. Each agent has two types of consumption from which he derives satisfaction: consumption of water services and consumption of a composite of current consumption goods (other than water services). We denote q^i the volume of water demanded/consumed by agent i and $\mathbf{X}^i$ the quantity of the composite consumption good.
3. Water pricing is made up of 3 blocks³. Each block is denoted by the letter b with $b = 1, 2, 3$. Each block b is characterised by a price per cubic metre, p_b , and a consumption threshold, noted k_b , above which the price increases to $p_{b+1} \geq p_b$.
4. The water operator incurs a fixed cost of water distribution, noted F , as well as a marginal cost (per unit of water consumed) noted μ . He charges each water consumer a subscription fee, the amount of which is noted S .

2.3 Consumers and water demand

We are interested here in the individual and aggregate water demand. Individual demand is derived from each agent's maximisation of his utility under his budget constraint. Aggre-

³See the next section for a generalized model with B blocks.

gate consumption is the sum of all individual demands, each of which is specific due to the heterogeneity of the agents.

2.3.1 Individual utility

The utility of agent i , denoted $U(q^i, \mathbf{X}^i)$, is of the CES form and is written:

$$U(q^i, \mathbf{X}^i) = \begin{cases} \left[\alpha^i f(q^i)^{\frac{\sigma-1}{\sigma}} + (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} & \text{if } \sigma \in]0, 1[\cup]1, +\infty[\\ f(q^i)^{\alpha^i} g(\mathbf{X}^i)^{1-\alpha^i} & \text{if } \sigma = 1 \end{cases} \quad (1)$$

- $\alpha^i \in (0, 1)$ represents the relative importance of the consumption of water services (compared to the composite consumer good) in utility. A higher α^i means that agents give greater importance to water consumption. Here, α^i is specific to each individual in the I^i income bracket and so each individual i has a specific utility and demand for water.
- The parameter σ is the elasticity of substitution between the consumption of water services and the consumption of the composite consumer good. When σ tends towards infinity, the 2 types of consumption are perfectly substitutable, whereas when σ approaches 0 the 2 types of consumption tend to be perfectly complementary. The case where $\sigma = 1$ is the Cobb-Douglas case, generally used in the literature.
- $f(q^i)$ represents the influence of water consumption services on the satisfaction of agent i , with q^i the volume of water actually consumed. For example, in the Stone-Geary case, we will have $f(q^i) = \varepsilon^i q^i - \underline{z}^i$ where $\varepsilon^i > 0$ measures the efficiency of the equipment used to benefit from the water and $\underline{z}^i > 0$ is the subsistence consumption. In the following, we will use the specification $f(q^i) = \varepsilon^i q^i$.
- $g(\mathbf{X}^i)$ represents the influence of the consumption of the composite consumption good on the satisfaction of the agent i , with $\mathbf{X}^i$ the quantity of goods consumed. It is possible to specify $g(\mathbf{X}^i)$ to take into account subsistence consumption, for example: $g(\mathbf{X}^i) \equiv \mathbf{X}^i - \underline{\mathbf{X}}^i$. In the following, we will use the specification $g(\mathbf{X}^i) \equiv \mathbf{X}^i$.

Each agent i has an income I^i he uses to consume water in quantity q^i , at a price which depends on the block in which his consumption falls. Thus, if he consumes a quantity q^i within consumption block 1 (i.e. below the k_1 threshold), he will pay each unit p_1 and therefore $p_1 q^i$ overall. If his consumption is in block 2 (between the k_1 threshold and the k_2 threshold), then he will pay p_1 for each unit of water below the k_1 threshold then he will pay p_2 for each unit above the k_1 threshold. His total bill will therefore be $p_1 k_1 + p_2 (q^i - k_1)$. If his consumption is in block 3 (above the k_2 threshold), then he will pay p_1 for each unit of water below the k_1 threshold, then he will pay p_2 for each unit between the k_1 and k_2 thresholds, then he will pay p_3 for the remaining units. His total bill will therefore be $p_1 k_1 + p_2 (k_2 - k_1) + p_3 (q^i - k_2)$.

Whatever his water consumption, the agent will also consume the composite consumption good in quantity $\mathbf{X}^i$ for a unit price p_x and he will pay for access to water S , so his budget constraint (depending on the quantity of water he consumes) can be summarised as follows:

$$\begin{cases} I^i = p_1 q^i + p_x \mathbf{X}^i + S & \text{if } q^i \leq k_1 \\ I^i = p_1 k_1 + p_2 (q^i - k_1) + p_x \mathbf{X}^i + S & \text{if } k_1 < q^i \leq k_2 \\ I^i = p_1 k_1 + p_2 (k_2 - k_1) + p_3 (q^i - k_2) + p_x \mathbf{X}^i + S & \text{if } q^i > k_2 \end{cases} \quad (2)$$

2.3.2 Individual consumption

We assume that $f(q^i) = \varepsilon^i q^i$, where $\varepsilon^i > 0$ measures the efficiency of the equipment used to benefit from water, and we assume $g(\mathbf{X}^i) \equiv \mathbf{X}^i$. By maximising his utility (equation 1) under his income constraint (equation 2), individual i determines his demand for water as well as his demand for composite consumer goods.

