ECONOMETRICA

JOURNAL OF THE ECONOMETRIC SOCIETY

An International Society for the Advancement of Economic Theory in its Relation to Statistics and Mathematics

http://www.econometricsociety.org/

Econometrica, Vol. 83, No. 5 (September, 2015), 1913–1961

THE VALUE OF FREE WATER: ANALYZING SOUTH AFRICA'S FREE BASIC WATER POLICY

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Econometrica, Vol. 83, No. 5 (September, 2015), 1913–1961

THE VALUE OF FREE WATER: ANALYZING SOUTH AFRICA'S FREE BASIC WATER POLICY

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This paper analyzes South Africa's Free Basic Water Policy, under which households receive a free water allowance equal to the World Health Organization's recommended minimum. I estimate residential water demand, evaluate the welfare effects of free water, and provide optimal price schedules derived from a social planner's problem. I use a data set of monthly metered billing data for 60,000 households for 2002–2009 from a particularly disadvantaged suburb of Pretoria, with rich price variation across 20 different nonlinear tariff schedules. I find that the free allowance acts as a lump-sum subsidy, without large effects on water consumption. However, it is possible to reallocate the current subsidy to form an optimal tariff without a free allowance, which would increase welfare while leaving the water provider's profit unchanged. This optimal tariff would also reduce the number of households consuming low quantities of water, a desirable policy goal according to the WHO.

KEYWORDS: Water demand, nonlinear pricing, developing countries.

"Water is life, sanitation is dignity." *Motto of the Department of Water and Sanitation, City of Tshwane*

1. INTRODUCTION

AS EXEMPLIFIED BY THE OPENING QUOTE, it is difficult to overestimate the significance attached to running water in many developing countries. The provision of affordable water to households requires not only developing the infrastructure for piped water and proper sanitation, but also determining the price of water for residential use. Throughout the developing world, governments and utilities are experimenting with various pricing structures, including unlimited free water (Tanzania before 1991), zero marginal rates with fixed fees (India, Pakistan, Zimbabwe, Kenya), uniform rates (Uganda), or standard block prices with multiple tiers (Ghana, Ivory Coast).[2]

[1]I would like to thank Amil Petrin and Patrick Bajari for their advice and support. I also thank Tom Holmes, Kyoo il Kim, Minjung Park, Chris Timmins, Gergely Ujhelyi, four anonymous referees, several friends and seminar participants at the University of Minnesota, as well as seminar participants at Yale, Georgia State, Texas A&M, University of Calgary, University of Houston, University of Maryland (AREC), RPI, the 2012 CFSP workshop at MIT, and NEUDC 2009 for comments and suggestions. I am grateful for the assistance and cooperation of Fazel Sheriff, Director of Water and Sanitation at the City of Tshwane, and Pieter Avenant, Chief Financial Officer of Odi Water, without whom this project would not have been possible. All views expressed in this paper are the author's and were not endorsed by the City of Tshwane or Odi Water.

[2]A block rate structure is one that defines different unit prices for various quantity blocks. See Whittington (1992), World Bank (1993), Berg and Mugisha (2010), and Diakite, Semenov, and Thomas (2009) for more information on the pricing practices in these countries.

 DOI: 10.3982/ECTA11917

The literature has addressed the impact of adequate water supply on water borne diseases (Zwane and Kremer (2007)), child mortality (Gamper-Rabindran, Khan, and Timmins (2010)), educational attainment (Gould, Lavy, and Paserman (2011)), and women's empowerment (Ivens (2008)), as well as its connection to corruption (Anbarci, Escaleras, and Register (2009)) and different systems of government (Deacon (2009)). The choice of a pricing scheme, which has received little attention, has similar far-reaching implications and it is one of the central problems for local governments and utilities.

Water pricing is an especially salient issue in post-apartheid South Africa, where who has access to water and how much they are charged for it is closely tied to issues of social justice. After the democratic elections of 1994, every household's right to a monthly allowance of free water was codified in the constitution, leaving the details of implementation to be worked out by future governments. The resulting unique pricing scheme, the Free Basic Water Policy, was introduced in 2001 and provides 6 kiloliters of water per month at no cost to households, regardless of income or household size. While the term "free water" is sometimes used in the literature to describe a situation with zero marginal price where households pay a fixed fee for the first units of water,[3] the South African scheme, which is motivated by equity concerns and in which water is actually free, is one of a handful of such policies in the world.

The goal of this paper is to analyze the welfare effects of free water and provide an optimal pricing scheme. To do this, I collected a data set containing seven years of monthly meter reading data for every household served by a local water provider (about 60,000 households) in a particularly disadvantaged suburb in Tshwane (the metropolitan area around Pretoria, the country's administrative capital). The data set contains rich price variation across 20 different tariff schedules, which allows the identification of demand parameters and a counterfactual analysis without free water. I find that, by itself, the free water allowance does not lead to large changes in consumption. However, it is possible to reallocate the current government subsidy embodied in the free allowance to form an optimal tariff without free water, which would increase welfare while leaving the water provider's profit unchanged. This optimal tariff would also reduce the number of households consuming particularly low quantities of clean water, which has been identified by the WHO as a desirable policy goal.

