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Threshold Effect in Residential Water Demand: Evidence from Smooth Transition Models

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Abstract

This paper aims to empirically examine the presence of nonlinear behavior in residential water demand for the case of Tunisia. We specifically explore the existence of nonlinearity with respect to the magnitude of water price changes through a logistic smooth transition regression (LSTR) framework and an increasing multi-step water pricing scheme. Using quarterly time series for the period 1980–2007 which describes residential water consumption and its main determinants, our results provide strong evidence that water consumption responds nonlinearly to the extent of price changes for the two consumption blocks considered. Water price elasticities are found to be higher when variation in tariffs surpasses a given threshold. More precisely, we find a unit elastic water demand for lower block consumers (low-income households) when price changes exceed a threshold of roughly 5%. For the upper block consumers (high-income households), water consumption is less elastic in comparison to low-income households, but still significant when the price variation exceeds a threshold of 2.6%. Our findings imply that increasing the length of the lower block of consumption may help achieve goals of social equity, while increasing tariff progressivity, at least for upper block consumers, helps promote water saving.

1 Introduction

According to the United Nations Development Program, per-capita renewable internal freshwater resources in Tunisia, in 2008, were equivalent to about 500 cubic meters.[1] The amount of renewable freshwater available per inhabitant is more than 50% below the water scarcity standard (1000 cubic meters per capita). However, annual rainfall shortages and the increase of annual average temperature have aggravated the situation. In addition, water supply suffers several problems as Tunisian water resources are characterized by a bad quality and spatial heterogeneity of its location. On the one hand, the remoteness of water resources from urban areas increases its mobilization cost. On the other hand, the high level of water salinity increases its treatment and distribution cost. Moreover, the limited water supply is unequally distributed across the country and intensively used. This has resulted in serious challenges such as increased degradation and risk of depletion.

In developing countries like Tunisia, water is increasingly considered as strategic resources which are the basis for sustainable socio-economic development especially in the Middle East and North Africa where population growth rate is elevated. Tunisian water resources are scarce characterized by a bad quality and are unequally distributed within the country. Tunisia is undergoing a real water supply crisis which will be accentuated during the next two decades. For many hygiene purposes, residential water consumption should be satisfied only by regular, soft, reliable, and pure water resource. In Tunisia, residential water demand is exponentially increasing as a result of rapid urban development. In this scheme of things, Tunisia needs to commit to managing water uses like other developing countries in order to boost its relatively fragile economy where

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[1] Arab Statistics are obtained from the UNDP website: http://www.arabstats.org/indicator.asp?ind=273

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tourism development requires more water of acceptable quality.

The Tunisian state-owned water distribution company has constantly concentrated on the adjustment of water supply to meet level-price water demand. The cost of supply enhancement continues to rise as the most accessible sources of water are tapped to capacity or depleted, causing tariff changes that subsequently affect the quantity demanded. Econometric estimates of residential demand try to define water management policies that fail to consider the time-path of adjustment risk outpacing consumers' ability to develop new habits or optimize their stocks of water-associated capital, such as landscaping, plumbing fixtures, and appliances.

Given the public benefits provided by many aspects of water supply and management, the price-setting public institutions should be able, in some way, to measure the true economic value of water supply and to use this information to establish economically rational water tariffs. Such an issue is particularly important in water-scarce countries in which the price of water does not reflect scarcity, often because management institutions are reluctant to raise prices.

As a scarce and precious commodity, water becomes a strategic resource which may be a cause of war or peace. Political tensions and risks of military conflict are likely to be aggravated by tensions over water resources. From the policy's point of view, two different types of policy responses to the problem of water scarcity are adopted. The aim of the supply-oriented policy is the mobilization of nonconventional resources, like the desalinization of sea water, to meet the households' water demand. This policy is unfortunately limited by the higher mobilization cost of these nonconventional resources. However, nontechnical solutions, like water conservation and management programs, are the only useful tools that are able to manage adequately households' water demand. Progressive water tariff is worldwide viewed as an incentive tool that can reduce excessive water consumption. It should in most cases achieve goals of social equity and efficiency in water use. Many issues are raised in terms of equity: in industrialized countries for example, consumption is more closely linked to the size of the household than to its financial resources (e.g., [21]), while in developing countries, water demand tends to be more closely related to household financial constraints (e.g., [18]).

The empirical estimation of water price elasticity has been a major issue in applied economics research during the last five decades. Indeed, several literature review papers [1, 8, 26] have demonstrated that households in industrialized countries are not affected by the water tariff progressivity. The water demand literature strand has interested on industrialized countries, while very few studies such as Nauges and Whittington [18] have considered some developing countries in studying the main determinants of residential water demand. Nauges

and Thomas [19] estimate a dynamic panel data model, for the case of France, and show evidence of short- and long-run price elasticities, respectively, equal to -0.26 and -0.40. However, for the case of Spain, Martinez-Espineira [17] estimated a long-run water price elasticity equal to -0.5 from a cointegration model and a short-run price elasticity equal to -0.1 from an error-correction model. The price elasticity of residential water demand, which is a critical issue in this literature, has generally been estimated in a linear context using the log-log linear function form of the water demand model. However, assuming that consumer sensitivity to changes in water tariffs is linear and symmetric would not be realistic given the heterogeneity of consumers in terms of both financial constraints and preferences. We hypothesize that different households behave differently with respect to the magnitude of change in water prices. Also, without considering the presence of a nonlinear mechanism in residential water consumption (which typically depends on a threshold value of water price variation), the role played by progressive water tariffs in conserving this precious resource could not be clearly explained. Thus, while previous empirical works assumed linearity rather than testing it, our study proposes to formally test the presence of a threshold effect in residential water consumption to better gauge consumer behavior.

To the extent that water consumption sensitivity may differ depending on the magnitude of price variation (small vs. large changes), we contribute to the related literature by empirically investigating the existence of a nonlinear dynamics in the residential water demand function for the case of Tunisia. Using the class of logistic smooth transition regression (LSTR) models as developed by Teräsvirta [23], our paper first tests for nonlinearity with respect to water price change as a transition variable. Water price elasticities are then estimated across the two extreme regimes, i.e., the lower and higher price change regimes.[2] This econometric setting enables us to understand the efficiency of the Tunisian water pricing system in conserving water over the last three decades. Our nonlinear modeling of residential water demand relies on a rich quarterly dataset, which consists of average demand for water, average water price, precipitations, temperature, and the number of subscribers in two distinctive consumption blocks (a lower block for low-income households and an upper block for high-income households) and household income.

To sum up the results of the present paper, we find that lower block consumers (i.e., low-income households) are

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[2] As outlined by Teräsvirta [24], smooth transition regression (STR) models are a generalization of the standard threshold models, in which a two-regime model is nested as a special case. The use of the family of STR models allows for the presence of a continuum of intermediate states between the two identified extreme regimes. Intuitively, the class of STR models would be more appropriate to describe the water consumption behavior given the progressivity of the Tunisian water tariff system.

more sensitive to water price increase. The most important result, which represents the contribution to the existing literature, is that the demand for water becomes elastic to its price when the latter exceeds a variation threshold of roughly 5%. However, the upper block consumers (i.e., high-income households) are less sensitive to water price changes but their water price elasticity becomes higher when the water price changes surpass the threshold of 2.6%. It reaches the -0.84 which is a higher elasticity compared to what is estimated in the previous literature using linear econometric models.

