



Research on Water Price and Quantity to Meet the Basic Living Needs of Urban Residents Based on Water Conservation

Based on the Survey Data of Zhengzhou City in China

Shujing Zhang¹ · Yanrong Wang¹

Received: 7 July 2023 / Accepted: 10 January 2024 / Published online: 9 February 2024
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

Abstract

Water price is an economic approach to effectively promote urban residents to save water. However, due to the excessively large water volume and low water price of each tier in the tiered water pricing model, the water-saving effect of urban residents is not obvious. Determining the first-tier water price and water volume for urban residents has become an urgent issue to be solved both in theory and practice. Based on the basic water demand characteristics of urban residents, this study employs the ELES model and QUAIDS model to formulate an improved water demand-price function. The improved function model can describe the nonlinear relationship between urban residents' water demand and water price. Then, based on the survey data of Zhengzhou City, combined with the improved function model and the Ramsey pricing method, a set of equations is built to calculate the basic water price and water volume that meet the basic living demand of urban residents. This method not only focuses on water conservation for urban residents but also considers their basic water needs and the water supply costs of enterprises, which provides a theoretical basis and practical guidance to promote resource conservation in China.

Keywords Water conservation · Urban residents · The first-tier water price · The basic living need

Highlight

- By introducing the ELES, this study constructs an improved QUAIDS based on the basic characteristic demand of urban residents and the nonlinear relationship between their water demand and water price.
- Based on the questionnaire survey, this study construct a set of equations based on the improved function, and combined with the Ramsey pricing to calculate the basic water price and water volume to meet the basic living needs of urban residents.
- The results show that the basic water volume for urban residents is reduced by 36 cubic meters per year compared with the current water volume standard, and the water price is more higher, which can effectively promote urban residents to save water.

Extended author information available on the last page of the article

1 Introduction

Water resources are crucial for economic and social development. The shortage of water resources has become a bottleneck limiting economic and social development in many countries (Huang et al. 2021; Uzel and Gurluk 2016). China's water resources are also not sufficient, with a per capita freshwater share of only 1/4 of the world average (Shi and Xu 2001). Currently, about 60% of cities in China suffer from the problem of water resource shortage, with 110 cities experiencing severe water shortages. Information on water prices for residents in major cities can be obtained from the China Water Network (<http://www.h2o-china.com>).

To effectively solve the problem, the government usually starts from the supply side, i.e., by developing new water sources or constructing new water conservancy facilities to increase the water supply (He et al. 2007; Liu et al. 2009). However, the construction of water conservancy projects has high costs, which makes water resources more expensive (Wang et al. 2018). In recent years, an increasing number of countries have begun to take demand-side policies as a necessary supplement. The core of policies is to promote water conservation through reasonable policies (Nauges and Thomas 2003). And the water demand of urban residents has become the key to implementing water resource conservation (Avni et al. 2015).

Much research has been conducted on water prices abroad, and it is generally considered that tiered water prices can better improve residents' water-saving awareness (Olmstead et al. 2007). However, domestic research is mainly conducted from qualitative and quantitative perspectives. Qualitative research mainly focuses on the superiority of the tiered water pricing policy to a single water pricing policy (Li and Liu 2005). Meanwhile, quantitative research mainly focuses on the price elasticity (Zhang and Brown 2005; Shi et al. 2022), the affordability (Yang and Abbaspour 2007), the setting of tiered water volume and pricing parameters for only one city, as well as the expected water-saving effect in a city (Yining 2010; Jiang 2020). However, there are still problems such as overall low water prices, weak water-saving awareness, and unclear water-saving behaviors. Additionally, the proportion of household water consumption expenditure to household disposable income in most cities is less than 1% (Yang and Cai 2003), and the setting of each tier water price and volume is unreasonable (Sebri 2014; Renwick and Archibald 2018; Baumann and Müller 1997), especially the low first-tier water price and excessive water volume, which results in less significant water conservation effects of urban residents (Balling and Gober 2007; Worthington and Hoffman 2008).

Water is not only a basic daily necessity but also an intermediate necessity and even a luxury good (Olmstead et al. 2007). For instance, water for daily drinking, cooking, and basic sanitation belongs to basic daily necessities; Water for washing machines and mopping floors is an intermediate demand, while water for swimming, garden watering, and pet bathing is a luxury. Generally, basic necessities, intermediate goods, and luxury goods have different Engel curves. The water demand of urban residents has the attributes of these three types of goods simultaneously (Martínez-Españeira and Nauges 2004), so these characteristics determine that the relationship between the water demand and water price is not linear.

Although the existing studies on water prices have achieved fruitful results, they mainly focus on the setting of tiered water prices but less consider how to formulate a reasonable water price and volumes of each tier and ignore the nonlinear characteristics of the price elasticity of residential water demand. Meanwhile, existing studies mainly

establish pricing models based on water supply costs and residents' affordability but ignore the impact of factors on residents' water prices under limited water supply. Therefore, this study establishes an improved QUAID model. Some factors such as household disposable income, household population size, local annual average temperature, the living space, and water supply costs have been included. The rest of this paper is organized as follows: Section 2 introduces the research methodology and model, Section 3 describes variable selection, Section 4 presents the empirical analysis, Section 5 provides further discussion, and Section 6 concludes this paper.

2 Research Methodology and Models

Firstly, this study constructs an ELES model for the basic water demand \bar{q} of urban residents and solves it through regression estimation. Secondly, an improved QUAIDS model is constructed, which can be employed to solve the functional relationship between water demand and prices, as well as the price elasticity of water demand at different price levels. Thirdly, the basic water price can be obtained by substituting the water supply cost and price elasticity into the Ramsey pricing rule. Finally, the basic water demand q is substituted into the improved QUAIDS model to obtain the corresponding basic water volume.