The data set used in this paper contains individual monthly meter reading data for every household served by a local water provider from January 2002

[3]For example, see Gibbs (1978), Dandy, Nguyen, and Davies (1997), Castro, Da-Rocha, and Delicado (2002), and Martinez-Espineira (2002). These pricing schemes are often used to make utilities' revenues more predictable, and the fixed fee tends to be large (often equal to the average price for a similar quantity on a different part of the tariff schedule). In other cases, utilities may have a small free tariff block for administrative reasons, for example, to simplify billing for a vacant apartment where a minor leak or water testing produces positive consumption.

to June 2009. This is a low-income population where a large number of households have monthly water consumption near subsistence levels. This population is 99% Black, with average monthly household income around 500 USD. About 11% of the households have running water but no sanitation, and 30% consume not more than 6 kiloliters of water per month, which is the WHO-recommended clean water consumption for a 5 person household. Consumption is recorded using modern technology and the data set provides a sufficiently long purchase history and over 3 million monthly observations.

I observe administrative data on prices, and during the observed seven-year period the water provider experimented with 20 different tariff structures, leading to substantial changes in prices over and above the inflation adjustments (including changes in the number of tariff blocks and changes from increasing to decreasing marginal prices). In addition, I take advantage of a 2007 policy experiment in which, in an effort to cut costs, Tshwane's Water Department introduced a new pricing policy that removed the free water allowance for most households while providing further discounts to the poorest. The extensive price variation in the data set allows me to identify the parameters of a demand model and perform a counterfactual analysis without free water.

The administrative data are complemented with a survey of 1000 households carried out in December 2010. A representative sample was surveyed to collect information on water usage behavior and household demographics. The survey also provides a measure of household income, which is a key element for the estimation.

Because the water utility uses a complex block pricing structure, regression methods result in biased estimates. Rational households base their consumption decisions on the entire price schedule rather than on a specific marginal or average price. In this sense, it is important to estimate the consumers' block choice in an integrated way. To identify the demand parameters necessary for a counterfactual analysis and the optimal pricing exercise, I pursue a structural estimation approach. To estimate water demand under the complex block pricing system used in Tshwane, I use an extension of the Burtless and Hausman (1978) demand model developed for labor supply. This model assumes heterogeneous preferences among households with an unobserved taste parameter in the utility function. As a consequence, I am able to recover household-level marginal effects and estimate household-level price elasticities.

Applying the Burtless and Hausman (1978) model to water and other commodities with nonlinear prices raises several difficulties.[4] First, while previous studies considered systems with monotonically increasing or decreasing marginal prices, the schedules analyzed in this paper feature a combination

[4]Previous studies on water demand estimation include Hewitt and Haneman (1995), Pint (1999), and Olmstead, Hanemann, and Stavins (2007). See also Arbues, Garcia-Valinas, and Martinez-Espineria (2003) and Olmstead (2009) for reviews. Related studies on electricity demand include Reiss and White (2005) and McRae (2015).

of increasing and decreasing marginal prices and, as a result, the econometric model becomes more complex. I show how to proceed with the estimation and derive the maximum likelihood function under these conditions. Second, if convexity of preferences is not satisfied, applying the estimation method mechanically will produce negative probabilities in the likelihood function. Because I work with an explicit utility structure, I am able to solve this problem by restricting the distribution of preference heterogeneity to ensure that convexity is satisfied. The analysis can be directly applied to other markets with similar pricing structures, including electricity and wireless phone service.

I find that, in this context where water spending is a large fraction of household income, consumers are responsive to the complex pricing schedules used by the provider. This is demonstrated both in the raw data as well as in the estimation results. Across all households, I estimate an average price elasticity of −0.98. This price sensitivity underscores the usefulness of price-based instruments to regulate water consumption in this setting.

In analyzing the Free Basic Water Policy, I first study a counterfactual scenario in which consumers do not receive any free water. Currently, the water provider assigns positive accounting prices to free water in order to receive a subsidy from the central government. This allows me to analyze a counterfactual scenario where I replace the zero prices with these positive prices. I find that household consumption changes very little without free water. In this sense, the policy acts as a lump-sum cash subsidy to households in this sample. However, the current policy of providing some water for free is only one possible way of allocating the government subsidy. Is there a welfare-improving way to subsidize water consumption?