The remainder of paper is organized as follows. Section 2 presents a brief literature review. Section 3 describes the data and Tunisian context. Section 4 introduces our econometric approach and nonlinear water consumption equation. Section 5 discusses the main empirical results. Section 6 concludes and discusses policy implications.

2 Brief Literature Review on Residential Water Demand Modeling

Residential water demand modeling has been considered as one of the most critical issues in applied economics over the last four decades. The numerical estimation of water price elasticity represents the main focus of this literature. Sound policy recommendations, which aim at conserving water as a precious and strategic resource, could only be established within a solid empirical investigation that delves into the specificity of the data.

As stated earlier in the introduction [1, 8, 26], the estimation of water price elasticity depends on many factors which significantly affect its estimated numerical value using historical or survey data. Espey and Shaw [12] meta-analysis shows that long-run water price elasticity is superior to short-run elasticity. They also show that adding climate variables such as rainfall and evapotranspiration in the specification of the water demand model significantly affects the estimated water price elasticity, especially as regards the case of the USA. By contrast, population density, family size, and temperature are not shown to have an impact on estimated water price elasticity.

However, most of the past research on residential water demand modeling has focused on developed countries, with very few studies examining the issue in underdeveloped nations [18]. Using French data, Nauges and Thomas [19] show that water demand for some French municipalities is inelastic to its price. The same result is confirmed by Nauges and Reynaud [20] using a panel data of French cities. However, Schleich and Hillenbrand [22] show that the price elasticity of water demand in Germany is around -0.24. Income elasticity is positive, decreases with higher income levels, and is at least three times higher in the new federal states than in the old federal states. For the case of the USA, Griffin and Chang [13] tested the role of seasonal fluctuations on water demand

behavior by estimating several monthly a water demand models. They show that in summer, consumers are more sensitive to water price changes than in winter. In magnitude, the difference between summer and winter in water price elasticity exceeds 30%. Moreover, using annual then seasonal dataset, Dandy et al. [9] estimate three linear water demand equations to differentiate summer from winter and compare elasticities with and without seasonal fluctuations. Their results show seasonal elasticities in the range of -0.29 to -0.45 for winter and -0.69 to -0.86 for summer, and income elasticities in the range of 0.32–0.38 for annual consumption, 0.28–0.33 for winter, and 0.41–0.49 for summer.

For the Tunisian case, Ben Zaied and Binet [4] demonstrated that, in the long run, users in the upper block of consumption (households which consume more than 40 m^3 per quarter) are characterized by small reactions to price increase than those in the lower block of consumption (those which consume less than 40 m^3 per quarter), where water is used basically to satisfy basic human needs (cocking, shower, etc.). They thus propose an increase of tariff progressivity to discourage higher consumption levels. When seasonality is introduced, their results further propose that the Tunisian water regulator (SONEDE) should increase the lower block consumption threshold to more than 40 m^3 to ensure the satisfaction of households' essential needs especially in summer.[3] However, an empirical regional study for Tunisia by Ben Zaied [5] shows that water tariffs should be decentralized to achieve social equity goals between coastal and interior regions. In Tunisia, the same water tariff scheme (the price tariffs increase with consumption) is applied to the whole country. Thus, using aggregated data at the national level is suitable and very interesting to conclude for the whole country.

Our paper also focuses on the residential water demand modeling in Tunisia, but goes a further step than previous studies by considering the nonlinear effects in the sensitivity of consumers to price changes through a nonlinear regime-switching model.[4] We typically assume that household behavior would be different with respect to the magnitude of change in water tariffs (large versus small). As shown later, water consumption sensitivity increases considerably once a threshold is surpassed and is specific to different blocks of consumers defined by financial constraints (low versus high incomes).

3 Data and Context Description

The dataset used in the present paper is private, original, and refers to several sources. It covers a long period from 1980 to

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[3] SONEDE (Société Nationale d'Exploitation et de Distribution des Eaux) is the national water distribution company in Tunisia.
[4] Nonlinear smooth transition models have been successfully applied to describing the behaviour of various financial and macroeconomic time series (see e.g. [3], for a recent survey).

2007. The data is collected from the national water distribution company (SONEDE) statistics. It includes quarterly observations for average domestic water consumption, average price, network expansion, rainfall, temperature, and yearly household income observations. Since Tunisia uses a nonlinear tariff structure in which prices are differentiated for different ranges of consumption, the choice of the price variable (average or marginal prices) is necessary to achieve a good residential water demand specification. Following Arbuès et al. [1], we choose the average price equal to the total bill for the household divided by the volume consumed, as we have semi-aggregate data. The average price is a weighted sum of the marginal prices, with the weights being given by the shares of consumption in each range.

In practice, the SONEDE has built a nonlinear pricing scheme across Tunisia using five ranges. Ayadi et al. [2], who conducted their empirical work on the same sample dataset but for a shorter period (1980–1996), have, however, shown that the best choice is to conduct estimations on a two-block breakdown (a lower and an upper block of consumers). The lower block will include the consumers in the first two brackets (0–40 m^3) while the upper block includes the top three brackets (consuming more than 41 m^3). Since different policies should be implemented for each block to monitor water demand as efficiently and fairly as possible, it is important to estimate one specific residential water demand equation for the considered block. The goal is not only to analyze the effect of price variations on demand for the upper block, but also to examine whether marginal price and the bracket size of the lower block help guarantee the satisfaction of the essential needs of low-income households.

Annual data on income, derived from budget surveys of the National Statistical Institute in Tunisia (Institut National de la Statistique, INS), were also collected. Network expansion is an appropriate variable to take into account the specific characteristics of a developing country with a rapidly expanding water distribution network. It measures the effect of new entrants to the network as a result of economic development or seasonal variations in consumption. If the average consumption of new entrants in one block is lower than that of existing consumers, we expect a negative coefficient for the network effect. Table 1 gives the list of variables as well as their summary descriptive statistics.

On average, the lower block represents 73% of subscribers and 53% of total domestic consumption. The upper block accounts for 9% of subscribers and 47% of total domestic consumption. The average yearly income is 1510 dinars (or around 755 Euros). The structural change that characterizes average water consumption and water price can be clearly seen from the seasonal time series graph in Figs. 1 and 2. The first graph shows the time series evolution of water price, which is the main determinant of the residential water consumption. In Tunisia, the progressive incentive water pricing

Table 1 Description of the variables and basic statistics

Variable	Mean	Max.	Min.
Residential consumption (lower block, m^3)	19.86	40	9.04
Price (lower block)	0.39	0.85	0.20
Residential consumption (upper block, m^3)	150.61	341.50	54.11
Price (upper block)	0.75	1.33	0.23
Yearly income, Dinars	1570	2549.50	1218
Rainfall	172	600.71	10.86
Network expansion (lower block)	73	85	55
Network expansion (upper block)	9	22	4

Source: National water distribution company in Tunisia (Société Nationale d'Exploitation et de Distribution des Eaux, SONEDE), Tunisian National Institute of Statistics (Institut National de la Statistique, INS) and the Tunisian Meteorology Institute (Institut National de la Météorologie, INM)

policy, applied by the water authorities (SONEDE), aims at reducing excessive water use by increasing the per-unit water price. We have used the nonlinear water tariff structure to calculate the average price variable, which represents the water bill received by each subscriber at the end of each quarter. As demonstrated by Arbuès et al. [1], the average water price is the best choice to estimate water price elasticity compared to marginal water price because it includes all the water bill components.

