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Advances in the Economic Analysis of Residential Water Use: An Introduction

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Abstract: The aim of this Special Issue is to gather evidence on the impact of price policies (PP) and non-price policies (NPP) in shaping residential water use in a context of increased water scarcity. Indeed, a large body of the empirical economic literature on residential water demand has been devoted to measuring the impact of PP (water price increases, use of block rate pricing or peak pricing, etc.). The consensus is that the residential water demand is inelastic with respect to water price, but not perfectly. Given the low water price elasticity, pricing schemes may not always be effective tools for modifying household water behaviors. This is puzzling since increasing the water price is still viewed by public authorities as the most direct economic tool for inducing water conservation behaviors. Additional evidence regarding the use of PP in shaping residential water use is then required. More recently, it has been argued that residential consumers may react to NPP, such as water conservation programs, education campaigns, or smart metering. NPP are based on the idea that residential water users can implement strategies that will result in water savings via changing their individual behaviors. Feedback information based on smart water metering is an example of approach used by some water utilities. There are still large gaps in the knowledge on the residential water demand, and in particular on the impact of PP and NPP on residential water use, household water affordability and water service performance. These topics are addressed in this Special Issue "Advances in the Economic Analysis of Residential Water Use".

Keywords: residential water use; price policies; non-price policies; household behaviors; smart meter; water price elasticity

1. Introduction

This Special Issue of the *Water* Journal focuses on household water consumption defined as the quantity of water used to cover household and related utility needs of the population through the water supply industry and self-supply, calculated as a total and per capita.

There are several reasons that call for a good understanding of household water use. First, most national allocation regimes define domestic and human needs as the highest priority use (OECD, 2015) [1]. Some exceptions include the Netherlands, a small number of Canadian provinces, water uses in Israel, and Peru. Second, most large-scale water assessment models predict some very significant changes in household water use (or more generally in urban water use) for the next 50 years (Hejazi, 2013) [2]. Third, water is an essential good for households in the sense that water has no good substitute for most indoor water uses (personal hygiene, cleaning, etc.).

Economists have been working on household water use for a long time. However, water demand modeling has taken on new importance with the need to better understand the role economic instruments (i.e., water pricing) might have to induce change in water user behaviors (i.e., reduction of water abstraction or polluted discharges). To this end, economists have developed a great variety of models allowing to predict water demands for industrial, agricultural and domestic users. For domestic users, the level of knowledge is quite advanced. Estimations of domestic water demand functions have been undertaken for a substantial number of countries all over the world, and the existing literature has already been summarized and reviewed by several authors [3–5].

In the following, we briefly review the existing scientific literature on household water demand modeling. We summarize the main methodological issues and discuss empirical findings, in particular in the European context. The remainder of this article is organised as follows. In Section 2, we briefly present the water demand function approach. In Section 3, we summarize the existing knowledge and gaps in household water demands. Finally, we briefly conclude by presenting the nine articles which are part of this Special Issue.

2. The Household Water Demand Approach

This section is adapted from the report [6]. Economic water demand modeling began in 1926, when Leonard Metcalf presented a hand-drawn regression on a double-logarithmic scale of price against water demand [7]. A few decades later, several articles were published estimating proper water demand functions (e.g., [8]). Since these initial studies, the literature on water demand modeling has produced an abundance of published and unpublished research papers, primarily focusing on household demand [9].

In this section, we provide some basic methodological foundations of the household water demand function approach.

2.1. The Water Demand Function Approach

The water demand function approach relies on standard neoclassical economic assumptions. In particular, it is assumed that, for each consumer, there exists a continuous utility function that is of the consumed commodity bundle and where the functional form is determined by underlying consumer preferences. The utility of each consumer is then maximized under a budget constraint and given the prices of the commodities. Thus, the demand for a commodity is assumed to depend on the income of consumers, on the price of the commodity and on the availability and prices of all other commodities that are substitutes or complements to the commodity in question, as well as on consumer preferences.