To investigate whether the pricing system of Tshwane can be improved, I consider various formulations of an optimal pricing problem. I assume that a social planner maximizes consumers' total expected utility subject to a profitability constraint for the provider. In an extension, I also include revenue and capacity constraints. I find that the optimal tariff contains gradually increasing positive marginal prices with no free allowance. This corresponds to the current government subsidy being spread more evenly across the lower segments. The optimal tariff increases welfare substantially while reducing the percentage of consumers with low water consumption. The intuition behind increased consumption is that consumers currently attempt to stay within the free allowance in order to avoid paying the higher marginal prices. I calculate the compensating variation to compare households' welfare under the various tariff schedules. I find that relative to the tariffs used in practice, the optimal price schedule derived here yields a welfare gain for the median household that is equivalent to 10–20% of the amount spent on water. Over a year, this adds up to approximately 3.5% of the median monthly income. In fact, removing the free allowance can improve welfare even for the lowest income consumers. In this sense, the high marginal prices made necessary by giving out the lowest quantities for free unintentionally hurt these households.

Even though pricing the existing water supply is a central concern to policymakers in many developing countries, the majority of water-related papers in the development literature focus on the availability of water rather than on pricing. One major obstacle to demand estimation is the lack of data, as individual meters are still not common in low-income areas of the developing word. A group of studies attempt to overcome this difficulty by using surveys to evaluate households' willingness to pay for various water sources without observed consumption data. For example, Davis, Kang, and Vincent (2001) asked 358 small business owners in Uganda about their willingness to pay for improved water connections, Whittington, Pattanayak, Yang, and Bal Kumar (2002) surveyed 1500 households in Nepal, Pattanayak, van den Berg, Yang, and van Houtven (2006) surveyed 1800 households in Sri Lanka, and Akram and Olmstead (2011) reported on a survey about service quality improvements of 197 households in Pakistan. Some of the difficulties of these contingent valuation surveys in the context of demand estimation are discussed in World Bank (1993). One common difficulty is that respondents often do not understand the terms used in the surveys.[5] I am aware of two previous studies which are based on observed consumption data from a developing country. Diakite, Semenov, and Thomas (2009) studied water demand in Cote d'Ivoire using aggregate consumption data at the community level. Strand and Walker (2005) had access to billing data for about 1000 households from six cities across Central America. By contrast, this paper estimates water demand using administrative, individually metered consumption data for large numbers of low-income households.

Apart from the Burtless and Hausman (1978) method that I extend here, I know of no other approach to estimating models with nonlinear tariff schedules that would be directly applicable to my setting. Blomquist and Newey (2002) provided a nonparametric estimation method for nonlinear budget sets. Their method is not applicable to my data set because I have important non-convexities in consumers' budget sets as a result of decreasing marginal prices between some segments. Non-convexities are present in 10 out of the 20 tariff schedules used here, covering 87.3% of all observations. Moreover, non-convexities are present near the mean and median consumption levels and affect a substantial fraction of the population.[6] More importantly, this method would allow me neither to compare welfare under counterfactual scenarios, nor to solve the social planner problem proposed in Section 7.2 and derive an

[5]Upon being asked about his maximum willingness to pay for water, one respondent in Haiti asked the interviewer, "What do you mean the maximum I would be willing to pay? You mean when someone has a gun to my head?" (World Bank (1993, p. 49)).

[6]Blomquist and Newey suggested including an additional function of observables to quantify the effect of ignoring the non-convexity (page 2460). This suggestion applies if non-convexities affect budget segments other than the last or second to last segment. In my data set, 3 out of the 10 non-convex tariff schedules have non-convexities on the last segment and 4 on the second to last segment.

optimal pricing schedule. In a recent working paper, Kowalski (2012) studied a health insurance application characterized only by non-convex budget segments. Instead of working with a closed form solution for the likelihood function, she proposed a simulated minimum distance estimator. However, this proposed method is not directly applicable to budget sets with a mixture of convex and non-convex segments.

The remainder of the paper is organized as follows: Section 2 describes the institutional context and introduces the data set, Section 3 presents a descriptive analysis, Section 4 provides the demand model, and Section 5 presents the details of the estimation. Section 6 presents the estimation results and Section 7 provides the welfare analysis of the Free Basic Water Policy and analyzes optimal price schedules. Section 8 concludes.

2. DATA AND BACKGROUND

Most of the Tshwane metropolitan area is served by a national bulk water supplier. However, several smaller areas inside the municipality boundaries are served by smaller public utilities. In the late 1990s, the city council faced political and social pressure to improve the quality of life of households living in "townships" (poor suburbs/villages) in the area. One key aspect of the development plan was to create designated institutions focusing on servicing specific less-developed areas. One of these institutions, Odi Water, provides water to particularly underdeveloped townships in the North–Western part of Tshwane, where average monthly household income is less than 500 USD. This area is a mixture of government housing projects and informal shacks. Piped water is available to all households, but 11% of the households have no water-using sanitation. In this sense, the area is a collection of typical South African townships in an urban area. Section S2 in the Supplemental Material (Szabo (2015)) illustrates some of the relevant features of this environment.