Figure 2 indicates that the residential water consumption for both consumption blocks is also characterized by a structural change. The downward trend becomes more significant after 1996 and can be explained by several factors including, among others, the impact of water tariffs which have increased rapidly over the last three decades. The tariff progressivity, which aims at reducing excessive water use (especially by upper block consumers who consume more than 40 m^3 per quarter) also played an important role. One of the main objectives of this present study is to empirically assess the impact of progressive water tariffs on household behavior, while moving from the linear model to the nonlinear model where water price change serves as the transition variable. This strategy enables one to estimate and test water price elasticity under different regimes of changes in water tariffs.

4 Empirical Approach

4.1 Model

We use a class of smooth transition regression (STR) models to capture nonlinearity in the residential water consumption equation. An STR model is defined as follows:

$$y_t = \theta_1 x_t + \theta_2 x_t G(s_t; \gamma, c) + u_t, \tag{1}$$
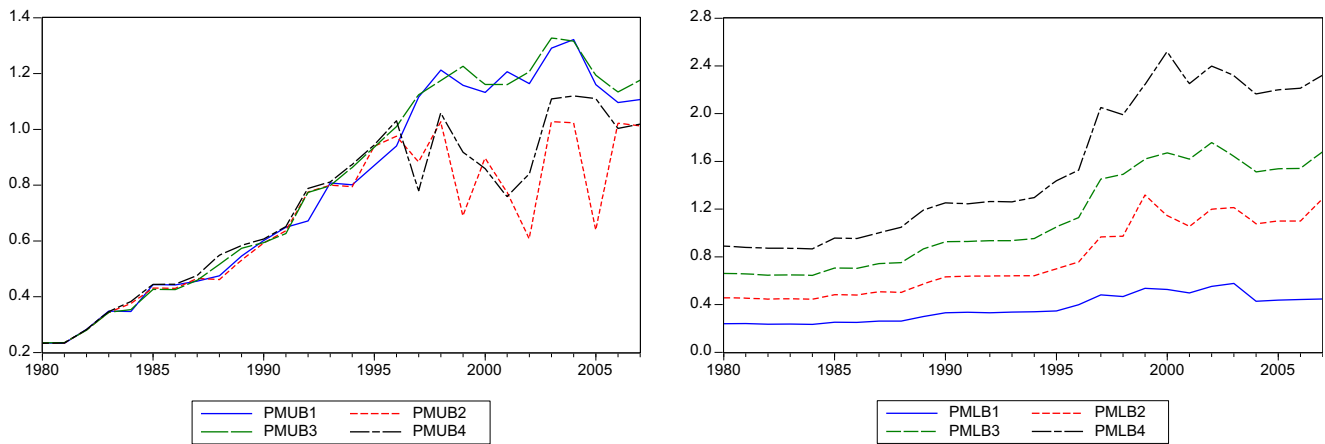
Fig. 1 Average water price per quarter. Source: National water distribution company in Tunisia (Société Nationale d'Exploitation et de Distribution des Eaux, SONEDE). PMUB$_i$ and PMLB$_i$ are, respectively, the average price for the upper and lower block per quarter for $i = 1, 2, 3, 4$.

where $u_t \sim iid(0, \sigma^2)$, θ_1 and θ_2 are the parameters of the linear and the nonlinear parts, respectively. $G(s_t; \gamma, c)$ is the transition function bounded between 0 and 1 and depends upon the transition variable (s_t), the slope parameter (γ), and the threshold level for transition function (c). The parameter γ is also called the speed of transition which determines the smoothness of the switching from one regime to the other. A popular choice for the transition function is the logistic specification that is given by

$$G(s_t; \gamma, c) = [1 + \exp\{-\gamma(s_t - c)\}]^{-1} \qquad (2)$$

Equations (1) and (2) jointly define the logistic smooth transition regression (LSTR) model. In this model, the nonlinear coefficients would represent different values depending on whether the transition variable is below or above the threshold c. Thus, the parameters $[\theta_1 + \theta_2 G(s_t; \gamma, c)]$ change monotonically as a function of s_t from θ_1 to $(\theta_1 + \theta_2)$. Indeed, if $(s_t - c) \to -\infty$, and then $G(s_t; \gamma, c) \to 0$, the model's coefficient corresponds to θ_1. If $(s_t - c) \to +\infty$, and then $G(s_t; \gamma, c) \to 1$, the coefficient becomes $(\theta_1 + \theta_2)$. Finally, if $s_t = c$, and then $G(s_t; \gamma, c) = 1/2$, the coefficient will be equal to $(\theta_1 + \theta_2/2)$.[5]

We assume that consumer behavior reacts to water price change in a nonlinear manner. Precisely, consumers are assumed to be more sensitive to higher price variation, which tends to increase the price elasticity of water consumption. Water price elasticity is assumed to be different and depends on whether price variation is above or below a certain threshold level. As explained above, a LSTR specification would be more relevant in describing this asymmetric and dynamic

behavior between negative and positive deviations of the transition variable s_t from the threshold level c.[6]

As discussed in Teräsvirta [23], the modeling strategy of STR models consists of three stages: specification, estimation, and evaluation. The first stage consists of testing for nonlinearity and choosing the appropriate threshold variable s_t and the most suitable form of the transition function, i.e., logistic or exponential specification. In the second stage, the parameters of the STR model are estimated using the nonlinear least squares (NLS) estimation technique which provides estimators that are consistent and asymptotically normal. Finding good starting values is crucial in this procedure. Thus, STR literature suggests constructing a grid search for estimating γ and c. The values for the grid search for γ were set between 0 and 100 for increments of 1, whereas c was estimated for all the ranked values of the transition variable s_t. For each value of γ and c, the residual sum of squares is computed. The values that correspond to the minimum of that sum are taken as starting values in the NLS procedure. This procedure increases the precision of the estimates and ensures faster convergence of the NLS algorithm.[7] In the final (evaluation) stage, the quality of the estimated STR model should be checked against misspecification as in the case of linear models. Several misspecification tests are used in the STR literature, such as LM test of no error autocorrelation, LM-type test of no ARCH, and Jarque-Bera normality test. Eitrheim and Teräsvirta [10] also suggest two additional LM-type misspecification tests, namely an LM test of no remaining nonlinearity and LM-type test of parameter constancy.

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[5] Another popular choice for the transition function which is often used in the literature is the exponential specification: $G(s_t; \gamma, c) = 1 - \exp\{-\gamma(s_t - c)^2\}$. The latter equation and (1) jointly define the exponential STR (ESTR) model. It is important to note that the dynamic behavior of the logistic form is different the exponential specification. The coefficient changes depending on whether s_t is near or far away from the threshold, regardless of whether the difference ($s_t - c$) is positive or negative.

[6] For instance, van Dijk et al. [25] mentioned that when modeling business cycles, LSTR can describe processes whose dynamic properties are different in expansions from what they are in recessions. For example, if the transition variable s_t is a business cycle indicator (such as output growth), and if $c \simeq 0$, the model distinguishes between periods of positive and negative growth, that is, between expansions and contractions.