2.1 Design of the Water Demand-Price Function of Urban Residents Based on ELES

The ELES model was developed by economist Liuch (1973). It divides residents' demand for goods or services into two components: basic needs and non-basic needs. Basic needs mainly refer to goods or services that meet the basic physiological and living needs of residents, including food, clothing, water, medical security, etc. Non-basic needs refer to goods or services other than meeting the basic needs, such as luxury goods, high-end cosmetics, high-end clothing, etc. Only when their basic needs are met, residents will use their remaining income to purchase luxury goods (Liuch 1973; Chen and Yang 2009).

To effectively analyze the characteristics of urban residents' water demand, this study regards water in different price ranges as different commodities. Then, the ELES model is adopted to construct the water demand-price function in different price ranges. The basic water demand in this study refers to the amount of water that can meet the basic living needs of household members, mainly including drinking, bathing, hygiene, etc.

First, the total utility function of urban residents' consumption expenditure is constructed based on the ELES model, as shown in Eq. (1):

$$U = b \cdot \ln(q - \bar{q}) + b_i \cdot \sum_{i=2}^n \ln(x_i - \bar{x}_i) \tag{1}$$

The constraints for maximizing the total utility function are as shown in Eq. (2):

$$p \cdot q + \sum_{i=2}^n p_i x_i - M = 0 \tag{2}$$

Where p represents the water price, p_i the price of other goods purchased by urban residents (except water expenses), and M the total household consumption expenditure.

Equation (1) can be further converted into a Lagrange function, as shown in Eq. (3):

$$L(x_1, x_2, x_3, \dots, \lambda) = b \cdot \ln(q - \bar{q}) + b_i \cdot \sum_{i=2}^n \ln(x_i - \bar{x}_i) + \lambda \left(M - \sum_{i=2}^n p_i x_i \right) \tag{3}$$

Therefore, the constraint for maximizing the utility function L in Eq. (3) can be expressed in Eq. (4):

$$\begin{cases} M - \sum_{i=1}^n p_i x_i = 0 \\ \frac{\partial L}{\partial x_i} = \frac{\frac{b}{q - \bar{q}}}{q - \bar{q}} - \lambda \cdot p \\ \frac{\partial L}{\partial x_i} = \frac{b_i}{x_i - \bar{x}_i} - \lambda \cdot p_i, (i = 2, 3, \dots, n) \end{cases} \tag{4}$$

According to the calculation and under the condition of maximum utility, the relationship between urban residents' water consumption and other commodity consumption is presented in Eq. (5):

$$\frac{b}{p(q - \bar{q})} = \frac{b_i}{p_i(x_i - \bar{x}_i)} \tag{5}$$

After conversion, Eq. (6) is obtained.

$$b_i p (q - \bar{q}) = b p_i (x_i - \bar{x}_i) \tag{6}$$

By summing all commodities i in Eq. (6), the expenditure E of water consumption of urban residents can be obtained in Eq. (7):

$$E = p \bar{q} + \frac{b}{\sum_{i=1}^n b_i} (M - \sum_{i=2}^n p_i \bar{x}_i) \tag{7}$$

Assume $\beta = \frac{b}{\sum_{i=1}^n b_i}$, where β indicates the marginal consumption tendency of urban residents. Then, Eq. (8) can be obtained as follows:

$$E = p \bar{q} + \beta (M - \sum_{i=2}^n p_i \bar{x}_i) \tag{8}$$

Let $\alpha = p \bar{x} - \beta \sum_{i=2}^n p_i \bar{x}_i$ and replace M with the disposable income I of urban households, Eqs. (9) and (10) can be obtained:

$$E = \alpha + \beta I \tag{9}$$

$$p \bar{q} = \alpha + \beta \frac{\sum_{i=2}^n \alpha_i}{(1 - \sum_{i=2}^n \beta_i)} \tag{10}$$

Finally, the water demand of urban residents under the condition of a single price can be obtained in Eq. (11):

$$q = \bar{q} + \frac{\beta}{p} (I - \sum_{i=2}^n p_i \bar{x}_i) \tag{11}$$

According to Eq. (11), this study further constructs a three-stage tiered water pricing model, and the per capita total water consumption model for residents is shown in Eq. (12).

$$\sum_{i=1}^3 q_i = \bar{q} + \sum_{i=1}^3 \frac{\beta_i}{p_i} (I - \sum_{i=2}^n p_i \bar{x}_i) \tag{12}$$

Where q denotes the total water consumption of urban residents, \bar{q} the water consumption of urban residents to meet their basic living needs, p the water price, p_i the price of other commodities, and \bar{x}_i the total consumption of residents for other commodities.

Then, OLS regression is applied to estimate q , β_1 , β_2 , and β_3 , and the water demand-price function is obtained by inspecting the four parameters. By regressing the ELES model, the basic water demand q can be obtained through regression estimation. Finally, this study will apply q to the improved QUAIDS model.

2.2 Design of the Improved QUAIDS

2.2.1 Limitations of the ELES

According to the ELES model, the estimation of the marginal consumption tendency β of urban residents' water demand is constant, i.e., the consumption budget share of urban residents' water consumption increases linearly with their income. However, the relationship between urban residents' water consumption budget share and household disposable income may not be linear. For example, when the water price does not change and with the increase in household disposable income, the budget share of their water consumption shows a marginal decline feature instead of a proportional growth trend. Meanwhile, changes in water prices will also affect the budget share. For instance, when household disposable income does not change and water price rises, it is necessary to increase household water consumption expenditure to meet the previous water demand, and the budget share of household water consumption will increase.