His demand for water is expressed as follows:

$$q^i = \begin{cases} q_1^i \equiv [1 + \varepsilon^i \varrho_1]^{-1} \left(\frac{R^i + D_1}{p_1} \right) & \text{if } R^i < \bar{R}_1^i \\ k_1 & \text{if } \bar{R}_1^i < R^i \leq \underline{R}_2^i \\ q_2^i \equiv [1 + \varepsilon^i \varrho_2]^{-1} \left(\frac{R^i + D_2}{p_2} \right) & \text{if } \underline{R}_2^i < R^i \leq \bar{R}_2^i \\ k_2 & \text{if } \bar{R}_2^i < R^i \leq \underline{R}_3^i \\ q_3^i \equiv [1 + \varepsilon^i \varrho_3]^{-1} \left(\frac{R^i + D_3}{p_3} \right) & \text{if } R^i > \underline{R}_3^i \end{cases} \quad (3)$$

where $\varrho_b \equiv (p_x/p_b)^{1-\sigma} \left(\frac{1-\alpha^i}{\varepsilon^i \alpha^i} \right)^\sigma$, $R^i = I^i - S$ is the arbitrary revenue, and the arbitrary revenue thresholds for tariff block b are defined by

$$\begin{aligned} \underline{R}_b^i &\equiv p_b \left[(1 + \varepsilon^i \varrho_b) k_{b-1} \right] - D_b \\ \bar{R}_b^i &\equiv p_b \left[(1 + \varepsilon^i \varrho_b) k_b \right] - D_b \end{aligned}$$

with

$$D_b \equiv \begin{cases} \sum_{m=1}^{b-1} k_m (p_{m+1} - p_m) > 0, & \text{si } b > 1 \\ = 0 & \text{if } b = 1 \end{cases}$$

is Nordin's D for the b tariff block.

The system of equations (3) tells us that if an individual i has an arbitrary income R^i , i.e. the income he can spend once the water subscription has been paid, between $\underline{R}_2^i$ and $\bar{R}_2^i$, he will consume in block 2 the volume q_2^i as defined in the system (3). And if an individual i has an arbitrary income R^i greater than $\bar{R}_3^i$, he will consume in block 3 the volume q_3^i as defined in the system (3). Note that whatever the block, the demand for water is always of the same

form, i.e. for block b :

$$q_b^i = \left[1 + \left(\frac{\varepsilon^i p_x}{p_b} \right)^{1-\sigma} \left(\frac{1 - \alpha^i}{\alpha^i} \right)^\sigma \right]^{-1} \left(\frac{R^i + D_b}{p_b} \right)$$

Individual water demand in the b block depends:

- positively on the resources that the individual can spend $(R^i + D_b)$ over the price of the tranche p_b .
- on the relative price of the slice compared to the price of the composite consumer good p_b/p_x . Note that the sign of this influence depends on the elasticity of substitution between the 2 types of consumption. When the 2 types tend to be complementary ($\sigma < 1$), an increase in p_b/p_x increases the demand for water.
- positively on the relative importance given to water consumption in utility (α^i).
- negatively on the efficiency of water consumption equipment (ε^i) when water and the composite consumption good tend to be complementary ($\sigma < 1$).

We can also express the demand for the composite consumer good, which will depend on the tariff block b in which the consumption of the individual i falls, since due to preferences and the budget constraint, this demand for the composite good is linked to water consumption:

$$\mathbf{X}_b^i = \left(\frac{p_b}{p_x} \left(\frac{1 - \alpha^i}{\varepsilon^i \alpha^i} \right) \right)^\sigma \varepsilon^i q_b^i$$

2.3.3 Aggregated consumption

To calculate aggregated water consumption, we first need to sum up individual consumption for each tariff block b (excluding threshold consumption), noted Q_b , and for each threshold level, noted K_b :

$$Q_b = \sum_i n_{q_b}^i q_b^i \quad \text{and} \quad K_b = \sum_i n_{k_b}^i k_b$$

where $n_{q_b}^i$ represents the number of individuals i with an arbitrary income $R^i \in]\underline{R}_b^i, \bar{R}_b^i]$, who therefore consume q_b^i . $n_{k_b}^i$ represents the number of individuals i with an arbitrary income $R^i \in]\bar{R}_b^i, \underline{R}_{b+1}^i]$, who therefore consume k_b . Aggregate consumption is obtained by summing over the whole population and all the blocks:

$$Q = \sum_{b=1}^3 Q_b + \sum_{b=1}^2 K_b = \sum_{b=1}^3 \sum_i n_{q_b}^i q_b^i + \sum_{b=1}^2 \sum_i n_{k_b}^i k_b$$

Note that, since $n_{q_b}^i$ is associated with income R^i compatible with consumption in tariff block b , if a shock causes individuals with income R^i to adjust their water consumption from block b to block $b - 1$, then $n_{q_b}^i$ will decrease while $n_{q_{b-1}}^i$ will increase. The same applies to $n_{k_b}^i$.