[7] It should also be noted that when constructing the grid, γ is not a scale-free. The transition parameter γ is therefore standardized by dividing it by the sample standard deviation of the transition variable, s_t.

Fig. 2 Average water
consumption per quarter. Source:
National water distribution
company in Tunisia (Société
Nationale d'Exploitation et de
Distribution des Eaux,
SONEDE). Note: CLB and CUB
are, respectively, lower block and
upper block water consumption in
the third and the fourth quarter
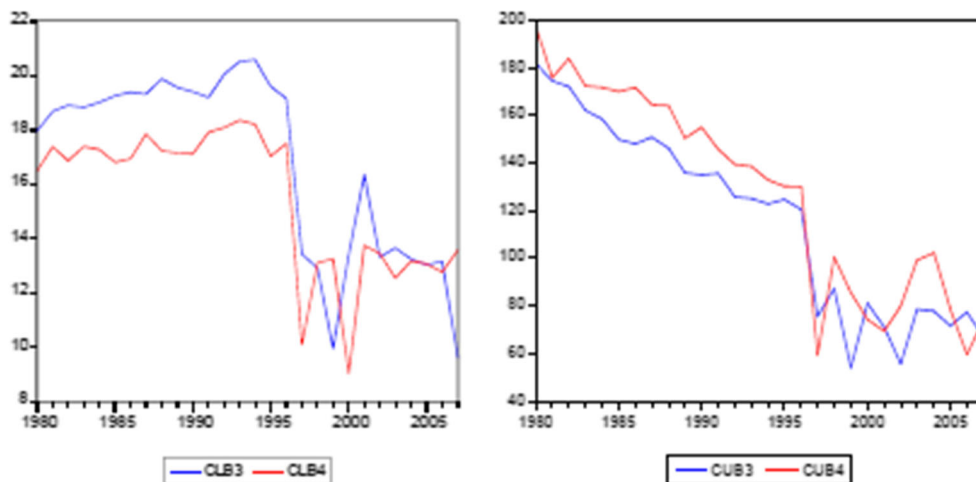
4.2 Nonlinear Specification for the Water Consumption Equation

In a linear context, the water demand model in the related
literature is usually defined as an equation in double log form
(see, e.g., [1]). The latter links household water demand to its
determinants suggested by classical economic theory such as
price and income, and then to control variables such as socio-
economic variables and weather conditions (temperature and
precipitations). In this paper, the water consumption equation
is defined quarterly at the national level for each consumption
block (lower and upper block), such as

$$c_t = \alpha + \beta p_t + \gamma y_t + \delta' Z_t + \text{quarterly dummies} + \varepsilon_t, \quad (3)$$

where c_t, p_t, and y_t denote, respectively, quarterly average
water consumption, average water price (the total bill of the
households divided by the volume consumed), and average
household income. Z_t is a vector of control variables, includ-
ing rainfall (rl_t), network expansion (ne_t), and temperature
(te_t). As data are not seasonally adjusted, quarterly dummy
variables are included to capture any seasonal effects.[8] The
ε_t is a zero mean error term normally distributed.

Given our assumption of nonlinearity in the re-
sponses of consumers to the size of water price change
Δp_t, we define a LSTR water consumption equation,
which consists of an extension of water consumption
model to nonlinear case as in eq. (4). Our study pro-
poses to investigate for the presence of a threshold ef-
fect in residential water consumption to better gauge
consumer behavior. The main advantage of using a non-
linear regime-switching model is that the presence of a
threshold effect is not given a priori but instead is cap-
tured endogenously from the data.

Before estimating our LSTR model, we have checked
the possibility of cointegrating a relationship into our
key variables in water demand eq. (3). Individual series
in level are non-stationary according to the efficient
unit-root test suggested by Elliott et al. [11], and the
Kwiatkowski et al. [16] test, extended by Carrion-i-
Silvestre and Sanso [7]. However, they do not appear
to be cointegrated according to Johansen's cointegration
tests [14, 15]. Consequently, log differences of the var-
iables are used in the estimation of the following non-
linear water demand equation:

$$\Delta c_t = \alpha + \sum_{j=1}^{N} \lambda_j \Delta c_{t-j} + \sum_{j=0}^{N} \gamma_j \Delta y_{t-j} + \delta' Z_t + \sum_{j=0}^{N} \beta_j \Delta p_{t-j} + \left(\sum_{j=0}^{N} \phi_j \Delta p_{t-j} \right) G(s_{t-j}; \gamma, c) + \text{quarterly dummies} + \varepsilon_t, \quad (4)$$

where $G(s_{t-j}; \gamma, c)$ is the logistic transition function driving
the nonlinear dynamics and the lagged price changes as tran-
sition variable $s_{t-j} = \Delta p_{t-j}$. According to eq. (4), the short-

run water price elasticity is given by the following time-
varying coefficients[9]:

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[8] See Ben Zaied and Binet [4] for a further discussion on the presence of
seasonal effects in residential water consumption.

[9] It is possible to define long-run water price elasticity as:
$\left[\sum_{j=0}^{N} \beta_j + \sum_{j=0}^{N} \phi_j G(s_{t-j}; \gamma, c) \right] / \left[1 - \sum_{j=1}^{N} \lambda_j \right]$. One major drawback
of this measure its sensitivity to the number of lags introduced in the
model, leading to inaccurate long-run elasticity. Hence, in our paper we
focus solely on the short-run water price effect.

$$\text{Water price elasticity} = \beta_0 + \phi_0 G\left(\Delta p_{t-j}; \gamma, c\right) \quad (5)$$

Water consumption sensitivity would take on different values depending on whether the transition variable $s_{t-j} = \Delta p_{t-j}$ is below or above the threshold value c. If $(\Delta p_{t-j} - c) \to -\infty$ (i.e., the price increase is below the threshold), water price elasticity is equal to β_0. This corresponds to the elasticity during a *low price change regime*, obtained when $G(\Delta p_{t-j}; \gamma, c) = 0$. By contrast, if $(\Delta p_{t-j} - c) \to +\infty$ (i.e., the price increase is above the threshold), water price elasticity becomes $\beta_0 + \phi_0$. The latter situation corresponds to the sensitivity during a *high price change regime*, achieved when $G(\Delta p_{t-j}; \gamma, c) = 1$. To determine the lag length of the variables, different information criteria, including Akaike information criterion (AIC), Bayesian information criterion (BIC), Lagrange multiplier (LM) test for residual serial correlation, Hannan–Quinn information criterion (HQ), general-to-specific (GTOS) reduction test, etc. As different selection criteria would lead to different results in terms of optimal lag length (see Table 2), a natural method is to base the decision on the data frequency. Given the quarterly frequency of our data, it is convenient to start with a maximum lag of 4 and then remove the variables sequentially corresponding to insignificant parameter estimates (see, e.g., [6]). Following the STR literature, we have adopted a general-to-specific approach to select the final specification which indicates an optimal lag length of $N = 4$. Then, we start with a model with a lag length of $N = 4$, and then drop sequentially the lagged variables for which the t statistic of the corresponding parameter is less than 1.0 in absolute value (see, e.g., van [25]).