Additionally, the ELES model can only analyze the impact of household disposable income and water price on the water demand. However, in practice, the water demand is not only subject to household disposable income and water price but also household population, water supply cost, and other factors. Therefore, only using the ELES has limitations in analyzing the relationship between urban residents' water demand and water price.

Therefore, this study adopts the QUAIDS model and combines it with the ELES function to establish an improved water demand-price function. The improved function can more comprehensively and effectively analyze the relationship between urban residents' water demand and water price.

2.2.2 Design of the Improved QUAIDS

The QUAIDS model was proposed by Bank et al. based on the nonlinear relationship between consumer spending and commodity prices (Banks et al. 1997).

Firstly, the model assumes a one-time correlation between the proportion of household consumption expenditure and the logarithmic form of total household consumption expenditure, and its corresponding consumer preference is called price-independent generalized logarithmic (PIGLOG) preference. The general functional form of PIGLOG preference is shown below.

$$\begin{cases} E_i = A_i(P) + B_i(P) \cdot \ln(P) + C_i(P) \cdot g(x) \\ x = m/a(P) \end{cases} \tag{13}$$

Where i denotes the i -th commodity consumed by households (assuming that residents collectively consume N commodities, $i=1,2,3,\dots,N$); E_i denotes the proportion of the consumption expenditure of the i -th commodity consumed by households to the total consumption expenditure; P denotes the N -dimensional price matrix of N products; $A_i(P)$, $B_i(P)$, and $C_i(P)$ denotes the differentiable functions of the price of the i -th commodity; $g(x)$ denotes the differentiable function of x , and $a(P)$ denotes the price index of commodity i .

In Eq. (13), if the proportion of the consumption expenditure of the i -th commodity to the total consumption expenditure is linearly related to the total consumption expenditure, $C_i(P)$ is close to 0. If the relationship between them is multiple nonlinearities, then the $C_i(P) \cdot g(x)$ function should exhibit multiple nonlinear characteristics.

Subsequently, Banks et al. (1997) extended the following theorem based on the PIGLOG preference function.

① $C_i(P)$ has the following functional form.

$$C_i(P) = d(P)B_i(P) \tag{14}$$

② The logarithm of the expenditure term is a function with a quadratic term and a rank of 3, and the corresponding indirect utility function is as follows.

$$\ln U = \left\{ \left[\frac{\ln(m) - \ln[a(p)]}{b(p)} \right]^{-1} + \lambda(p) \right\}^{-1} \tag{15}$$

Where $c \left[\frac{\ln(m) - \ln[a(p)]}{b(p)} \right]$ corresponds to the indirect utility function in the PIGLOG preference function, $\lambda(p)$ denotes differentiable zero-degree homogeneous function of price p , and m denotes household consumption expenditure.

According to Roy's equation, the proportion function of household consumption expenditure can be further derived as follows.

$$\omega = \frac{pq}{E} = \frac{\partial \ln[a(P)]}{\partial \ln(p)} + \frac{\partial \ln[b(P)]}{\partial \ln(p)} \times \ln(x) + \frac{\partial \lambda}{\partial \ln(p)} \times \frac{1}{b(P)} \times [\ln(x)]^2 \tag{16}$$

Equation (16) corresponds to the PLGLOG preference function as $\ln(x) = \ln(I) - \ln[a(P)]$.

Then, Bank et al. attempted to construct a consumer demand system with nonlinear characteristics and further proposed the QUAIDS model. The specific function form is as follows.

$$\omega_i = \frac{p_i q_i}{E} = \alpha_i + \sum_{j=1}^n \gamma_{ij} \cdot \ln(p) + \beta_i \cdot \ln \left[\frac{I}{a(p)} \right] + \frac{\lambda_i}{b(p)} \cdot \left\{ \ln \left[\frac{I}{a(p)} \right] \right\}^2 \tag{17}$$

Compared with the ELES model, the QUAIDS model has two advantages: (1) QUAIDS fully considers the non-linear characteristics of residents' consumption expenditure on commodities, and it fits with the theory of diminishing marginal utility; (2) QUAIDS can be expanded according to the consumption characteristics of residents, such as the number

of family population, annual average temperature, etc. Therefore, QUAIDS has been widely used in theory and practice.

Following the literature (Olmstead et al. 2007), the water consumption expenditure of urban residents can be divided into two components: water expenditure to meet basic living needs and water expenditure exceeding basic living needs. Thus, this study further expands the QUAIDS model and incorporates factors such as the water expenditure to meet the basic living needs of urban residents, the number of household populations, as well as the living space into the function. Finally, the improved QUAIDS model is constructed.

Assuming that there are n types of commodities to meet the living needs of urban households, the living consumption expenditure is $\sum_2^n p_i q_i$ (excluding the basic water expenses). Therefore, the basic water consumption q can be estimated by the water demand-price function based on the ELES model, as shown in Eq. (18):

$$\bar{q} = q - \frac{\beta}{p} (I - \sum_{i=2}^n p_i q_i) \tag{18}$$

After the above household living consumption expenditure is excluded (i.e., excluding the basic expenditure for water consumption), the remaining household disposable income is $I' = I - \sum_2^n p_i q_i$. When basic water consumption expenditure $p q$ is eliminated, the additional water consumption expenditure that exceeds the basic water consumption is $p q' = p q - p q$, as shown in Eq. (19).