So $n_{q_b}^i$ and $n_{k_b}^i$ are endogenous and depend on the tariff structure and what is happening in the economy.

2.4 Balancing the water operator's budget

The operator's budget is balanced when the total cost of supplying water (noted CT) equals the total revenue from this supply (which equals the total expenditure on water by individuals noted DT).

Conventionally, total cost is made up of the fixed cost of production (F) and the variable cost, the product of marginal cost (μ) and aggregate consumption (Q):

$$CT = F + \mu \cdot Q = F + \mu \cdot \left(\sum_{b=1}^3 Q_b + \sum_{b=1}^2 K_b \right)$$

Total expenditure associated with water demand (excluding subscriptions) is the sum of aggregate expenditure by tariff block:

- For the block 1 (outside the threshold), $p_1 Q_1$.
- For the block 1 threshold, $p_1 K_1$.
- For the block 2 (outside the threshold), each individual i who consumes less than k_2 spends $p_1 k_1 + p_2 (q_2^i - k_1)$. There are $n_{q_2}^i$ of them, so for the population as a whole, total expenditure amounts to $\sum_i [p_2 q_2^i - D_2] n_{q_2}^i$.
- For the threshold of block 2, each individual spends $p_1 k_1 + p_2 (k_2 - k_1)$. There are $n_{k_2}^i$, so for the population as a whole, the total expenditure is $\sum_i [p_2 k_2 - D_2] n_{k_2}^i$.
- For block 3, each individual i who consumes q_3^i spends $p_1 k_1 + p_2 k_2 + p_3 (q_3^i - k_2)$. There are $n_{q_3}^i$, so for the population as a whole, the total expenditure is $\sum_i [p_3 q_3^i - D_3] n_{q_3}^i$.

So total expenditure, including subscriptions, is given by ⁴:

$$DT = \sum_{b=1}^3 \sum_i n_{q_b}^i (p_b q_b^i - D_b) + \sum_{b=1}^2 \sum_i n_{k_b}^i (p_b k_b - D_b) + nS = \sum_{b=1}^3 [p_b Q_b - n_b D_b] + \sum_{b=1}^2 p_b K_b + nS$$

where $n_b = \sum_i (n_{q_b}^i + n_{k_b}^i)$ represents the size of the population consuming in tariff block b (threshold b included), with $\sum_b^3 n_b = n$ the total size of the population. Total expenditure thus equals total consumption in value $\sum_{b=1}^3 p_b Q_b + \sum_{b=1}^2 p_b K_b$, plus the subscription for the whole population, nS , from which we must remove all Nordin's D s which capture the fact that consumption in tariff blocks below b is billed at lower prices than consumption in tariff block b .

Balancing the budget, that is $CT = DT$, we obtain

$$\sum_{b=1}^3 [(p_b - \mu) Q_b - n_b D_b] + \sum_{b=1}^2 (p_b - \mu) K_b = F - nS$$

⁴Here we simplify by using $\sum_{b=1}^3 \sum_i n_{q_b}^i D_b + \sum_{b=1}^2 \sum_i n_{k_b}^i D_b = \sum_{b=1}^3 n_b D_b$ (because $n_{k_3}^i = 0$).

We will investigate this relationship in the next section.

3 The generalized heterogeneous agent model

In this section, we will be extending our framework to a more general case of a B-block tariff, following the presentation of the special case of a 3-bloc tariff. The initial step in this process is to redefine the pricing system to accentuate the progressive nature of the tariff. This is achieved by demonstrating that the tariff can be reduced to the price of the initial bracket, complemented by the progressive price coefficients that span the range between brackets.

3.1 The redefinition of the block pricing system

In order to facilitate the usefulness of the model and to understand the levers available to the operator to define the tariff, from a perspective of budget balancing but also of tariff affordability constraints, the block pricing system is reduced to two key variables: the price of the 1st tranche and the progressivity of the tariff.

Thus, the price of the second block can be summed up as the price of the 1st block p_1 and the progressivity coefficient ϖ_2 between block 1 and block 2, and the price of the third block can be summed up as the price of the second block and the progressivity coefficient ϖ_3 between block 2 and block 3:

$$p_2 = \varpi_2 p_1 \quad \text{and} \quad p_3 = \varpi_3 p_2 = \varpi_3 \varpi_2 p_1$$

In general, the price of the b block is a function of the price of the initial block and the progressivity of the pricing:

$$p_b = \Omega_b p_1 \quad \text{with} \quad \Omega_b \equiv \prod_{m=2}^b \varpi_m$$

where $\varpi_m \geq 1$ measures the progressivity of the pricing between blocks $m - 1$ and m , and p_1 is the price of the initial block. Ω_b captures the progressivity between the first bracket and the b^{th} bracket.