Table 2 Lag length selection

Criterion	Suggested lag length	
	Lower block	Upper block
AIC	4	6
BIC	2	4
LM	4	4
HQ	6	6
GTOS	4	4

To check the lag length of the variables introduced in eq. (4), different information criteria are used: Akaike information criterion (AIC), Bayesian information criterion (BIC), Lagrange multiplier (LM) test for residual serial correlation, Hannan–Quinn information criterion (HQ), and general-to-specific (GTOS) reduction test, starting with maximum lags number $N = 8$.

5 Empirical Results

Our study investigates whether the average residential water consumption responds nonlinearly to the average price changes in Tunisia over a period of 28 years from 1980 to 2007. Our LSTR specification considers explicitly the presence of nonlinearity in data allowing us the estimation of water price elasticity across two regimes, i.e., a small price change regime and a high price change regime. Moreover, the water demand modeling literature has put forward the hypothesis that the responsiveness of water consumption depends negatively on water price variation (see, e.g., [12]). This finding characterizes water as a necessary economic commodity elastic to its price. Consequently, we initially aim to explore the possible regime dependence in water consumption with respect to tariff variation in a nonlinear fashion. As a first step, the specification test of linearity is conducted following Teräsvirta [23]. We consider the lagged price variation as the driving factor of the nonlinearity, that is, $s_{t-j} = \Delta p_{t-j}$. The linearity tests are conducted for each lagged price variation, $s_{t-j} = \Delta p_{t-j}$, with $j = 1, 2, 3, 4$. The choice of the adequate lagged price change as a transition variable by means of linearity tests is reported in Table 3.

To construct the linearity test, Teräsvirta [23] suggested approximating the logistic function (2) in (1) by a third-order Taylor expansion around the null hypothesis $\gamma = 0$. The resulting test has power against both the LSTR and ESTR models. Assuming that the transition variable s_{t-j} is an element in x_t and let $x_t = (1, \tilde{x}_t')'$, where $\tilde{x}_t$ is an $(m \times 1)$. Taylor approximation yields the following auxiliary regression:

$$y_t = \alpha_0' x_t + \sum_{k=1}^{3} \alpha_j' \tilde{x}_t' s_t^k + u_t^*, \qquad t = 1, \ldots, T \quad (6)$$

where $u_t^* = u_t + R_3(\gamma, c, s_t)\theta_2 x_t$, with $R_3(\gamma, c, s_t)$ the residual of Taylor expansion. The null hypothesis of linearity is H_0: $\alpha_1 = \alpha_2 = \alpha_3 = 0$. van Dijk et al. [25] suggest the use of F-versions of LM test statistic, which has an approximate F-distribution with $3m$ and $T - 4m - 1$ degrees of freedom under H_0. Linearity tests are executed for each of the potential transition variables, which are lagged water price changes in our case. Once linearity has been rejected, one has to choose whether a logistic or exponential function should be specified. The choice between these two types of models is based on the auxiliary regression (6). Teräsvirta [23] suggests that this choice can be based on testing the following sequence of nested null hypotheses:

1. Test H_{04}: $\alpha_3 = 0$
2. Test H_{03}: $\alpha_2 = 0 \mid \alpha_3 = 0$
3. Test H_{02}: $\alpha_1 = 0 \mid \alpha_2 = \alpha_3 = 0$

Table 3 Linearity tests

	Lower block				Upper block			
	Δp_{t-1}	Δp_{t-2}	Δp_{t-3}	Δp_{t-4}	Δp_{t-1}	Δp_{t-2}	Δp_{t-3}	Δp_{t-4}
H_0	0.000	0.000	0.056	0.000	0.001	0.002	0.101	0.142
H_{04}	0.000	0.039	0.403	0.000	0.054	0.033	0.266	0.170
H_{03}	0.063	0.000	0.394	0.001	0.101	0.155	0.510	0.597
H_{02}	0.000	0.000	0.002	0.000	0.002	0.005	0.007	0.085
Specification	LSTR	LSTR	Linear	LSTR	LSTR	LSTR	Linear	Linear

The numbers are p- values of F versions of the LM linearity tests. The first row shows the test of linearity against the alternative of STR nonlinearity. The second to fourth rows are the p- values of the sequential test for choosing the adequate transition function. The decision rule is the following: if the test of H_{03} yields the strongest rejection of the null hypothesis, we choose the ESTR model. Otherwise, we select the LSTR model. The last row gives the selected model.

The decision rule is the following: if the H_{03} test yields the strongest rejection measured in the p- value, the ESTR model is selected. Otherwise, the LSTR model is preferred. Table 3 provides the p- values of the F-version of the LM test with the different lags for the water price changes, Δp_{t-j}. In the first row, we report the test of the null hypothesis of linearity against the alternative of STR nonlinear model. The following rows in Table 3 show the sequence of null hypotheses for choosing the LSTR or ESTR model. Accordingly, the LSTR model is found to be the best specification to capture this kind of behavior for the average water consumer in Tunisia. Figure 2 clearly shows that a structural change in consumer behavior has taken place. This structural change, which reflects the profound structural transformation in Tunisian lifestyles and family habits, is due to the length of the study period (28 years).

Next, the NLS estimates of our LSTR models are summarized in Table 4 and Table 5 for the two consumption blocks: lower block consumers and upper block consumers. The price elasticity for the lower block (PELB hereafter) and the price elasticity of upper block (PEUB hereafter) are calculated for the two extreme regimes, i.e., $G(\Delta p_{t-j}; \gamma, c) = 0$ and $G(\Delta p_{t-j}; \gamma, c) = 1$, as defined in eq. (5). We compute the sum of squared residual ratio (SSR_{ratio}) between the LSTR model and the linear specification, which suggests a better fit for the nonlinear model. We also check the quality of the estimated LSTR models by running several misspecification tests. As reported in Table 4 and Table 5, in most cases, the selected LSTR models pass the main diagnostic tests including no error autocorrelation, no conditional heteroscedasticity, parameter constancy, and no remaining nonlinearity.

Table 4 Estimation results for lower block consumers

$$\Delta c_t = \underset{(0.474)}{0.147} - \underset{(-5.461)}{1.324}\, \Delta c_{t-2} - \underset{(-3.543)}{0.914}\, \Delta c_{t-4} + \underset{(2.058)}{0.297}\, \Delta y_t + \underset{(1.507)}{0.508}\, \Delta y_{t-2} - \underset{(-2.921)}{0.010}\, rl_t - \underset{(-1.659)}{0.317}\, ne_t$$

$$+ \underset{(1.962)}{0.026}\, te_t + \underset{(2.656)}{0.259}\, \Delta p_t - \underset{(-2.095)}{0.272}\, \Delta p_{t-3} - \underset{(-3.483)}{0.344}\, \Delta p_{t-4} + \left[\underset{(2.656)}{0.757}\, \Delta p_t - \underset{(-2.921)}{0.868}\, \Delta p_{t-1} \right.$$

$$\left. + \underset{(2.365)}{0.508}\, \Delta p_{t-3} \right] G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) + \hat{\varepsilon}_t,$$

$$G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) = \left(1 + \exp\left\{ \underset{(2.353)}{-7.797} \left(\Delta p_{t-4} - \underset{(2.785)}{0.048} \right) / 0.246 \right\}\right)^{-1}$$