The data used in this paper come from two different sources: (i) administrative data on tariff schedules and household-level consumption with basic household characteristics; (ii) detailed household characteristics and information on water use practices from a survey designed and implemented by the author in 2010. Each of these data sources is described in detail below.

2.1. *Water Consumption Data*

I collected the administrative data used in this paper directly from Odi Water. This data set contains monthly residential water billing data for all their customers, or about 60,000 households, for the period January 2002–June 2009. All households in the data set have individually metered running water on their property.[7] Since most of the area had no running water 15 years

[7]In particular, there are no shared connections. Due to the frequent quality checks, theft is also uncommon. My data set includes any problems reported by the meter reader at the monthly

ago, the utility had to develop the entire infrastructure at that time. This included the installation of the individual water meters using modern technology. Given the sophisticated individual meters and Odi Water's tight quality control, consumption is measured precisely. In addition, since I observe the entire population of consumers, the consumption and price data are free of selection problems. The Supplemental Material contains a detailed description on how the final data set was generated. In particular, I dropped commercial users and observations where the meter reader recorded any problems which prevented properly reading the meter (e.g., dirty dial). I also dropped observations with a monthly consumption higher than 50 kl (3.4% of observations). This is four times the average consumption and is likely associated with unreported leaks or commercial activities. The final data set includes 3,036,871 household-month observations. Summary statistics appear in Table I.

It should be noted that no close substitutes for piped water are available in this area. In particular, communal taps are only available in neighboring areas which do not have water connections. In my survey, less than 0.6% of respondents indicated using any other source of water besides piped water (such as boreholes, wells, or communal taps). There is also no resale of piped water in any organized manner. In the survey, only 0.5% of respondents indicated ever having purchased water from anybody but the water provider. Three point seven percent reported ever lending water to a neighbor, and only 0.5% reported doing so at least once a week.

2.2. *Household Characteristics*

The variables used to describe household characteristics include administrative information from the water provider as well as data from a survey carried out in 2010 for this project. The survey was administered by a survey company using a local team of fieldworkers with extensive experience in this area. The goal of the survey was to collect information on water usage behavior and household demographics to complement the consumption data provided by Odi Water. The objective of the sampling design was to yield a sample of 1000 households that is representative of the surveyed population, the residential consumers of Odi Water, based on information that was available prior to the survey. This included monthly water consumption, indigent status, whether the consumer was restricted, and the supply area. Details on the survey can be found in the Supplemental Material. Table I contains detailed summary statistics.

Indigent Status. Households can register with the municipality as "indigent" to receive various government subsidies (such as discounted electricity), and I can identify the accounts of indigent households on a monthly basis in the

reading. This includes illegal connections, dirty dial, etc. (see the Supplemental Material). I drop observations with *any* problems reported, which is 1.7% of the data.

TABLE I

SUMMARY STATISTICS[a]

Variable	Mean	Std. Dev.	10%	90%
Panel A: Administrative data				
Consumption, kl/month	13.196	9.816	3	27
Average max daily temperature (°F)	71.420	6.220	61.742	78.968
Indigent	0.120	–	–	–
Restricted	0.187	–	–	–
Sanitation	0.873	–	–	–
Supply area 1	0.291	–	–	–
Supply area 2	0.194	–	–	–
Supply area 3	0.515	–	–	–
Panel B: Survey data				
Household income*	4772.50	3815.84	1103.34	9146.56
Number of flush toilets	1.189	0.621	1	2
Number of standpipes	1.716	1.148	1	4
Number of bathtubs	0.654	0.716	0	2
Number of showers	0.104	0.305	0	1
Number of kitchen taps	0.824	0.648	0	2
Number of bathroom taps	0.865	0.977	0	2
Washing machine	0.569	–	–	–
Lawn area	0.526	–	–	–
Flower garden	0.368	–	–	–
Vegetable garden	0.184	–	–	–
Winter irrigation**	0.284	–	–	–
Summer irrigation**	0.467	–	–	–
Carwash***	0.274	–	–	–
Primary school or less	0.079	–	–	–
Some high school	0.226	–	–	–
High school graduate	0.404	–	–	–
Some higher education	0.174	–	–	–
Completed higher education	0.117	–	–	–
Number of adults	2.832	1.329	1	5
Number of teens	0.949	0.967	0	2
Number of children	1.041	0.994	0	3
Number of people working outside the home	1.218	0.894	0	2
Number of persons on the property	4.822	2.314	2	8

[a]Panel A presents summary statistics for the administrative data set of the population of consumers across eight tariff years 2002–2009. Supply areas are created by the utility and have no special meaning other than describing a geographical area. Pricing, water quality, and water supply are the same across these areas. Supply area 1 is Garankuwa, Zone 1–9, 16, and 20–25. Supply area 2 is Ga Tsebe and Bothshabelo and Garankuwa Zone 17. Supply area 3 is Mabopane, Block A–Block X and Winterveld. $N = 3{,}036{,}871$. Panel B presents summary statistics from the 2010 survey of a random sample of 1000 households. *Household income is in 2008 Rand. It is estimated based on the ownership of various household appliances as described in the text and in Appendix A.5. **At least once during the season. ***Equals 1 if household washes car(s) at home using water purchased from the utility.