3.2 Individual and aggregate demand

The individual water demand of agent i in pricing block b , noted q_b^i is then written :

$$q_b^i = \begin{cases} \left[1 + \left(\frac{\varepsilon^i p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1 - \alpha^i}{\alpha^i} \right)^\sigma \right]^{-1} \left(\frac{R^i + D_b}{\Omega_b p_1} \right), & \text{if } \underline{R}_b^i < R^i \leq \bar{R}_b^i \\ k_b, & \text{if } \bar{R}_b^i < R^i \leq \underline{R}_{b+1}^i \end{cases} \quad (4)$$

where $R^i = I^i - S$ is arbitrary income, and

$$\begin{aligned}\underline{R}_b^i &\equiv \Omega_b p_1 \left(1 + \left(\frac{\varepsilon^i p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1 - \alpha^i}{\alpha^i} \right)^\sigma \right) k_{b-1} - D_b \\ \bar{R}_b^i &\equiv \Omega_b p_1 \left(1 + \left(\frac{\varepsilon^i p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1 - \alpha^i}{\alpha^i} \right)^\sigma \right) k_b - D_b\end{aligned}$$

with the D of Nordin defined as

$$D_b \equiv \begin{cases} p_1 \sum_{m=1}^{b-1} \Omega_m k_m (\varpi_{m+1} - 1) > 0, & \text{if } b > 1 \\ 0 & \text{if } b = 1 \end{cases}$$

Individual demand for income group i in block b is therefore defined as a function $\mathcal{D}(\cdot)$ of different types of variables in the economy:

$$q_b^i = \mathcal{D}(\underbrace{\Omega_b, p_1, k_b, S}_T; \underbrace{\alpha^i, \sigma}_U; \underbrace{\varepsilon^i, p_x, I^i}_E) \quad (5)$$

There are 3 main types of variable determining individual demand for water.

The "T" variables concern the pricing system and are chosen by the operator when defining its pricing system. They include the price of the 1st instalment (p_1), the progressivity of the tariff system (captured by Ω_b), the definition of the threshold (k_b) above which a new tariff is applied and the amount of the subscription defined by the operator (S). These are therefore exogenous variables, which can be considered as economic policy variables insofar as they are manipulated to obtain an objective for water consumption (individual and/or aggregate) and/or an objective for the affordability of the water supply system.

The "U" variables concern the preferences (utility) of the agents, whether in terms of the structure of preferences (with the elasticity of substitution σ between water services and the composite consumption good) and the relative importance of water consumption (α^i) in relation to other consumption⁵. These variables are given by individual characteristics and are therefore imposed on the operator.

The "E" variables bring together the elements of the water consumer's environment: the agent's income i which is influenced by what is happening in the wider economy, the price of the composite good (p_x) which could be interpreted here as a consumer price index (excluding water), and the efficiency of the water supply systems (whether this concerns the operator's own system or the equipment available to the consumer). These variables are also data for the operator.

⁵Subsistence consumption, when taken into account (see below), is also part of these preference variables.

Aggregate demand is therefore as follows:

$$Q = \sum_{b=1}^B \sum_i \underbrace{n_{q_b}^i}_P \mathcal{D}(\Omega_b, p_1, k_b, S; \alpha^i, \sigma; \varepsilon^i, p_x, I^i) + \sum_{b=1}^{B-1} \sum_i \underbrace{n_{k_b}^i}_P k_b \quad (6)$$

Equation (6) indicates the presence of an additional variable that governs water consumption at the aggregate level: the distribution of income in the population (by convention, it is noted as **the variable “P”**, for population). This distribution, in conjunction with other variables, establishes the quantity of consumers in each tariff block $n_{q_b}^i$ and $n_{k_b}^i$. As previously mentioned, this suggests that the number of individuals in each tariff block is endogenous and is influenced by the same variables that determine individual water demand.

3.3 The operator's balanced budget

We can now rewrite the operator's balanced budget as follows:

$$\sum_{b=1}^3 \left(\sum_i n_{q_b}^i (p_1 \Omega_b - \mu) \mathcal{D}(\Omega_b, p_1, k_b, S; \alpha^i, \sigma; \varepsilon^i, p_x, I^i) - n_b D_b \right) + \sum_{b=1}^2 (p_1 \Omega_b - \mu) K_b + nS = F$$

The revenue generated from the production/distribution of water must be sufficient to cover the fixed costs associated with these activities. As demonstrated above, under specific environmental variables, given preferences, and within a certain population, the operator possesses the capacity to delineate the parameters of the block tariff (price of the 1st instalment p_1 , progressivity of the tariff Ω_b , threshold levels of consumption k_b , amount of the subscription S) to balance his budget.

Therefore, this equilibrium relationship indicates that the parameters of the block tariff are contingent on agents' preferences, the distribution of income within the population, and external "macro" factors. Consequently, in the event of external shocks, the tariff should be adjusted to either eliminate surpluses or absorb deficits.

It has been demonstrated that pricing can function as a mechanism to regulate water usage in a manner that is both environmentally sustainable and financially responsible. This approach can be employed to meet both individual and collective consumption goals, as well as ensure equitable distribution of water resources and enhance overall well-being.

4 Variants of the model

Once the general framework of the heterogeneous agent model has been established, it is interesting to examine a certain number of variants which allow important characteristics linked to water demand to be introduced into the analysis.