Most scholars have made the assumption of weak separability of water with respect to other goods. Under this assumption, household water consumption does not depend on the price of other goods consumed. As discussed in [10], there is no logical difficulty in imposing separability of water with respect to other goods. First, most indoor water uses (personal hygiene, cleaning, etc.) have no good substitutes. Second, household habits may be considered constant, at least in the short run. Third, complementary goods related to domestic water consumption are typically durable equipment (washing machines, sanitary equipment, etc.) that is unlikely to be changed in the short term in reaction to a water price change. Under this separability assumption, the Marshallian demand in water can be written as:

$$y = y^*(p, I, Z) \tag{1}$$

where y is the water consumption either per capita or per household, and p and I denote the unit water price (representing both water supply and the sewage treatment services) and the representative household income, respectively. Z is a vector of exogenous variables assumed to influence water consumption (climate conditions, household and housing characteristics, etc.).

We are especially interested in providing empirical evidence on the relationship between water price and household water consumption, as well as the relationship between household income and household water consumption. A simple way to measure these relationships is to compute the *price elasticity* of the water demand and the *income elasticity* of the water demand. The price elasticity of the water demand measures the responsiveness (or elasticity) of the water use to a change in water price, all other things being equal. To be more precise, it gives the percentage change in household water use in response to a 1% change in price (all other things being equal, i.e., holding all other determinants of demand, such as income, constant). The price elasticity of the water demand may be written as:

$$\epsilon_p = \frac{\partial y^*(.)}{\partial p} \times \frac{p}{y^*}. \tag{2}$$

Similarly, the income elasticity of the water demand measures the responsiveness (or elasticity) of the water use to a change in household income, all other things being equal. To be more accurate, it gives the percentage change in household water use in response to a 1% change in household income. The income elasticity of the water demand may be written as:

$$\epsilon_I = \frac{\partial y^*(.)}{\partial I} \times \frac{I}{y^*}. \tag{3}$$

Water demand functions can be used for computing the implications of alternative water pricing policies on consumer behaviors. In addition, they provide some tools for developing welfare analysis. For instance, the welfare effects of an alternative pricing policy on households can be measured (approximated, in fact) using the household water demand function (consumer surplus).

2.2. Theoretical and Empirical Considerations

A first implicit assumption we have made when writing Equation (1) is that water is a homogenous good. In reality, however, water that is used by households is a composite good. It consists of the direct use of water for drinking water (which in general represents a small share of the total water consumption, also due to increasing bottled water consumption [11]) and the indirect use for water as a complement to different household activities (washing, cooking, hygiene, gardening, etc.). Water is therefore a necessity in households in a number of its uses and, as such, has no substitute, while it is not a necessity in many other of its uses. In the latter case, the demand for water is likely to be more affected by price changes. Since it is not usually possible to separate the different types of demand, the estimated elasticities are usually based on an aggregated household demand for water as depicted in Equation (1). However, alternative specifications, such as a Stone–Geary utility function, which allows identifying a volume of water covering basic needs, have also been explored [12].

A second implicit assumption in Equation (1) is that water is considered as a homogenous good in terms of its quality. However, in practice, tap water quality is likely to differ from one water service to another (urban versus rural water services, small versus large water services, etc.). Some studies have then focused on analyzing the impact of water quality on household water consumption (see, among others, [13] for an example in the United States).

Equation (1) assumes that all households face the same unit water price, p. However, in practice, for efficiency or for affordability reasons, water service may use much more complex pricing schemes. To address water affordability issues, water service may indeed implement water tariff such that low-water users or some specific groups of vulnerable users benefit from lower per unit charges. Such approaches are usually called "social tariffs". These may include increasing block rates, subsidized volumetric rates in the lowest (lifeline) block, or minimum quantity allowances delivered for free. Identifying the residential water demand function (and the price elasticity) in that case requires specific econometric techniques which are discussed in [14,15].

One should also stress that the price and income elasticities of the water demand function presented in Equations (2) and (3) provide only a local measure of the responsiveness of the water demand to changes in water price and household income. For any given household, it is likely that the price elasticity may vary depending on the level of the water price and income.