administrative data. To qualify for indigent status, individuals must be South African citizens, own the property they reside on, the property's value must not exceed a certain threshold, and the total gross monthly income of all members of the household must not exceed a specified threshold (between R1700 and R2400 ($\simeq$\$170–240) depending on the year). The percentage of registered households is stable at around 12 percent for most of the seven-year period, with a 3 percentage point increase in registration in the second half of 2007, when the utility discontinued the provision of free water without registration. While registration entitles a household to a lower water price, it also has some costs associated with the provision of other services. For example, in the case of electricity, registered households are automatically enrolled in a prepaid plan where they have to purchase electricity allowances in advance. Moreover, once a household is registered, it must agree to stay in the program for at least 6 months. These features make registration costly, and in practice not all eligible households register. On the other hand, the government encourages households to register, and there appears to be some flexibility in determining a given household's eligibility status. Because there could be relevant behavioral differences between indigent and non-indigent households, I include a dummy variable for indigent households in the estimation.

Restriction. Each month about 19.4% of households in the Odi Water area receive restricted service. Restriction will apply if the household has an unpaid balance for more than 40 days. These consumers receive various restriction devices that limit the water flow to around 1 liter/minute. The main reason for non-payment seems to be high water bills due to negligence, such as leaving the tap running throughout the day. Some households also use water for luxury items they cannot afford, such as watering the lawn or a flowerbed in an arid African area. Restricted households get the 6 kl free water through a limited flow. Until the balance is fully paid, they have the option to prepay for additional kiloliters, which are added to the free amount and divided throughout the month by the flow limiter. For this reason, even restricted consumers may be price sensitive. The average duration of restriction is 5 months. In this paper, I do not model the process through which consumers become restricted, but rather control for restricted status in the estimation by including a dummy variable for the duration that households had the restriction device on their tap.

Sanitation. Odi Water serves several townships in the North–Western part of Tshwane. Some of the areas are undeveloped, and households may have metered running water on their property but no water-using sanitation. For these households, comprising 11% of the population, the municipality provides chemical toilets, or they use shared sanitation facilities. Households do not choose whether to have sanitation. Some areas simply lack the infrastructure necessary for sanitation, and all households have sanitation when it is available. Households with no sanitation use, on average, 25 percent less water than similar households with water-using sanitation facilities. In addition, they need to pay only water and not the separate sanitation charge (see the next section). I include a dummy for households without sanitation.

The above variables are available monthly for the entire population since 2002. The following variables were collected as part of the 2010 survey.

Income. The survey contained several questions to get a measure of household-level income. First, we asked the respondent about his or her own monthly income. This could be answered either by indicating the exact amount, or by indicating the range from a list of thirty-three options (from "R1–R199" to "R20,000+"). Then, we asked them to estimate how much other members of the household may earn. The response rate for these questions was 57%. To get an income measure for all surveyed households, I regress reported household income on the respondent's education, the number of employed adults in the household, ownership of various household appliances (hot running water, TV, DVD player, car, cell phone, and refrigerator), and all pairwise interactions of these variables. I use this regression to predict household income for all households (see Section A.5 in the Appendix). The median monthly household income is R3653 ($\simeq$\$365).[8] Table VIII in the Appendix contains detailed summary statistics.

Water-Using Fixtures. The survey included 21 questions about the number and type of water-using fixtures used by each household. I have information on the number of standpipes, kitchen taps, bathtubs, showers, and washing machines, if any, owned by the household. I also asked the households whether they use the water purchased from the provider for irrigation and any other outdoor use, such as car washing.

Other Characteristics. I observe residential area codes (Area 1, 2, and 3), and also collected information on the average maximum daily temperature per month to capture weather-related consumption changes.[9] In addition, I include from the survey the education level of the primary wage earner and the number of people living on the property.

Throughout the paper, estimation results that use only the variables available from the administrative data cover 3,036,871 monthly observations (the entire population), while results that also include household characteristics from the survey cover 63,178 monthly observations (corresponding to the surveyed households).

2.3. *Tariff Structure*

The tariff structure considered in this paper has a unique feature: It contains a mixture of increasing and decreasing block tariffs. Because Odi Wa-

[8]All monetary values in the paper are in 2008 Rand. Price index data are from http://www.statssa.gov.za (Consumer price index: group and product indices for primary urban areas by year, month and Items, All items, Base year = 2008).