4.1 Stone-Geary utility

The general presentation of the model ignored an important component of residential water consumption behaviour: subsistence water consumption. To take this into account, we assume that $f(q^i) = \varepsilon^i q^i - \underline{z}^i$ where $\underline{z}^i > 0$ is subsistence consumption.

The demand for water for tariff block b is then written:

$$q_b^i = \begin{cases} \left[1 + \left(\frac{\varepsilon^i p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i} \right)^\sigma \right]^{-1} \left(\frac{R^i + D_b}{\Omega_b p_1} + \left(\frac{p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\varepsilon^i \alpha^i} \right)^\sigma \underline{z}^i \right), & \text{if } \underline{R}_b^i < R^i \leq \bar{R}_b^i \\ k_b, & \text{if } \bar{R}_b^i < R^i \leq \underline{R}_{b+1}^i \end{cases} \quad (7)$$

with

$$\begin{aligned} \underline{R}_b^i &\equiv p_b \left[\left(1 + \left(\frac{\varepsilon^i p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i} \right)^\sigma \right) k_{b-1} - \left(\frac{p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\varepsilon^i \alpha^i} \right)^\sigma \underline{z}^i \right] - D_b \\ \bar{R}_b^i &\equiv p_b \left[\left(1 + \left(\frac{\varepsilon^i p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i} \right)^\sigma \right) k_b - \left(\frac{p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\varepsilon^i \alpha^i} \right)^\sigma \underline{z}^i \right] - D_b \end{aligned}$$

It appears that taking subsistence consumption into account does not qualitatively modify the results of the reference model: the level of subsistence consumption $\underline{z}^i$ now has a positive influence on individual consumption. However, it does complicate the influence of relative prices p_x/p_b and the efficiency of water consumption equipment ε^i on individual water demand (see equations (4) and (7)) and it also affects the threshold income levels that determine in which block the individual i consumes.

4.2 Taking account of perception problems

Consumers' poor perception of the tariffs to which they are subject, or of the quantities they consume, is an element which has been the subject of numerous studies in the theoretical and empirical literature (see [Attari, 2014](#); [Brent and Ward, 2019](#); [Garcia-Valinas et al., 2021](#), among others). Our aim here is to examine the implications for individual and aggregate consumption levels and, more generally, for the budgetary equilibrium of the system.

4.2.1 Misperception of quantities consumed

When you turn on the water tap, for most of the uses to which water is put, it is very difficult to fully understand the quantities actually consumed. So, alongside the poor perception of water prices, there is also a poor perception of the quantities consumed, which leads to changes in the expected effects of pricing. Thus [Attari \(2014\)](#) shows, on a panel of 1020 participants in the USA, that individuals tend to systematically underestimate their water consumption, whatever the intended use of the water, and this misperception increases with the quantities consumed

6.

⁶See also [Brent and Ward \(2019\)](#) concerning the misperception of volumes consumed.

A very simple way of capturing this in our model is to specify $f(q^i)$ of the utility function (equation 1) as follows ⁷:

$$f(q^i) \equiv \left(\frac{q^i}{\hat{q}^i}\right)^{\psi^i} q^i \quad \text{with} \quad \psi^i \in [-1, 1]$$

The parameter ψ^i measures the perception of the quantities consumed by the individual i . When $\psi^i = 0$, the perception of the design is perfect. When $\psi^i < 0$ (respectively $\psi^i > 0$), the individual over-estimates (respectively under-estimates) his water consumption as long as his actual consumption is below a threshold noted $\hat{q}^i$ (Cf. the graph taken from Attari (2014)). In accordance with the graph below from Attari (2014), we assume that $\hat{q}^i$ is sufficiently low and $\psi^i < 0$, so that the individual underestimates his water consumption most of the time. When the individual i determines his demand for water, he takes as given the term $(q^i/\hat{q}^i)^{\psi^i}$ in his utility.

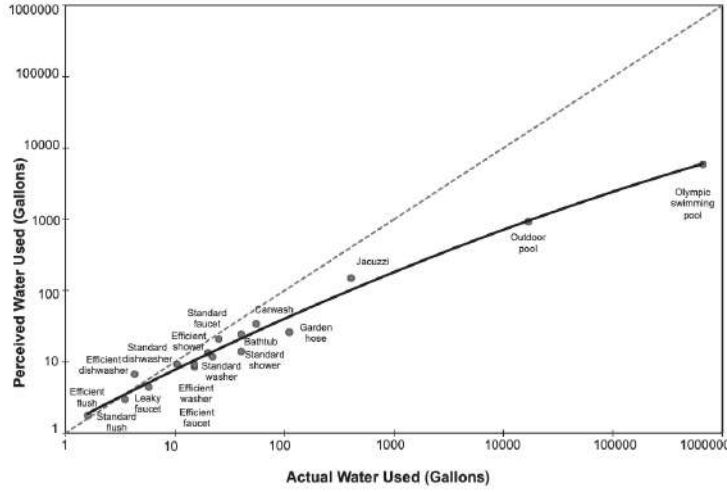


Fig. 3. Mean perceptions of water use as a function of actual water use for 17 different behaviors and activities. Error bars for 95% confidence intervals are omitted because they are typically no taller than the symbols themselves. The diagonal dashed line represents perfect accuracy.