$$\omega' = \frac{p q'}{E} = \alpha + \sum_{j=1}^n \gamma_{ij} \cdot \ln(p) + \beta \cdot \ln \left[\frac{I'}{a(p)} \right] + \frac{\lambda}{b(p)} \cdot \left\{ \ln \left[\frac{I'}{a(p)} \right] \right\}^2 \tag{19}$$

Where E denotes the total household expenditure, and $\ln a(p)$ is the translog function of the water price p . The specific function form is shown in Eq. (14).

$$\ln a(p) = \alpha_0 + \alpha \cdot \ln p + \frac{1}{2} \gamma (\ln p)^2 \tag{20}$$

Where $b(p)$ is the Cobb-Douglas price function of water price p . The function form is shown below.

$$b(p) = \prod_1^n p_i^{\beta_i} \tag{21}$$

Then, the improved QUAIDS can be expressed in Eq. (22).

$$\omega' = \frac{p q - p \bar{q}}{E} = \alpha + \gamma \cdot \ln p + \beta \left[\ln I' - \alpha \cdot \ln p - \frac{1}{2} \gamma (\ln p)^2 \right] + \frac{\lambda}{p^\beta} \left[\ln I' - \alpha \cdot \ln p - \frac{1}{2} \gamma (\ln p)^2 \right]^2 + \epsilon \tag{22}$$

First, the basic domestic water consumption \bar{q} is estimated by the ELES model; second, q is substituted into Eq. (22), and the parameters in Eq. (22) can be estimated. Then, the relationship function between the water demand and the water price can be established. Finally, the improved QUAIDS can be obtained, as shown in Eq. (23).

$$\begin{aligned} \frac{p}{E} q = \frac{p}{E} \bar{q} + \alpha + \gamma \cdot \ln p + \beta \cdot \left[\ln I' - \alpha \cdot \ln p - \frac{1}{2} \gamma (\ln p)^2 \right] \\ + \frac{\lambda}{p^\beta} \left[\ln I' - \alpha \cdot \ln p - \frac{1}{2} \gamma (\ln p)^2 \right]^2 + \epsilon' \end{aligned} \tag{23}$$

According to the research of Bank et al., QUAIDS is an extensible function (Banks et al. 1997), i.e., other influencing factors can also be extended into the function in the form of a natural logarithm. As the water demand of urban residents is not only affected by disposable income but also by other factors, such as the living space, the number of household populations, etc., this study also incorporates these factors into the function. The number of household population is represented by size, the disposable income by PCDI, and the living space by area. Then, the improved QUAIDS of urban residents is shown in Eq. (24). Substituting the q obtained from the ELES regression estimation in Section 3.2 into Eq. (23) yields Eq. (24).

$$\begin{aligned} \frac{p}{E}q = & \theta \cdot \frac{p}{E} \bar{q} + \alpha + \gamma \cdot \ln p + \beta \cdot \left[\ln I' - \alpha \cdot \ln p - \frac{1}{2} \gamma (\ln p)^2 \right] \\ & + \frac{\lambda}{p^\beta} \left[\ln I' - \alpha \cdot \ln p - \frac{1}{2} \gamma (\ln p)^2 \right]^2 + \varphi_1 \ln size + \varphi_2 \ln PCDI + \varphi_3 \ln space + \varepsilon' \end{aligned} \tag{24}$$

The price elasticity of urban residents' water demand corresponding to the water price can be further calculated by Eq. (24), and the basic water demand under the equilibrium condition of demand and supply be obtained by combining the Ramsey pricing.

2.3 Calculation of Water Price Based on Demand-Supply

By constructing the demand-price function based on the improved QUAIDS, this study analyzes the relationship between urban residents' water demand and price and calculates the demand-price elasticity. Meanwhile, the improved QUAIDS needs to consider both supply and demand, to calculate the basic-living water price of urban residents (Ramsey 1927). The Ramsey pricing method incorporates demand elasticity and supply cost into one framework, so it can be used in this study.

According to Ramsey pricing, the price elasticity ϵ of water demand can be obtained from the improved demand-price function and the Ramsey coefficient $R = \frac{\lambda+1}{\lambda}$. Therefore, the water price corresponding to the maximization of consumption surplus urban residents can be calculated, as shown in Eq. (25).

$$p = \frac{MC}{1 - R/|\epsilon|} \tag{25}$$

Where p is the water price, MC the marginal production cost of water supply enterprises, R the Ramsey coefficient, and ϵ the price elasticity of water demand.

According to the Ramsey pricing method, when the Ramsey coefficient R falls within 0~0.1, the consumer welfare surplus of urban residents and the profit of water supply enterprises can reach an overall equilibrium state. When Ramsey coefficient $R = 0$, water supply enterprises can achieve cost recovery (Ruester and Zschille 2010; Friedmann 2006). Therefore, the basic water price and volume that can meet the basic needs of urban residents and the water supply enterprises can achieve cost recovery, and partial profits can be obtained finally.

Table 1 The current tiered water pricing for residents in Zhengzhou City

Tiered water price	Price(yuan)	Amount of water (cubic meter)	Sewage treatment fee	Water resource tax	Paid-in water price
First step	3.1	0-180	0.95	0.35	4.4
Second step	4.65	181–300	0.95	0.35	5.95
Third step	9.3	Above 300	0.95	0.35	10.6

3 Variable Selection

3.1 Variable Selection

Many related factors affect water prices. The research object is the water price of urban residents, which is mainly subject to water supply and demand. Therefore, this study selects influencing factors based on the two.

In term of supply, existing research suggests that multiple factors can affect water supply, including water quality (Nauges and Whittington 2017), economic development level (Dharmaratna and Harris 2012), and social development level (Grafton et al. 2011). These factors basically affect water supply costs and ultimately affect water prices. Therefore, this study considers water supply costs as the key factor that affects water prices.