$R^2 = 0.926$;	$SSR_{ratio} = 0.655$;	$pJB = 0.234$;	$pLM_{AR(4)} = 0.807$;
$pLM_{ARCH(4)} = 0.997$;	$pLM_c = 0.688$;	$pLM_{RNL} = 0.715$	

Water price elasticities

Low price-change regime: $G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) = 0$ — High price-change regime: $G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) = 1$

$PELB = -0.259_{(-2.656)}$ — $PELB = -1.016_{(-8.559)}$

Table reports estimation of water consumption equation from LSTR eq. (4). PELB are price elasticities of water consumption for lower block consumers. Numbers in parentheses are t-stat of estimates. R^2 denotes the coefficient of determination and SSR_{ratio} is the ratio of the sum of squared residuals between the LSTR model and the linear specification. The following rows correspond to the misspecification tests: pJB is the p- values of the Jarque-Bera normality test, $pLM_{AR(4)}$ is the p- values of the LM test of no error autocorrelation up to the fourth order, $pLM_{ARCH(4)}$ is the p- values of the LM test of no ARCH effects up to the fourth order, pLM_c is the p- values of the LM test of parameter constancy, and pLM_{RNL} is the p- values of the LM test of no remaining nonlinearity.

Table 5 Estimation results for upper block consumers

$$\Delta c_t = \underset{(1.320)}{0.144} - \underset{(-3.352)}{0.991}\ \Delta c_{t-1} - \underset{(-3.127)}{0.873}\ \Delta c_{t-2} + \underset{(2.079)}{0.522}\ \Delta c_{t-4} + \underset{(2.242)}{0.778}\ \Delta y_t + \underset{(1.091)}{0.291}\ \Delta y_{t-1} - \underset{(-1.803)}{0.028}\ rl_t$$

$$- \underset{(-1.757)}{0.330}\ ne_t + \underset{(2.035)}{0.198}\ te_t + \underset{(1.713)}{0.051}\ \Delta p_t - \underset{(-1.517)}{0.508}\ \Delta p_{t-1} - \underset{(-1.219)}{0.305}\ \Delta p_{t-2} + \underset{(1.327)}{0.328}\ \Delta p_{t-3}$$

$$+ \left[- \underset{(-4.054)}{0.784}\ \Delta p_{t-1} - \underset{(-1.341)}{0.504}\ \Delta p_{t-4} \right] G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) + \hat{\varepsilon}_t,$$

$$G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) = \left(1 + \exp\left\{ -\underset{(1.689)}{21.520} \left(\Delta p_{t-2} - \underset{(11.299)}{0.026} \right) / 0.092 \right\} \right)^{-1}$$

$R^2 = 0.958$;	$SSR_{ratio} = 0.819$;	$pJB = 0.216$;	$pLM_{AR(4)} = 0.780$;
$pLM_{ARCH(4)} = 0.612$;	$pLM_c = 0.374$;	$pLM_{RNL} = 0.628$	

Water price elasticities

Low price-change regime: $G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) = 0$	High price-change regime: $G\left(\Delta p_{t-j}; \hat{\gamma}, \hat{c}\right) = 1$
$PEUB = -0.051_{(-1.713)}$	$PEUB = -0.835_{(-4.361)}$

Table reports estimation of water consumption equation from LSTR eq. (4). PEUB are price elasticities of water consumption for upper block consumers. The numbers in parentheses are t-stat of estimates. R^2 denotes the coefficient of determination and SSR_{ratio} is the ratio of sum of squared residuals between the LSTR model and the linear specification. The following rows correspond to the misspecification tests: pJB is the p- values of the Jarque-Bera normality test, $pLM_{AR(4)}$ is the p- values of the LM test of no error autocorrelation up to the fourth order, $pLM_{ARCH(4)}$ is the p- values of the LM test of no ARCH effects up to the fourth order, pLM_c is the p- values of the LM test of parameter constancy, and pLM_{RNL} is the p- values of the LM test of no remaining nonlinearity

The estimation results in Table 4 and Table 5 show the presence of significant threshold levels of price changes for the two consumption blocks. This finding reveals, as expected, the presence of two distinct regimes, whereby water demand dynamics differs on each side of the threshold, depending on whether the price changes are above or below the threshold level. It is important to note that estimated thresholds do also differ considerably across consumption blocks. For the lower block, the estimated threshold is about 5% ($\hat{c} = 0.048$), which is more significant than the threshold for the upper consumption block with a value is equal to 2.6% ($\hat{c} = 0.026$). These results clearly indicate different behaviors in the water consumption. Indeed, the low-income consumers are likely to be sensitive to water pricing policy when the latter surpasses a threshold of variation of roughly 5%. Moreover, the upper block consumers, which are basically high-income consumers, become more sensitive to water price variation when the latter surpasses the threshold of 2.6%. As indicated in Table 5, the elasticity of the high price regime is near the unit.

As reported in Table 4 and Table 5, the price elasticities PELB and PEUB for the lower and the upper block, respectively, are statistically significant, thus corroborating the findings of the previous literature. Our NLS estimates indicate a significant regime dependence of the water price elasticity in the sense that when the price of water increases above the threshold, its elasticity becomes higher. For low-income households, water demand is more sensitive to price for large water bill changes. As shown in Table 4, PELB is equal to − 1.016 when tariffs increase above the threshold of 5%. For high-income consumers, PEUB is equal to − 0.05 when water price change is below the threshold of 2.6%, but beyond this threshold level, price elasticity becomes higher and reaches − 0.83. It

is worth noting that when changes in water tariffs are above the estimated threshold, water demand is elastic to its price (unitary elasticity) and this finding only holds for the lower block. It thus implies that the consumer response to water price variation, through reducing excessive water use, depends on the magnitude of changes to the consumer's water bill.

The empirical estimation of the nonlinear water demand model shows the relevance of a threshold effect in the residential water demand. Typically, residential water use responds negatively to the progressive water pricing scheme through a nonlinear mechanism. This pricing scheme, which is progressive and nonlinear, has a strategic objective of promoting water saving for the next generation. As we can see from these results, the water tariff system becomes efficient and incentivizes water saving only for the high price regime (above the threshold), as price elasticity becomes higher. Lower block consumers, generally low-income households, are more sensitive to water prices than upper block consumers. Consequently, an incentive pricing policy would lead to a loss in the welfare of these largely lower-income families. However, as the price elasticity of the upper block is negative, a decentralized and effective pricing strategy could result in a decrease in the water consumption of well-to-do people by raising prices in this block. Therefore, the water authority could increase the range of the lower block's brackets to achieve social equity goals.