[9]Weather data are from http://www.wunderground.com/history/airport/FAJS/2001/4/1/MonthlyHistory.html.

ter needs to price water and sanitation separately due to accounting reasons, they designed the block tariff structures separately. Both charges are based on a single water meter reading, thus water and sanitation cannot be consumed separately. Although both the water and the sanitation charge form a regular increasing/decreasing price structure when taken separately, their sum does not yield a monotonic price structure.

I have administrative tariff data from January 2002 to June 2009. Tariff structures are reviewed each year in July, so my data contain up to eight different tariff years for both water and sanitation. However, the number of different tariff structures in the data is 20. This is because in some years indigent and non-indigent households faced different tariffs, and because households with and without sanitation face different tariffs.[10] I provide more details on these tariff structures below.

Water tariffs are given in increasing block tariffs, where consumers pay a lower price for each unit up to a certain quantity, and then a higher price. There are 7 blocks in the first three tariff years, 8 in the fourth, 6 in the fifth and sixth, and 8 in the last two tariff years (see Figure 1 for an illustration of

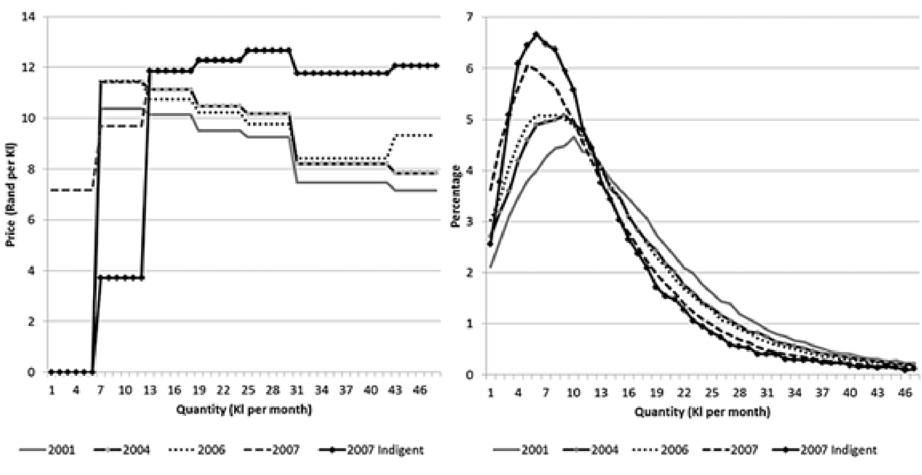

FIGURE 1.—Selected tariff schedules and corresponding consumption distribution in the population. *Notes*: The figure shows selected price schedules and corresponding consumption distributions for all households in the administrative data. The first panel shows the marginal prices per kiloliter under different tariff schedules. The second panel shows the distribution of consumption levels (up to 50 kl) corresponding to each of these schedules. The 2007 pricing features separate schedules for indigent ("2007 indigent") and non-indigent ("2007") households.

[10] Specifically, households with and without sanitation faced different schedules in every tariff year, and in tariff years 6 and 7 indigent and non-indigent households also faced different schedules. Thus, we have two different schedules in each of the first six tariff years, and four different schedules in each of the last two years.

some of these tariff schedules). The sanitation charge consists of two different elements. First, there is a sanitation charge per kiloliter which is a uniform price in the first five tariff years, a continuously decreasing block tariff structure in the sixth year, and an increasing block tariff structure in the last two years. The second component of the sanitation charge is a multiplier which determines the fraction of consumed water after which the sanitation charge is paid. The multiplier changes with the consumption level, but it is fixed over the observed period. There is no sanitation charge for households without water-using sanitation facilities. Sanitation multipliers and summary statistics of the tariff structures are in the Supplemental Material.

Based on my experience in the field, the local government makes extensive efforts to advertise the tariff structure and tariff changes when they occur. This includes special flyers as well as announcements in the local newspaper and at community meetings. In addition, the provider employs "education officers" who regularly educate households about different aspects of water consumption. Given these efforts, most households should understand the consumption and billing process enough to be able to respond to price changes if they wish to do so.

As the above description of the tariff structures shows, Odi Water experimented with many different tariff structures over the years. This creates much more price variation than is typical; for example, U.S. water tariffs are usually fixed over time after adjusting for inflation. Odi Water's frequently changing tariff structure provides a useful source of identification in the data.

The observed period includes a policy change in 2007, when the utility created separate tariff structures for registered indigent households. Previously, consumers received the first 6 kl water for free. From July 2007, Odi Water charged non-indigent households for every kiloliter they consumed. Registered indigent households continued to receive 6 kl free water as well as substantially lower prices between 6 and 12 kl (see Figure 1 as well as detailed graphs in the Supplemental Material).[11] This policy change will provide an important source of identification for the counterfactual analysis under alternative price schedules, since it means that positive prices at each kiloliter, including the first 6 kl, are actually observed in the data in some years for 88% of the population.