In term of demand, factors that affect water demand are mainly household internal factors, such as household disposable income, the number of household populations, etc. Due to the development of the economy and society, the per capita disposable income is increasing. Generally, the higher the disposable income, the more water bills they will spend, which indicates that their water demand will rise (Liao et al. 2016; Nieswiadomy 1992). Additionally, the number of household populations is a common indicator that has been extensively studied in existing literature. Most studies believe that household disposable income and household population (Mostafavi et al. 2018; Arbues et al. 2010; Fan et al. 2017) are key factors that significantly affect residents' water demand. Moreover, urban households need to clean their houses regularly or irregularly, and the larger the living space, the greater the water demand. Therefore, the living space is also an important factor.

Therefore, this study selects factors such as the cost of water supply, household disposable income, the number of household populations, and the living space as key factors.

3.2 Variable Measurement

The specific measurement methods for these factors are introduced below.

(1) Water supply cost

According to the current “minimum profit” water pricing policy in China, the cost price is its water supply cost. Therefore, the water supply cost, represented as AMC, is obtained from official data, as listed in Table 1.

(2) Household disposable income

There is a significant positive correlation between household disposable income and water consumption, i.e., household water consumption increases with household disposable income. Per Capita Disposable Income (PCDI) is adopted to represent the disposable income of urban households, and the specific data is obtained from the questionnaire in this study.

(3) The number of household populations

This indicator is measured by the actual number of household population, represented by size. The data is obtained from the questionnaire.

(4) The living space of urban residents

The living space is also an important factor (Suárez-Varela 2020; García-Valiñas and Suárez-Fernández 2022). Since urban residents generally need to clean their houses regularly or irregularly, i.e., they need water for cleaning, and the amount of water used for cleaning is generally related to their living space. This indicator is represented by area. The data is obtained from the questionnaire.

4 Empirical Analysis

4.1 Overview of Water Resources in Zhengzhou City

As the capital of Henan Province, Zhengzhou has a permanent resident population of 12.828 million by the end of 2022, with a per capita water resource occupancy of 123 cubic meters, which is about 1/16 of the national average and only 1.5% of the world average. Therefore, Zhengzhou City is in serious shortage of water resources. In addition, due to the rapid increase in urban population, and the water consumption in Zhengzhou has been increasing year by year; and as household income increases, residents' water consumption also gradually increases. The overall water demand of urban residents in Zhengzhou City in the past decade is shown in Fig. 1.

In recent years, although Zhengzhou City has continuously increased its water resource supply in various ways and the tiered water pricing policy has been implemented, the overall contradiction between water supply and demand remains prominent due to the fact that the water pricing standard is relatively low, and the tiered water quantity standard is relatively high. Thus, designing a reasonable basic water price and water volume plan can help residents save water.

4.2 Questionnaire Survey

This study conducted a comprehensive questionnaire survey on water prices among urban households in Zhengzhou. 830 questionnaires were distributed and 757 questionnaires were collected finally. After invalid or unqualified questionnaires were excluded (such as filling out questionnaires for no more than 120 s, significant abnormalities in household disposable income, household consumption expenditure, etc.), a total of 652 valid questionnaires were collected, with an effective rate of 86.12%. The descriptive statistical analysis results are shown in Tables 2 and 3.

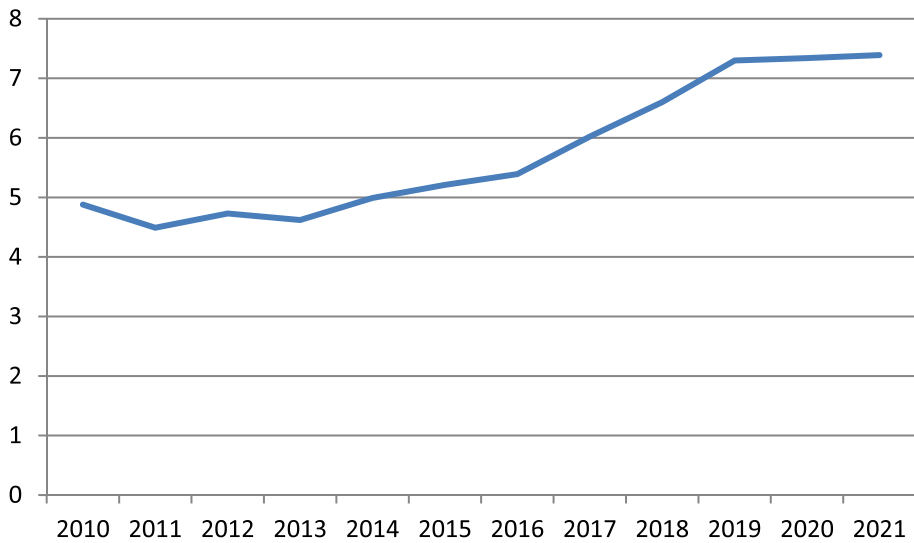


Fig. 1 Changes in the water consumption of urban residents in Zhengzhou City (Unit: 100 million cubic meters, Data Source: Zhengzhou City Water Resources Bulletin 2011–2022)

Table 2 The household profile of the residents in Zhengzhou City

Average population	Per capita disposable income	Living space of urban residents
3.82	41,049	86.04