As discussed in [9], the existing literature has debated on a large number of methodological and empirical issues. Methodological issues include the appropriated level and structure of data for estimation (micro data versus aggregated data), the appropriate price specification (marginal water price versus average water price) and the appropriate functional form to be used for estimating Equation (1). Empirical issues include the magnitude and variation of estimated price and income elasticities [4,16,17], the existence of seasonal differences, the long- and short-run differences in water consumption, differences due to ownership of the utilities that manage the water service [18] and geographic or income group differences in water consumption. The literature offers vast coverage. Estimations have been undertaken in several countries [9]. The literature has already been summarized and reviewed by several authors [3–5]. In addition, four meta-analyses have been conducted, more specifically on the price and income elasticities of the household water demand [9,16,17,19]. The interested reader should also refer to Kelly Gardner's PhD dissertation [9] for a more extensive discussion on methodological and empirical aspects of household water use modeling.

3. Existing Knowledge and Gaps on Household Water Demands

In this section we summarize the empirical literature on household water demand. A few general and quite robust conclusions may be drawn from this literature, but some gaps may also be identified.

3.1. Measuring Household Water Use

Our focus is on understanding and modeling the drivers of *household water use*. By reference to the United Nations Economic Commission for Europe, we define household water use as the quantity of water used to cover the household and related utility needs of the population through the water supply industry and self-supply, calculated as a total and per capita. Our focus is on household water use per capita.

Although this definition may appear simple at first, it raises substantial issues when considering a cross-country analysis since the definition used in each country might differ from the proposed one. First, household water use may be mixed with water use for some other types of consumers (typically, small industrial or commercial establishments). Second, some countries may not report the water actually used by households but a volume including distribution network losses. In such cases, the distribution losses have been excluded when computing household water use. Third, in some countries, self-supply is included in the household water use. Finally, for computing household water use per capita, some countries use the total population, whereas others rely on the population connected to the water network. This issue is not important if almost all households are connected to the water network, but it may really matter otherwise.

3.2. Water Price and Water Tariffs

Most economists working on domestic water use generally recognize that domestic water consumption reacts to changes in water prices. It is however usually found that the household water demand function is price inelastic which means that water consumption decreases by less than 1% for every 1% increase in price, the price-elasticity typically varying between -0.1 and -1.0. In his recent meta-analysis, Sebri [19] reported mean and median price elasticities equal to -0.365 and -0.291, respectively. A few studies have found a price-elastic household water demand (for example, [20] in Italy and [21] in Spain). As explained by the former, the high tariffs characterizing Emilia Romagna, with respect to other regions in Italy, may explain their results. In [21], the highest price elasticity (in absolute value) is found for a single-person household. For a typical household made up of four persons, the price elasticity is equal to -0.27. Moreover, some tariff setting methods allow water operators to charge customers higher tariffs to cover their costs if water consumption is lower than expected.

Most published studies provide single price elasticity for the household water demand function. However, some authors have investigated the heterogeneity of price elasticity. First, price elasticity varies depending on the type of water use. Essential uses such as water for human consumption or for cooking are found to be very price inelastic, whereas water-related leisure activities (watering the garden or making use of swimming pools) are usually much more price reactive. Second, price elasticity also varies over time. Demand studies using summer data appear to exhibit higher price elasticity in absolute value [3]. Third, price elasticity is found to vary depending upon some characteristics of households. It is for instance documented that elasticity varies with household size [21,22]. In developed countries, it is also usually found that price elasticity varies with household income, lower income groups being more price-responsive than higher income groups. For Cyprus, Hajispyrou et al. [23] reported a price elasticity equal to -0.79 for the lowest income group compared to -0.39 for the highest income group. In Belgium, the price elasticity for the lowest income quintile is estimated to be -0.76 compared to -0.25 for the highest income quintile [22]. Since households will react in a very different way to water pricing depending on their level of income, any change in the water price policy will have to address some social and equity issues. Fourth, price elasticities differ in the short and in the long run. Short-run elasticities are usually found to be smaller than their long-run counterparts, suggesting that consumers might need time to adjust water-using capital stocks and to learn about the effects of use on their bills. For Spain, Martínez-Espiñeira [24] found that the price elasticity of demand is around -0.1 in the short run and -0.5 in the long run. For France the short- and long-run price elasticities reported by Nauges and Thomas [25] are, respectively, -0.26 and -0.40. Using a panel of 101 Italian municipalities, Musolesi and Nosvelli [26] found short- and long-term elasticities for the Italian household water demand equal to -0.27 and -0.47, respectively. For the Czech Republic, the water demand was shown by Hortová and Kristoufek [27] to be more elastic in the long run than in the short run, as the price elasticity in the short run is estimated to be -0.20, while the price elasticity in the long run is -0.54. Lastly, spatial variations in price elasticities have also been documented. Dalhuisen et al. [17] reported that price elasticities tend to be smaller in Europe compared to the United States, and price elasticities within the United States are greater in absolute value in the arid West. These spatial patterns have also been recently reported in [19].