3. DESCRIPTIVE ANALYSIS

3.1. *Patterns in the Data*

Figure 1 illustrates a subset of the price schedules and the corresponding distribution of consumption levels in the raw data for the entire population. The

[11] Between 6 and 12 kl, the government removed the water charge for these households. Thus, indigent households with no sanitation received 12 kl free water while those with sanitation only had to pay the sanitation charge. For simplicity, I will describe this policy as providing "12 kl for free" to indigent households (and no free water to non-indigent households).

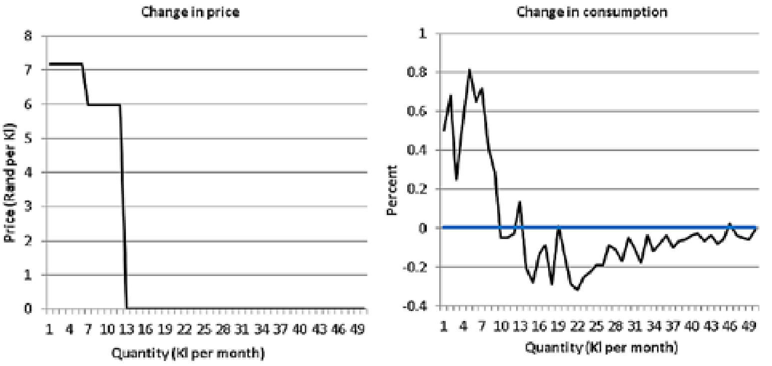

FIGURE 2.—Policy change and the consumption of non-indigent versus indigent households, 2006–2007. *Notes*: The first panel shows the price difference between non-indigent and indigent households after the 2007 policy change. The second panel shows the differential change in the consumption distributions between 2006 and 2007 for non-indigent relative to indigent households in the administrative data. The latter is computed as $(f_{\text{nind}}^{2007} - f_{\text{ind}}^{2007}) - (f_{\text{nind}}^{2006} - f_{\text{ind}}^{2006})$, where f_i^t is the consumption distribution of group i in year t in 1 kl increments.

left hand panel shows the marginal price corresponding to different quantities under five different tariff schedules. The right hand panel shows the corresponding densities of consumption levels. The patterns shown on the graph are broadly consistent with consumers being responsive to price changes. The 2007 indigent tariff, which features the lowest marginal prices below 12 kl and the highest marginal prices above it, yields the most right-skewed consumption distribution. As the successive tariff schedules feature lower and lower marginal prices, the density functions shift to the right roughly in the same order.

The effect of the 2007 policy change, when the subsidy was removed for non-indigent consumers and increased for indigent consumers, is highlighted on Figure 2. The left hand panel shows the difference in price per kiloliter between non-indigent and indigent households after the policy change (the two tariff schedules were identical before the change). The right hand panel shows the corresponding change in the distribution of non-indigent consumption relative to indigents. The graph suggests a *differential* response to the policy in the two groups. Non-indigent households, who experienced a price increase, reduced their consumption relative to indigent households, reallocating consumption from higher to lower segments.

The Supplemental Material presents detailed information on the distribution of consumption across all tariff schedules in the data. Twenty-eight point three percent of the households consume below 6 kiloliters, which is the free allowance under most tariff schedules. Seventy-six point five percent of all observations are concentrated on the first three price blocks (up to 18 kl).

Figure 3 presents a detailed histogram of the consumption levels for the 1000 households with available survey data (63,178 observations). I graph the distribution of consumption levels in March of each year (March consumption is