Table 3 Descriptive statistical analysis of the samples in Zhengzhou City

Variable	Obs	Mean	Std.Dev	Min	Max
Household water consumption (cubic meters/year)	652	176.892	318.412	3.200	842.000
Number of households (person)	652	3.761	1.207	1.000	9.000
Household disposable income (thousand yuan/year)	652	143.945	136.035	3.000	1400.000
Household consumption expenditure (thousand yuan/year)	652	79.349	94.079	5.000	1200.000
Household water expenditure (yuan/year)	652	724.659	865.745	12.000	6000.000
Living space (square meter)	652	84.725	63.412	46.326	267.867

The average annual water consumption of households is about 176 cubic meters, equivalent to 14.67 cubic meters per month, which approximates the first-tier water consumption standard of 180 cubic meters per year in Zhengzhou. The minimum water consumption of residential households is 3.2 cubic meters, and this is mainly due to the small water consumption of individual household. The maximum water consumption is 842 cubic meters, which is mainly due to the high water consumption of some high-income households. For urban households in Zhengzhou, the average number of populations is 3.761. The average annual water consumption per capita is about 46.796 cubic meters. Meanwhile, the average

Table 4 The regression results of ELES in Zhengzhou City

Var	Coef.	Std. Err.	P> t	[95% Conf. Inter- val]	
\bar{q}	143.623	13.657	0.000	111.562	169.756
β_1	0.048	0.051	0.036	-0.004	0.116
β_2	0.021	0.032	0.045	-0.003	0.096
β_3	0.009	0.019	0.071	-0.002	0.099

Table 5 The regression results of the QUAIDS

var	Coef.	Std. Err.	P> t
θ	1.596	0.236	0.000
α	0.898	1.786	0.586
β	2.365	4.126	0.063
γ	-0.685	0.376	0.045
λ	-0.003	0.003	0.245
φ_1	0.014	0.012	0.038
φ_2	0.021	0.013	0.033
φ_3	0.001	0.001	0.044

annual income of urban households is about 143,945 yuan, with a per capita disposable income of 38,273 yuan, which is lower than the national per capita disposable income of 49,300 yuan in 2022. This may be because the overall economic level of Henan Province is lower than the national average. The average annual consumption expenditure of the households in Zhengzhou is 79,349 yuan, and the average annual water bill expenditure of the households is 725 yuan. The data investigated in this study (Table 3) is relatively close to the statistical results of Zhengzhou government departments (Table 2), indicating that the survey data in this study is highly representative.

4.3 Empirical and Result Analysis

4.3.1 Empirical evidence

Firstly, this study employed the Eq. (12) for Bootstap-OLS regression analysis and estimation. The coefficient q , β_1 , β_2 , and β_3 of Eq. (12) can be estimated. As listed in Table 4, the annual basic water demand of urban households (q) is approximately 143.62 cubic meters per year. As the average number of household populations is 3.761, the annual basic water demand per capita of urban households is calculated to be approximately 38.18 cubic meters per year.

Secondly, this study employed the Eq. (24) for Bootstap-OLS regression analysis and estimation. The coefficient of Eq. (24) can be estimated (Table 5). Through investigating Zhengzhou Waterworks in February 2023, its water supply cost is obtained as 3.1 yuan/cubic meter. By combining the improved QUAIDS model (Eq. (24)) and the Ramsey pricing (Eq. (25)), the demand price elasticity under the above cost condition is obtained to be -0.42. Based on the Ramsey coefficient interval $R=0\sim 0.1$, this study further solves the

corresponding water price range, which is 3.10 yuan to 4.07 yuan, and it can be defined as the water price that meets the basic needs of urban residents in Zhengzhou.

The actual water fees paid by urban residents in China include urban sewage treatment fees and water resource taxes, which are 0.95 yuan and 0.35 yuan, respectively. Therefore, the final range of basic water fees for urban residents in Zhengzhou should be 4.40 yuan to 5.78 yuan, which can be defined as the water fee to meet the basic needs of urban residents in Zhengzhou.

4.3.2 Results

Finally, the comparison with the first-tier water price and water volume in the existing tiered water prices is listed in Table 6.

The basic-demand water price is higher than the current first-tier water price. The basic-demand water price balances both supply and demand, and it also guides urban residents to save water. However, the current first-tier water price in Zhengzhou is relatively low. Although the relatively low first-tier water price can ensure the breakeven operation of water supply enterprises, it is difficult to guide residents to save water and not conducive to the long-term development of enterprises. Therefore, setting the first-step water price to 5.78 yuan can not only enable enterprises to achieve partial profits but also promote residents to save water. Meanwhile, the current water volume in Zhengzhou is 180 cubic meters per year, which is higher than that of the basic water demand scheme. Therefore, taking 144 cubic meters per year as the first-tier water volume can better promote water conservation for residents.

Some countries and regions have introduced some suggested standards. The Ministry of Housing and Urban Rural Development of China issued the “Revised Water Consumption Standards for Urban Residents” (GB/T 50,331–2002) in July 2023, which suggests that the basic water needs for a family of three members is 100–120 L per person per day. The family members studied in this study are 3.761. If converted based on the same number of Urban Residents, then the basic water needs studied in this study coincides with the requirements of this standard.

Price is a market-oriented means of regulating demand and supply. When *Ceteris paribus*, raising prices will reduce or restrain consumer demand. The increase in water price suppresses the water demand for urban residents, thereby effectively promoting their water conservation. Besides, by setting a lower basic water volume, this study not only ensures the basic water demand of urban households but also raises the overall water price, especially the water price exceeding the basic demand, thereby greatly improving the water resource utilization of urban residents. To sum up, setting a higher water price and a lower water quantity can not only meet the basic water needs of urban residents but also effectively promote their water conservation.