We also plot, in Fig. 3 and Fig. 4, the estimated transition functions and water price elasticity as a function of the lagged price variation ($s_{t-j} = \Delta p_{t-j}$) for both the lower and upper block consumers. The regime-dependence pattern is quite clear, i.e., there is a negative link between water price elasticity and the level of price changes. For the two consumption blocks considered, water consumption sensitivity is
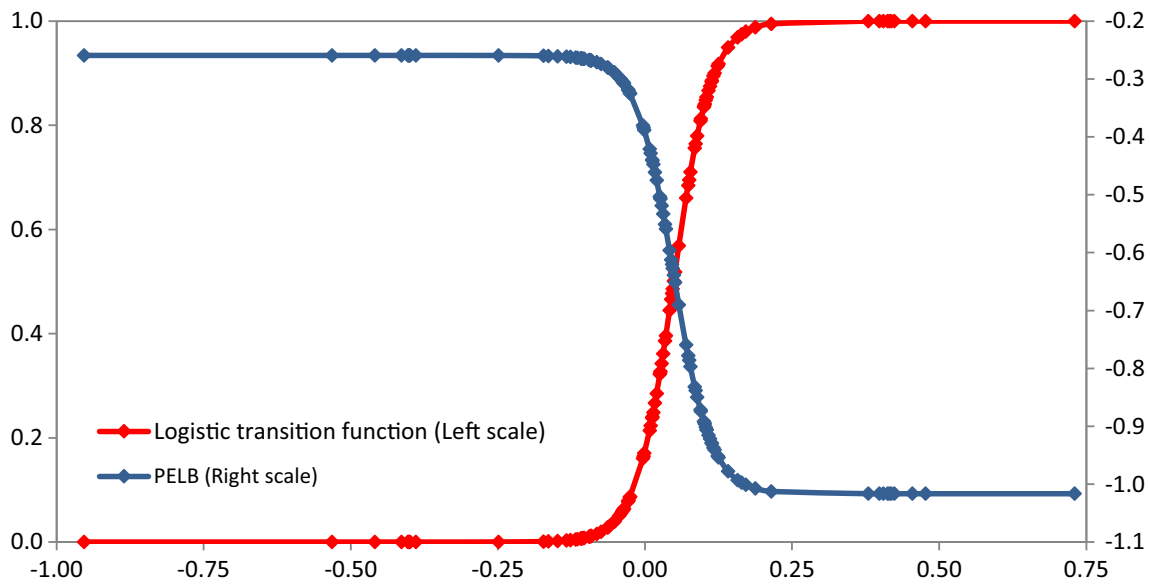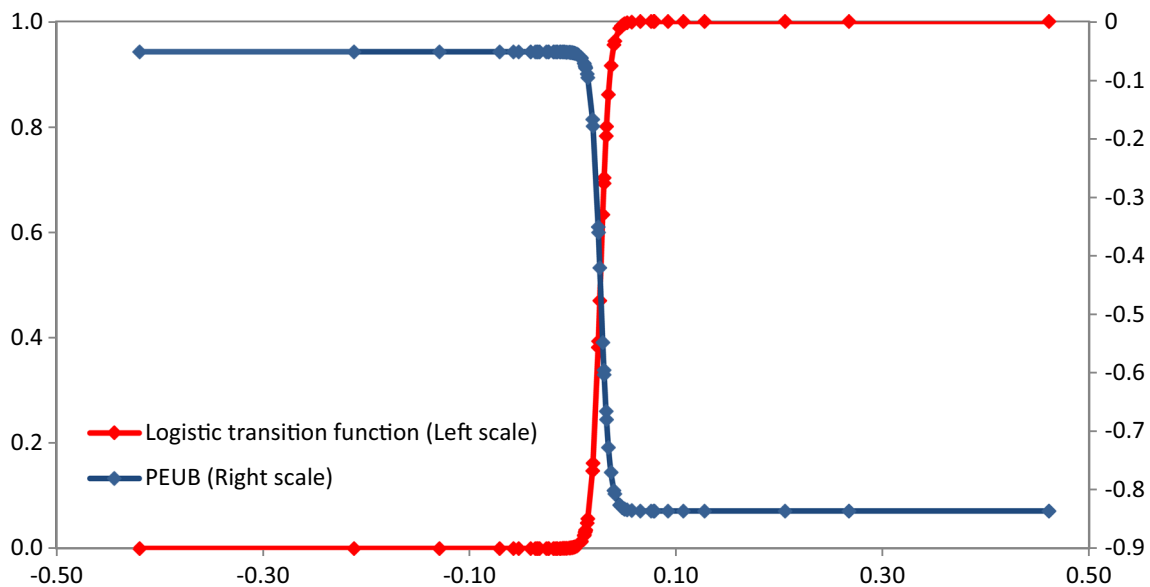
Fig. 3 Estimated transition function and water price elasticity for the lower block (PELB) as a function of water price changes. Note: transition function and PELB are estimated from eq. (4) with $s_{t-j} = \Delta p_{t-4}$.

significantly greater when price variation is above a certain threshold. Also, plots reveal that the transition between both extreme regimes, i.e., $G(\Delta p_{t-j}; \gamma, c) = 0$ and $G(\Delta p_{t-j}; \gamma, c) = 1$, is rather smooth for the case of lower block consumers. This can be confirmed by the estimated parameters $\hat{\gamma}$ — —the so-called speed of transition that determines the smoothness of the switching across regimes—reported in Table 4 and Table 5. The smooth transition from the low regime to the higher regime characterizes only the lower consumption block ($\hat{\gamma} \approx 7.8$). However, for the upper consumption block, the transition is brutal and faster ($\hat{\gamma} = 21.5$) compared to the lower block case. This divergence of behavior between the two

consumption blocks considered is mainly due to the progressivity of the Tunisian water tariff system and the gap between the quarterly consumed quantities of water for the upper and the lower block. Indeed, the marginal price in the upper block is four times higher than the lower block marginal price, and in the meantime, the mean of water consumption of the upper block is six times higher than the lower block (Table 1). The change in consumer behaviors with respect to water price variation is thus gradual and smooth for the lower block, but brutal and faster for the upper block.

In order to give further insight on the presence of regime-dependence in the sensitivity of water consumption, we plot