Attari

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Individual demand in the presence of poor price perception, noted $\tilde{q}_b^i$, is then expressed implicitly:

$$\tilde{q}_b^i \left[1 + \left(\frac{\tilde{q}_b^i}{\hat{q}^i}\right)^{\psi^i(1-\sigma)} \left(\frac{p_x}{\Omega_b p_1}\right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i}\right)^\sigma \right] = \frac{R^i + D_b}{\Omega_b p_1}$$

Remembering that individual demand with perfect perception is defined by the equation above for $\psi^i = 0$, and under the hypothesis that $\hat{q}^i$ is sufficiently small for $\tilde{q}_b^i > \hat{q}^i$, we can show that

$$\tilde{q}_b^i > q_b^i \quad \text{if } \psi^i(1-\sigma) < 0$$

It is interesting to note that it is not only the index of wrong perception ψ^i that determines whether wrong perception leads to over- or under-consumption of water in the presence, compared to the case of perfect perception, it is also the value of the elasticity of substitution

⁷To simplify the presentation, we abstract from the efficiency of water equipment (captured by the parameter ε^i) as well as from the level of subsistence water consumption (z^i).

(σ greater or less than 1), i.e. the degree of substitution between the water services and the composite consumption good in the utility that plays a role ⁸.

Thus, when the individual underestimates his water consumption ($\psi^i < 0$), we would expect him to consume more than in the case of perfect perception ($\tilde{q}_b^i > q_b^i$), yet this is not the case when the water services and the composite consumption good tend to be substitutable ($\sigma > 1$). This is because the individual perceives that each unit of water he consumes contributes less to his utility, so that he consumes relatively less water than the composite consumer good when substituting with the composite good. As a result, his water consumption decreases.

Another interesting element is that the threshold incomes $\bar{R}_b^i$ and $\underline{R}_{b+1}^i$ are now defined as follows:

$$\begin{aligned}\bar{R}_b^i &= \Omega_{b-1} p_1 k_{b-1} \left[1 + \left(\frac{k_b}{\tilde{q}^i} \right)^{\psi^i(1-\sigma)} \left(\frac{p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i} \right)^\sigma \right] - D_b \\ \underline{R}_{b+1}^i &= \Omega_b p_1 k_b \left[1 + \left(\frac{k_b}{\tilde{q}^i} \right)^{\psi^i(1-\sigma)} \left(\frac{p_x}{\Omega_b p_1} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i} \right)^\sigma \right] - D_b\end{aligned}$$

and are therefore affected by the misperception of quantities. For $\psi^i(1-\sigma) < 0$, the arbitrary threshold incomes are higher, so that for a given tariff block, individuals with higher incomes will consume more, compared with the case of perfect perception of quantities.

4.2.2 Price Misperception

We now consider the case where individuals have a poor perception of water prices because of the block structure of pricing ⁹. We take up the formulation of [Shin \(1985\)](#), which defines the price charged by individual i for block b , denoted by $\hat{\pi}_b^i$, as the combination between the “true” price of block b , p_b , and the “wrong” price, denoted p_w^i :

$$\hat{\pi}_b^i = (p_b)^{\phi_b^i} (p_w^i)^{1-\phi_b^i}$$

where $\phi_b^i \in (0, 1)$ captures the level of price perception, with $\phi_b^i = 1$ when an individual i has a perfect perception of prices and $\phi_b^i = 0$ when the wrong perception is maximal.

We assume that the “wrong” price p_w^i can be either a presumed price, denoted by p_s ¹⁰ or the average price of his last bill, noted $\bar{p}^i$ ¹¹. The average price is defined as the ratio between the last bill received and the volume of water actually consumed as shown on that bill. It means that it depends on the block in which the agent actually consumes, that is $\bar{p}^i \equiv p_b - D_b/q_b^i$ if

⁸Note that in the presence of a Cobb-Douglas utility ($\sigma = 1$) the poor perception of quantities, as formalised here, has no influence on the demand for water.

⁹See [Brent and Ward \(2019\)](#), [Garcia-Valinas et al. \(2021\)](#), among others.

¹⁰The presumed price could be either the price of block 1 if the agent is aware of a change in the price of the first block or, when the agent is absolutely myopic, the price of the previous tariff (before the implementation of block tariff) called p_0 , such that $p_s = p_1^\beta p_0^{1-\beta}$, with $\beta \in \{0, 1\}$.