Table 6 Comparison between the basic demand scheme design and the existing first-tier standards

Tiered water price	Water price (yuan/cubic meter)	Amount of water (cubic meter/year)
Basic demand water pricing scheme guided by water conservation	4.4–5.78	<=144
The existing first-step pricing	4.4	<=180

5 Further Discussion

The existing water pricing include fixed water pricing, two-part water pricing, and tiered water pricing. Fixed water pricing cannot charge different water prices to different consumers, which is not conducive to water conservation for residents. The disadvantage of the two part water pricing method is that it is hard to determine a reasonable capacity water price and water quantity. In order to promote water conservation among residents, most cities in China adopt tiered water pricing. However, water prices and corresponding water quantity standards of each tier implemented in China are unreasonable, with low water price and high water volume, which are not conducive to save water. Therefore, this study has carried out research on Water Price and Quantity to meet the basic living needs of urban residents based on water conservation.

In demand, the disposable income of urban households is gradually increasing, and the water demand also grows correspondingly (Liu and Yang 2012). Specifically, the increase in disposable income will lead to a decrease in the proportion of water expenses to household disposable income. Meanwhile, the increase in household disposable income will further result in an increase in non-basic water demand to pursue a higher quality of life, thereby exacerbating the urban water crisis. Moreover, with the development of urbanization in China, the growth of the urban population will also increase the water demand. Faced with the continuous growth of water demand, water supply enterprises need to invest a large amount of funds to build new supply facilities, which will lead to an increase in water prices.

In supply, water supply companies need to charge a partial premium. Currently, most water supply enterprises have been transformed into state-owned enterprises, and they have to bear their own profits and losses. That is, in addition to achieving a basic balance between income and expenditure to maintain normal business operations, enterprises also need to obtain a portion of the premium to invest in new water supply facilities, such as the construction and expansion of urban water supply networks. If enterprises cannot obtain a partial premium (profit), they can only provide basic water supply services (barely survive), and they will fail to expand water supply infrastructure and cannot meet the growing needs.

However, the basic demand scheme may face some challenges in its implementation. As raising water price and lowering water standards may exceed the psychological and economic affordability of some urban households, especially low-income families, it is not conducive to social stability. Therefore, it is suggested to implement it step by step, i.e., gradually increasing the basic demand water prices and lowering the water volume while providing water subsidies to low-income households.

Currently, China has basically adopted a tiered water pricing model in cities across the country. The central government has designed an overall framework for the tiered water pricing model, and each city determines specific tiered water pricing and water quantity standards based on its own socio-economic situation (Zhang et al. 2017). In summary, the survey and model analysis in this study fully consider factors such as the disposable income and household population of Chinese urban households. Moreover, Zhengzhou is the capital city of Henan Province and has high representativeness. Although there are differences in population and economic development levels among different cities, this study further supplements the survey results and suggestions by fully considering the impact of factors such as urban water supply costs, disposable

income of households, and population size. Therefore, the models proposed in this study have significant reference for other cities.

6 Conclusions

By constructing a water-saving oriented pricing model for urban residents' basic needs, this study investigated the issue of water prices for urban residents in Zhengzhou through questionnaire survey research and empirical analysis. The following conclusions are obtained.

- (1) The water prices of urban residents are affected by various factors, such as the water supply cost, the number of urban households, disposable income, and the living space of urban residents. That is, the increase in the four factors can significantly increase their water demand. Additionally, there are some basic characteristics of water demand in urban households, such as the larger the number of household populations, the greater the basic living needs.
- (2) By establishing a comprehensive water price model based on demand and supply, this study calculated the water price of the basic demand for households in Zhengzhou to be about 4.4–5.78 yuan/cubic meter, corresponding to a water volume of 143.62 cubic meters/year. Compared with the current tiered water prices and volume, the water price has increased by 1.38 yuan and the water volume has decreased by 36 cubic meters per year. It greatly promotes water conservation and rational utilization of water resources for urban residents.

Finally, some policy recommendations are provided. When designing tiered water prices for Chinese cities, both supply and demand factors should be considered. The design of water prices should not only guide resident households to save water but also meet their basic water needs. And when promoting water conservation through a water pricing policy, other related measures are required, such as increasing residents' water-saving awareness, promoting water-saving subsidies etc.

Future outlook Residents may lack sufficient awareness of water scarcity, and some residents do not even believe that water resources are scarce. Therefore, we will investigate residents' awareness of water scarcity in the future.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by zhang shujing and all authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data Availability The data on the current situation of water resources can be downloaded from the Chinese government website. And the survey data used in this study was obtained by paying some questionnaire fees, which can be obtained from the author if needed.

Declarations

The authors have no relevant financial or non-financial interests to disclose.

Competing interests The authors have declared that no competing interests exist.