3.3. Water Quality

In developed countries, a few studies have focused on analyzing the impact of water quality on household water consumption. In the United States, Piper [13] reported that water quality has a strong impact both on residential water demand and on the cost of water. For Spain, Garcia-Valinas [28] analyzed the effects of drought and restrictions on residential water demand in Seville. This paper considers a dummy variable which is equal to one when water chemical parameters are not complying with the minimum requirements defined by the water quality regulation. It is found that water quality deterioration leads to very significant reductions in water consumption. A substantial number of papers have focused on the substitution between bottled and tap water, induced by bad tap water quality. Households have been shown to undertake preventive actions to protect themselves against the risk of drinking contaminated water [29–31]. For France, Bontemps and Nauges [30] found that raw water quality has a significant impact on the choice between bottled and tap water. For French households living in a municipality where raw water quality is low, the probability to drink tap water increases by 9%. In the United States, Zivin and Neidell [31] identified a significant increase in bottled water sales (between 17% and 22%) as a consequence of several tap water quality violations. It is then estimated that US consumers were willing to pay nearly US$60 million to avoid such violations.

3.4. Household Income

It is widely accepted and has been empirically demonstrated that domestic water consumption is positively correlated with income [17]. The explanation is quite simple. A high level of income is associated with high living standards, which could imply a higher quantity of water-consuming appliances and a higher probability of the presence of high-water demanding outdoor uses such as lawn gardens and swimming pools. Some of the environmental Kuznets curve papers have however found that the relationship between water consumption and household income is in fact monotonically increasing up to a point from which it starts to be decreasing (e.g., [32]). More recent works have provided evidence questioning the robustness of that finding (e.g., [33]).

3.5. Population Characteristics

The age distribution within the household also affects residential water use, even if the impact of age on water use still needs to be explored. It is usually found that older people, all else being equal, consume less water than younger people. Nauges and Thomas [34] supported this finding and observed that communities with more seniors have lower water consumption, and similar results were found by Martins and Adelino [14], Martínez-Espiñeira [35] and Musolesi and Nosvelli [26]. By contrast, Schleich and Hillenbrand [36] found the converse, namely that, as people get older, they consume more water per person, and proposed three types of explanations. Water use may increase with age because retired people spend more time at home and gardening, because children use less water for washing and hygiene than adults, or because health reasons may force older people to use the bathroom more frequently. A variable that has a positive effect on household water consumption is the number of people in a residence [37].

3.6. Housing Characteristics

Residential characteristics associated with houses and properties have, in some studies, been shown to affect household water consumption. Some authors found a statistically significant effect between household water consumption increases and house size, and also lawn size. Using French data from 116 communities, Nauges and Thomas [34] found that, all else being equal, the older the house the more water is consumed.

3.7. Climate

Climate is one of the most studied drivers of domestic water demand. Indeed, it is considered that household water consumption varies depending on variables, such as temperature and rainfall, which may influence the amount and/or frequency of activities that involve water-consumption activities, such as garden watering, swimming pool use and personal hygiene [18]. The climatic indicators usually considered include rainfalls (annual or in the summer, and number of rainy days), evapotranspiration, temperature (maximal or average) and solar radiation in particular.