¹¹This assumption allows us to easily account for the 2 behaviours of “*schmeduling*” which are “*spotlighting*” and “*ironing*” (see among others [Liebman and Zeckhauser, 2003](#); [Rees-Jones and Taubinsky, 2019](#)).

he is consuming in block b ¹². As a consequence the individual who consumes q_b^i evaluates a mean price higher than the price of the previous block ($b - 1$) but lower than the price of his actual block (b). So the "wrong" price is defined as follows:

$$p_w^i = (p_s^i)^{1-\kappa^i} (\bar{p}^i)^{\kappa^i}$$

with $\kappa^i = \{0, 1\}$. When $\kappa^i = 0$, the wrong price is the average price, while when $\kappa^i = 1$, the wrong price is the presumed price. The perceived price is therefore written as a combination of the effective price, the presumed price and the average price according to the value of the parameters κ^i and ϕ_b^i :

$$\hat{\pi}_b^i = p_b^{\phi_b^i} (p_s^i)^{(1-\kappa^i)(1-\phi_b^i)} (\bar{p}^i)^{\kappa^i(1-\phi_b^i)}$$

Thus, our definition of perceived price allows us to capture two levels of misperception. A first level of misperception between the "wrong price" and the actual price (through the ϕ_b^i parameter). A second level of misperception, for the wrong price (through the κ^i parameter), associated with the behaviour of "*schmeduling*" (Cf. [Liebman and Zeckhauser, 2003](#)), leading the latter to think that pricing is either binary or at the average price:

- $\phi_b^i = 1$: the perception of the price is perfect and we find the benchmark case of the model;
- $\phi_b^i = 0$: the wrong perception is complete.
 - $\kappa^i = 0$: the individual i thinks that the price is that of bracket 1 (result of a "*spotlighting*" behaviour)
 - $\kappa^i = 1$: individual i thinks that the price is the average price (result of an "*ironing*" behaviour)
- $\phi_b^i \in]0, 1[$, the perception of the price is imperfect and the individual i reasons on a sort of weighted average of different prices.

In its general form the perceived price is given by:

$$\hat{\pi}_b^i = p_b \left[\frac{\bar{p}^i}{p_b} \left(\frac{\bar{p}^i}{p_s^i} \right)^{\kappa^i - 1} \right]^{1-\phi_b^i} \geq p_b$$

The individual water demand of agent i is therefore written as:

$$\hat{q}_b^i = \begin{cases} \left[1 + \left(\frac{\varepsilon^i p_x}{\hat{\pi}_b^i} \right)^{1-\sigma} \left(\frac{1-\alpha^i}{\alpha^i} \right)^\sigma \right]^{-1} \frac{R^i + \hat{D}_b}{\hat{\pi}_b^i}, & \text{if } \underline{R}_b^i < R^i \leq \bar{R}_b^i \\ k_b, & \text{if } \bar{R}_b^i < R^i \leq \underline{R}_{b+1}^i \end{cases}$$

¹²In the case of a 3 block tariff, the average price could take 3 different values, depending on whether the individual is actually subject to the 1st tariff block ($\bar{p}^i = p_1$), 2nd tariff block ($\bar{p}^i = [p_2 q_2^i - (p_2 - p) k_1] / q_2^i$) or 3rd tariff block ($\bar{p}^i = [p_3 q_3^i - ((p_2 - p) k_1 + (p_3 - p_2) k_2)] / q_3^i$).

where

$$\begin{aligned}\underline{R}_b^i &\equiv \hat{\pi}_b^i \left(1 + \left(\frac{\varepsilon^i p_x}{\hat{\pi}_b^i} \right)^{1-\sigma} \left(\frac{1 - \alpha^i}{\alpha^i} \right)^\sigma \right) k_{b-1} - \hat{D}_b \\ \bar{R}_b^i &\equiv \hat{\pi}_b^i \left(1 + \left(\frac{\varepsilon^i p_x}{\hat{\pi}_b^i} \right)^{1-\sigma} \left(\frac{1 - \alpha^i}{\alpha^i} \right)^\sigma \right) k_b - \hat{D}_b\end{aligned}$$

and $\hat{D}$ is Nordin's D incorporating the perceived price for the b tariff block:

$$\hat{D}_b \equiv \begin{cases} \sum_{m=1}^{b-1} k_m (\hat{\pi}_{m+1}^i - \hat{\pi}_m^i) > 0, & \text{si } b > 1 \\ = 0 & \text{if } b = 1 \end{cases}$$

The lower the perception (ϕ_b^i decreases), the more linear the water consumption profile should be in relation to income distribution, representing the phenomenon of “*schmeduling*” identified in the literature on poor price perception.

5 Concluding remarks

The purpose of this paper is to present a theoretical model that we developed to study water demand in the presence of heterogeneous agents and block tariffs. The results of our work are of several kinds.

1. We have developed a theoretical model that serves as a tool for implementing and evaluating water pricing and/or management policies. This model can be calibrated using local data to replicate the demand behavior of a conurbation or region. Thus, it can be used to examine how individuals and groups react to changes in water pricing or the effects on affordability of the tariff.
2. A second important element is the model's modularity, which allows alternative hypotheses to be added to enrich the analysis of water demand in the presence of heterogeneous agents (e.g., perception problems or habitual behavior). Enhancements to the model could include integrating different types of water consumption (e.g., hot/cold water, differentiated water use) and the consumption of complementary goods (e.g., electricity). This analytical framework should enable us to analyze the effects of rising electricity and/or gas prices on residential water demand and the potential impact of a "tariff shield" policy, as recently implemented in France. Additionally, it is possible to examine the effects of introducing a super-progressive pricing system, as exists in Spain.