References

- Arbues F, Villanua I, Barberán R (2010) Household size and residential water demand: an empirical approach. *Aust J Agric Resour Econ* 54(1):61–80
- Avni N, Fishbain B, Shamir U (2015) Water consumption patterns as a basis for water demand modeling. *Water Resour Res* 51(10):8165–8181
- Balling RC, Gober P (2007) Climate variability and residential water use in the city of Phoenix, Arizona. *J Appl Meteorol Climatol* 46(7):1130–1137
- Banks J, Blundell R, Lewbel A (1997) Quadratic Engel curves and consumer demand. *Rev Econ Stat* 79(4):527–539
- Baumann URS, Müller MT (1997) Determination of anaerobic biodegradability with a simple continuous fixed-bed reactor. *Water Res* 31(6):1513–1517
- Chen H, Yang ZF (2009) Residential water demand model under block rate pricing: a case study of Beijing, China. *Commun Nonlinear Sci Numer Simul* 14(5):2462–2468
- Dharmaratna D, Harris E (2012) Estimating residential water demand using the Stone-Geary functional form: the case of Sri Lanka. *Water Resour Manage* 26:2283–2299
- Fan L, Gai L, Tong Y, Li R (2017) Urban water consumption and its influencing factors in China: evidence from 286 cities. *J Clean Prod* 166:124–133
- Friedmann J (2006) Four theses in the study of China's urbanization. *Int J Urban Reg Res* 30(2):440–451
- García-Valiñas MÁ, Suárez-Fernández S (2022) Are economic tools useful to manage residential water demand? A review of old issues and emerging topics. *Water* 14(16)
- Grafton RQ, Ward MB, To H, Kompas T (2011) Determinants of residential water consumption: evidence and analysis from a 10-country household survey. *Water Resour Res* 47(8)
- He J, Chen X, Shi Y, Li A (2007) Dynamic computable general equilibrium model and sensitivity analysis for shadow price of water resource in China. *Water Resour Manage* 21(9):1517–1533
- Huang WC, Wu B, Wang X, Wang HT (2021) An analysis on relationship between municipal water saving and economic development based on water pricing schemes. *Water Secur Asia: Opportunities Challenges Context Clim Change*. https://doi.org/10.1007/978-3-319-54612-4_34
- Jiang X (2020) Comparative study on the water-saving effect of tiered water prices for urban residents—analysis of the water-saving effect of tiered water pricing for residents in Hangzhou, 07,70–73 + 120
- Li M, Liu Y (2005) Economic analysis of water conservation for urban residents and discussion on stepped water prices. *Price: Theory Pract* 12:36–37
- Liao X, Xia E, Wang Z (2016) The impact of tiered water prices on urban residents' water consumption and low-income family welfare. *Resour Sci* 38(10):1935–1947
- Liu X, Chen X, Wang S (2009) Evaluating and predicting shadow prices of water resources in China and its nine major river basins. *Water Resour Manage* 23:1467–1478
- Liu J, Yang W (2012) Water sustainability for China and beyond. *Science* 337(6095):649–650
- Liuch C (1973) The extended linear expenditure system. *Eur Econ Rev* 4(1):21–32
- Martínez-Españeira R, Nauges C (2004) Is all domestic water consumption sensitive to price control? *Appl Econ* 36(15):1697–1703
- Mostafavi N, Shojaei HR, Beheshtian A, Hoque S (2018) Residential water consumption modeling in the integrated urban metabolism analysis tool (IUMAT). *Resour Conserv Recycl* 131:64–74
- Nauges C, Thomas A (2003) Long-run study of residential water consumption. *Environ Resource Econ* 26:25–43
- Nauges C, Whittington D (2017) Evaluating the performance of alternative municipal water tariff designs: quantifying the tradeoffs between equity, economic efficiency, and cost recovery. *World Dev* 91:125–143
- Nieswiadomy ML (1992) Estimating urban residential water demand: effects of price structure, conservation, and education. *Water Resour Res* 28(3):609–615
- Olmstead SM, Hanemann WM, Stavins RN (2007) Water demand under alternative price structures. *J Environ Econ Manag* 54(2):181–198
- Ramsey FP (1927) A contribution to the theory of Taxation. *Econ J* 37(145):47–61
- Renwick ME, Archibald SO (2018) Demand side management policies for residential water use: who bears the conservation burden? *Economics of Water resources*. Routledge, Abingdon, pp 373–389

- Ruester S, Zschille M (2010) The impact of governance structure on firm performance: an application to the German water distribution sector. *Utilities Policy* 18(3):154–162
- Sebri M (2014) A meta-analysis of residential water demand studies. *Environ Dev Sustain* 16:499–520
- Shi L, Wang L, Li H, Zhao Y, Wang J, Zhu Y, He G (2022) Impact of residential water saving devices on urban water security: the case of Beijing, China. *Environ Sci: Water Res Technol* 8(2):326–342
- Shi Z, Xu L (2001) Water pricing policy in Tarim Basin of China. *Tsinghua Sci Technol* 6(5):469–474
- Suárez-Varela M (2020) Modeling residential water demand: an approach based on household demand systems. *J Environ Manage* 261
- Uzel G, Gurluk S (2016) Water resources management, allocation and pricing issues: the case of Turkey. *J Environ Prot Ecol* 17(1):64
- Wang W, Xie H, Zhang N, Xiang D (2018) Sustainable water use and water shadow price in China's urban industry. *Resour Conserv Recycl* 128:489–498
- Worthington AC, Hoffman M (2008) An empirical survey of residential water demand modelling. *J Economic Surveys* 22(5):842–871
- Yang H, Abbaspour KC (2007) Analysis of wastewater reuse potential in Beijing. *Desalination* 212(1–3):238–250
- Yang DT, Cai F (2003) The political economy of China's rural-urban divide. How far across the River, pp 389–416
- Yining W (2010) Urban water supply industry marketization of China in view of public water service and water resource management. *Chin J Popul Resour Environ* 8(2):55–60
- Zhang HH, Brown DF (2005) Understanding urban residential water use in Beijing and Tianjin, China. *Habitat Int* 29(3):469–491
- Zhang B, Fang KH, Baerenklau KA (2017) Have Chinese water pricing reforms reduced urban residential water demand? *Water Resour Res* 53(6):5057–5069

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Shujing Zhang¹ · Yanrong Wang¹

✉ Yanrong Wang
wyr223@126.com

Shujing Zhang
zsjing85@163.com

¹ School of Management and Economics, North China University of Water Resources and Electric Power, Zhengzhou, China