With respect to weather conditions, Martínez-Espiñeira [35] (Northwest Spain) found that water use was highest in summer. In addition, Martínez-Espiñeira [35] and Schleich and Hillenbrand [36] (for Germany) found that water consumption decreases as the number of rainy days increases. In contrast, Arbués and Villanúa [38] reported an association between high temperatures and low water consumption in the city of Zaragoza in Spain, which they suggested was due to consumption levels tapering off in the summer because of the outflow of residents to holiday destinations. Focusing also on Spain, García-Valiñas [39] observed higher price elasticity in peak periods (summer) than in off-peak periods (all other seasons). In Portugal, Martins [14] demonstrated that high temperatures tend to result in an increase of the demand for water, although rainfall has no significant association with it. Finally, in Italy, water consumption has been found to be higher at lower altitudes, and it increases in periods of drought and in dry areas [18].

3.8. Non-Price Policies

Non-Price Policies (NPP) correspond to all non-market-based programmes designed to increase the efficiency of water use or water conservation. Although NPP are by nature very heterogeneous, they may be classified into three categories: public education, technological improvements and water restrictions.

A number of papers have considered the impact of NPP on residential water use. Public education programmes have been shown to have a limited impact on residential water use, especially in the short term. The literature suggests that a certain critical mass of educational programmes is necessary to generate significant benefits [40].

Somewhat more attention has been paid to understanding the effectiveness of technological changes, especially indoor retrofitting of water-using devices such as toilets, showerheads and washing machines. Studies with this focus are frequently based on engineering assumptions of expected reductions [40]. One notable exception was provided by Millock and Nauges [41]. Using survey data on 10 OECD countries, the authors showed that the adoption of water-efficient equipment is strongly affected by housing ownership status, by being water-metered and charged with a volumetric price on water consumption and by behavioral factors. Environmental attitudes are shown to be strong predictors of the adoption of water-efficient equipment, with a marginal effect that exceeds ownership status in some cases. Gilg and Barr [42] also focused on attitudinal factors that determine water consumption behavior (in particular on environmental preferences, intrinsic motivations and social norms). This study reveals that it is possible to classify households into relatively homogenous groups based on their water consumption behavior. These attitudinal differences should then be taken into account when designing NPP.

Lastly, some authors specifically focused their attention on the efficiency of restrictions in water use. For Spain, Garcia-Valinas [28] measured the impact on consumers of rationing policies implemented during water shortages. The author demonstrates that the restrictions implemented during the drought in Seville have had an important impact on water demands. Some authors, whose articles generally focus on the comparison of voluntary programmes versus mandatory programmes, analyzed the effectiveness of outdoor watering restrictions and consistently show significant savings from mandatory restrictions (sometimes 30% or more). Findings regarding voluntary restrictions are much more variable.

3.9. Attitudinal and Behavioral Drivers

Attitudinal characteristics and environmental concerns increase the likelihood for households of undertaking certain specific and self-reported water-saving behavior [43,44]. Some attitudinal characteristics and environmental concerns also increase the rate of adoption of a low volume/dual-flush toilet that reduces household water consumption. The Spanish study by Domene and Saurí [45] is one of the very few to examine the influence of attitudinal variables on household water consumption, and it finds a significant association.

4. Conclusions

Despite the empirical evidence accumulated on the residential water demand, there are still some gaps. In this Special Issue, we have then gathered nine articles focusing of residential water use (or urban water use). These papers cover a large number of countries (Spain, France, Jordan, Australia, Bangladesh, Brazil, Lithuania, Peru, Poland, Russia, Serbia, Tanzania, Zambia, Zimbabwe, Colombia, India and Unites States of America). Some papers deal with the impact of water metering on residential water use (i.e., [46–48]), while others consider pricing policies (i.e., [49,50]), non-price policies (i.e., [51,52]) or the performance of water services (i.e., [53,54]). All selected papers contribute to a better understanding of residential water use, and they provide relevant results for policy-makers in charge of water management.

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Abbreviations

The following abbreviations are used in this manuscript:

PP	Price Policy
NPP	Non Price Policy

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