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APPENDIX

I The individual water demand

Individual utility of agent i is given by:

$$U(q^i, \mathbf{X}^i) = \left[\alpha^i f(q^i)^{\frac{\sigma-1}{\sigma}} + (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\frac{\sigma-1}{\sigma}}} \quad (\text{I.1})$$

The program of the consumer:

$$\begin{aligned} \max_{q^i, \mathbf{X}^i} U(q^i, \mathbf{X}^i) &= \left[\alpha^i f(q^i)^{\frac{\sigma-1}{\sigma}} + (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\frac{\sigma-1}{\sigma}}} \\ \text{s.t.} \quad &\begin{cases} I^i = p_1 q^i + p_x \mathbf{X}^i + S & \text{if } q^i \leq k_1 \\ I^i = p_1 k_1 + p_2 (q^i - k_1) + p_x \mathbf{X}^i + S & \text{if } k_1 < q^i \leq k_2 \\ I^i = p_1 k_1 + p_2 (k_2 - k_1) + p_3 (q^i - k_2) + p_x \mathbf{X}^i + S & \text{if } q^i > k_2 \end{cases} \end{aligned} \quad (\text{I.2})$$

The Lagrangian is written as:

$$\begin{aligned} \mathcal{L} &= \left[\alpha^i f(q^i)^{\frac{\sigma-1}{\sigma}} + (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\frac{\sigma-1}{\sigma}}} \\ &+ \lambda \left[I^i - \left(p_1 \min(q^i, k_1) + \sum_{b=2}^4 p_b \min(\max(q^i - k_{b-1}, 0), k_b - k_{b-1}) + p_x \mathbf{X}^i + S \right) \right] \end{aligned} \quad (\text{I.3})$$

First-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial q^i} = 0 \quad \Rightarrow \quad \left[\alpha^i f(q^i)^{\frac{\sigma-1}{\sigma}} + (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\phi}-1} \varepsilon^i \alpha^i f(q^i)^{\phi-1} = \lambda p_b \quad (\text{I.4})$$

$$\frac{\partial \mathcal{L}}{\partial \mathbf{X}^i} = 0 \quad \Rightarrow \quad \left[\alpha^i f(q^i)^{\frac{\sigma-1}{\sigma}} + (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\phi}} (1 - \alpha^i) g(\mathbf{X}^i)^{\frac{\sigma-1}{\sigma}-1} = \lambda p_x \quad (\text{I.5})$$

Equations (I.4) over (I.5), give the demand for consumption goods when agents spent water in block b :

$$\mathbf{X}^i_b = \left(\frac{p_b}{p_x} \left(\frac{1 - \alpha^i}{\varepsilon^i \alpha^i} \right) \right)^{\sigma} f(q^i) \quad (\text{I.6})$$

where $\sigma \equiv 1/(1 - \phi)$ is the elasticity of substitution between water consumption and other goods in utility

As a consequence, using budget constraint, the individual demand of water for an household i in the block-tariff b , denoted by q^i_b , can be written as (under the assumption that $f(q^i) \equiv \varepsilon^i q^i$):¹

$$q^i_b = \begin{cases} [1 + \varepsilon^i \varrho_b]^{-1} \left(\frac{R^i + D_b}{p_b} + \varrho_b \underline{z}^i \right), & \text{if } \underline{R}^i_b < R^i \leq \bar{R}^i_b \\ k_b, & \text{if } \bar{R}^i_b < R^i \leq \underline{R}^i_{b+1} \end{cases} \quad (\text{I.7})$$

¹We have re-written $p_1 \min(q^i, k_1) + \sum_{b=2}^4 p_b \min(\max(q^i - k_{b-1}, 0), k_b - k_{b-1})$ as $p_b q - D_b$ where $d_b \equiv \sum_{m=1}^b k_m (p_{m+1} - p_m)$ is the Nordin D.

where $\varrho_b \equiv (p_x/p_b)^{1-\sigma} \left(\frac{1-\alpha^i}{\varepsilon^i \alpha^i} \right)^\sigma$, $R^i = I^i - S$ is the arbitrary revenue, and

$$\underline{R}_b^i \equiv p_b \left[\left(1 + \varepsilon^i \varrho_b \right) k_{b-1} - \varrho_b \underline{z}^i \right] - D_b \quad (\text{I.8})$$

$$\bar{R}_b^i \equiv p_b \left[\left(1 + \varepsilon^i \varrho_b \right) k_b - \varrho_b \bar{z}^i \right] - D_b \quad (\text{I.9})$$

with

$$D_b \equiv \begin{cases} \sum_{m=1}^{b-1} k_m (p_{m+1} - p_m) > 0, & \text{if } b > 1 \\ = 0 & \text{if } b = 1 \end{cases} \quad (\text{I.10})$$

is the Nordin D for block-tariff b .

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