Fig. 4 Estimated transition function and water price elasticity for the upper block (PEUB) as a function of water price changes. Note: transition function and PEUB are estimated from eq. (4) with $s_{t-j} = \Delta p_{t-2}$
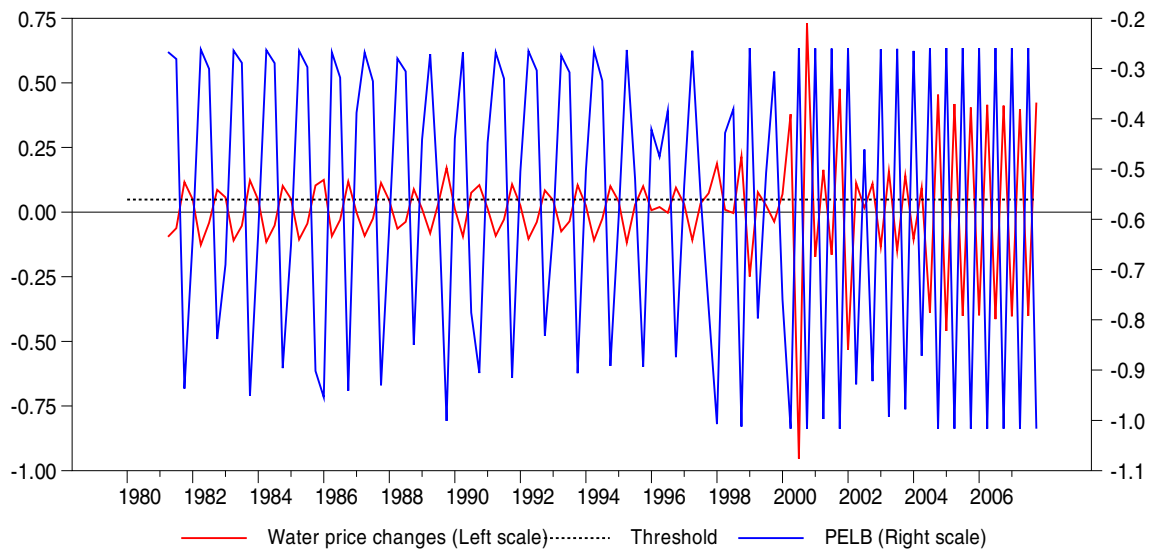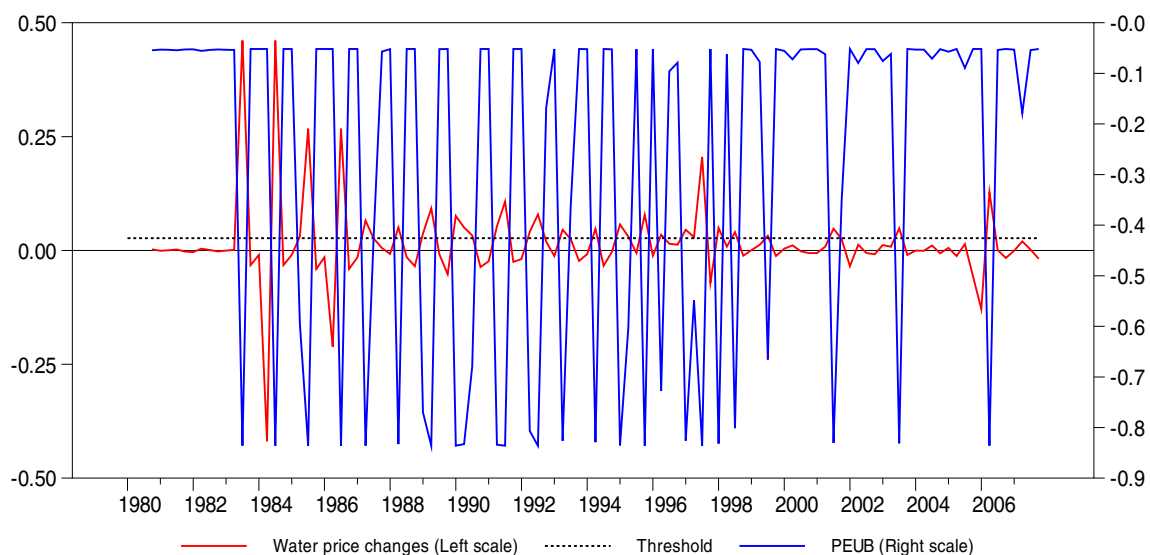
Fig. 5 Time-varying water price elasticity for the lower block (PELB) and water price changes. Note: time-varying PELB and water price changes over 1980–2007. Results are obtained from eq. (4) with $s_{t-j} = \Delta p_{t-4}$.

time-varying coefficients of water price elasticity over the 1980–2007 period. On the same graphs, we also report lagged price changes ($s_{t-j} = \Delta p_{t-j}$) and the estimated threshold levels. Figure 5 and Fig. 6 show that each time price variation surpasses the threshold level, water consumption sensitivity becomes higher for the lower and upper water consumption blocks. A careful inspection of the plot for low-income consumers (Fig. 5) reveals that water demand has often been elastic since the beginning of the 2000s. This is not the case for the upper block, where residential demand has been less elastic in recent years. In 2001, the Tunisian water authorities decided to apply a so-called highly progressive pricing system to keep the demand for water under control and reduce excessive use. Lower block consumers with quarterly consumption

under the threshold of 40 m^3 were, as a result, negatively affected by this tariff change (Fig. 5). This category of water consumers is mainly composed of poor families unable to pay their expensive water bills. However, this is not the case for the upper block consumers with a quarterly consumption above the threshold of 40 m^3, who are not affected by the highly progressive water pricing system. The estimated water price elasticity for both regimes confirms that their water consumption is not elastic to water price variation.

The other determinants also affect significantly quarterly water consumption for the two blocks. The negative effect of network expansion can be attributed to the downward shift of certain consumers from the higher consumption block to the lower one in winter. The climate variable coefficient

Fig. 6 Time-varying water price elasticity for the upper block (PEUB) and water price changes. Note: this graph shows the time-varying PEUB and water price changes over 1980–2007. Results are obtained from eq. (4) with $s_{t-j} = \Delta p_{t-2}$.

confirms our initial expectation that rainfall decreases water use and temperature increases water consumption, especially for the upper block. However, compared to the impact of rainfall on water demand, the impact of temperature is always more significant in magnitude for the lower block (+ 0.026 for temperature and − 0.01 for rainfall, see Table 4), and for the upper block (+ 0.19 for temperature and − 0.028 for rainfall, see Table 5). For all consumers, temperature increases have a significant and positive effect on residential water consumption. The impact is, however, more significant for the upper block, which is composed of big consumers. This finding confirms the hypothesis that only outdoor use of water is sensitive to climate variables, and not the essential use characterizing the demand of lower block consumers. As suggested by microeconomic theory, household income has a positive impact on water demand. This impact is more significant for upper block consumers compared to lower block consumers. Also, we reveal that low-income households are more sensitive to average income changes.

6 Conclusion and Policy Implications

We propose to adequately examine the nonlinear response of residential water demand in Tunisia to price changes through a logistic smooth transition regression (LSTR) model in which price changes are used as the transition variable. In particular, this model allows capturing nonlinear dynamics of water price elasticity across two regimes, i.e., low and high price variation regimes.

We firstly perform linearity tests, using quarterly data over 1980–2007, to check for the presence of a nonlinear dynamics in water consumption with respect to price changes (as it is considered the transition variable). Following this preliminary test, we accept without ambiguity the LSTR specification for the two consumption blocks. In the second step, we turn to the estimation of the different LSTR models for the lower and upper water consumption blocks, and consequently, the assessment of water price elasticities under low and high price variation regimes. The estimation results presented in Table 4 and Table 5 show notably that lower block consumers who consume between 0 and 40 m^3 per quarter are usually more sensitive to water tariffs compared to upper block consumers who consume more than 40 m^3 per quarter. Moreover, for the lower block, we found a unit elastic water demand ($PELB = -1.016$) when price changes surpass the threshold of about 5%. For the upper block, water consumption is less elastic in comparison to small consumers, but still significant when the price variation exceeds a threshold of 2.6% ($PEUB = -0.835$).

The investigations conducted by this paper show that water demand management and water pricing system designs must be seriously considered in Tunisia as well as in other MENA countries, while taking into account household behavior. Water consumption sensitivity (water price elasticity) takes on different values depending on the magnitude of water bill changes, i.e., below or above a certain threshold value. Our results also reveal relatively large price elasticity for high levels of water tariff changes. Therefore, increasing the range of the lower consumer block could help achieve social equity goals because these low-income households consume more in the summer period, for example, to satisfy their basic needs. However, upper block consumers are high-income households that are less sensitive to water price increases, which may give policymakers a room to increase water tariffs for this category and thus achieve water conservation goals.

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