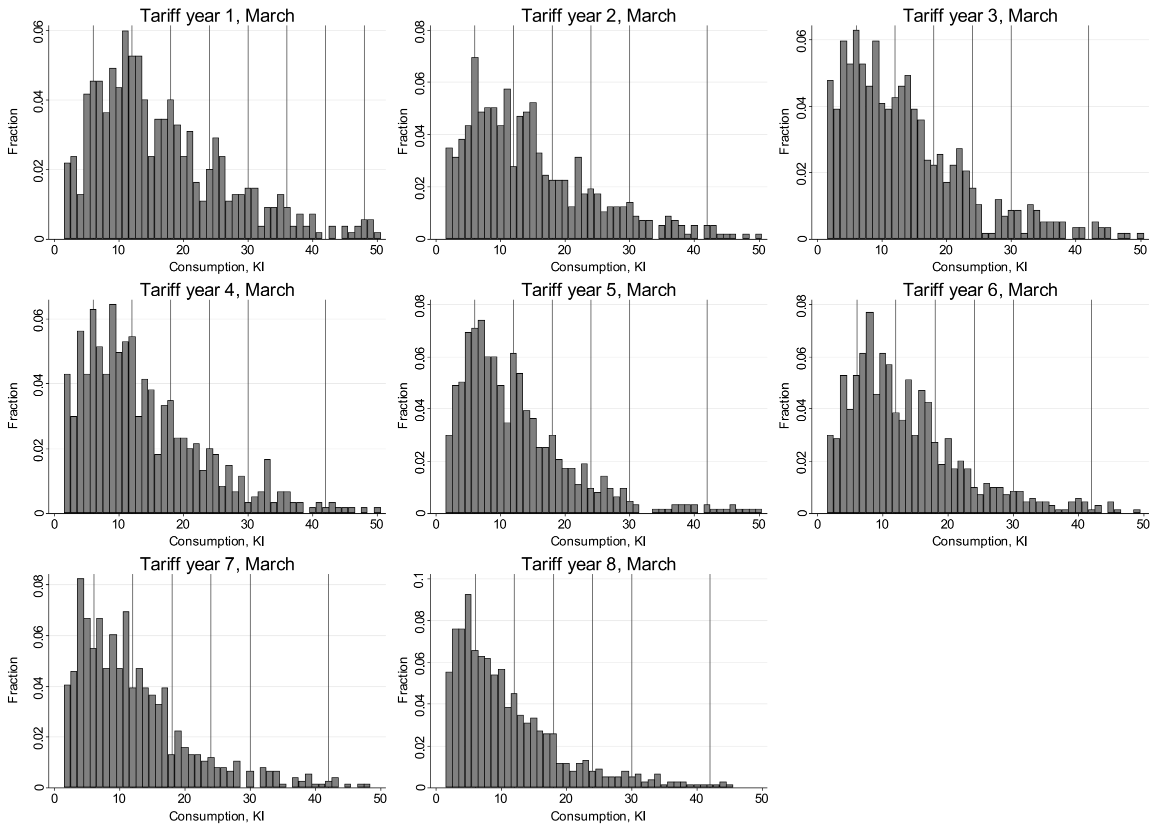

FIGURE 3.—Consumption distribution across price blocks. *Notes*: The figure presents histograms of consumption levels in March of each tariff year. Each bar corresponds to a 1 kl increment in consumed quantity. Vertical lines represent the kink points of each tariff schedule.

typically closest to the average). In each of these figures, every bar corresponds to 1 kl increments in consumption. The kink points in the tariff schedule are indicated by vertical lines. The figures show some concentration of consumption levels at the kink points of the tariff schedule. Specifically, the distribution has modes at the 6 kl and 12 kl kink points in most years, and at the 18 kl kink point in tariff years 1, 4, 6, and 7. This pattern is consistent with consumers being responsive to the block nature of the tariff schedule.

Finally, the Supplemental Material also presents various comparisons of consumption distributions over time. These provide suggestive evidence that consumers respond to revisions of the price schedule in successive tariff years, perhaps with a lag of a month or two.

3.2. *Regression Analysis*

In her review of the literature, Olmstead (2009) noted that out of 400 price elasticity studies of water demand produced between 1963 and 2004, only three used maximum likelihood models, while the rest used OLS and instrumental variable methods. To relate my work to this earlier literature, this section estimates a linear demand function using various regression methods.

To investigate the correlation between prices and consumption levels in the data, I run regressions of the form

$$w_{it} = \alpha P_{it} + \boldsymbol{\beta}\mathbf{X}_{it} + u_{it}, \tag{1}$$

where the dependent variable is metered consumption in month t for household i, and the regressors are the price of water P, and a vector of controls $\mathbf{X}$ that includes individual household characteristics and weather. To include the complex price schedule in this regression, one has to use proxies, typically the average price for each unit of observed consumption, or simply the marginal price of observed consumption. In either case, estimating (1) using OLS introduces an upward bias in the presence of increasing block tariffs, and a downward bias when the block pricing is decreasing. For example, an increasing block structure automatically creates a positive correlation between the marginal or average price and the error term, since above-average consumption levels are necessarily associated with higher prices. While under an everywhere-increasing or everywhere-decreasing tariff structure this bias can at least be signed a priori, this is not possible in my data featuring a mixture of increasing and decreasing price segments. As shown in the Supplemental Material, estimating (1) using OLS produces an upward sloping demand curve in these data. This likely reflects the fact that the increasing portions of the price schedules have more influence on the estimates, since most of the consumption occurs over the lower quantities, where prices are monotonically increasing (see Figure 1 above and Table S-II in the Supplemental Material).

Several water studies use instrumental variables to correct the bias of the OLS estimates. The idea is to instrument the marginal or average price with various summary statistics of the nonlinear price schedule—for example, the marginal prices corresponding to specific predetermined quantities. Essentially, this amounts to approximating the nonlinear price schedule with a linear function of the marginal prices. This procedure is valid to the extent that this linear approximation holds (so that the observed marginal prices are strongly correlated with the instruments) and to the extent that the error term is uncorrelated with the characteristics of the tariff structure used as instruments (so that the exclusion restriction is satisfied).

In the first row of Table II, I estimate equation (1) instrumenting the average price by the marginal prices of consuming six preset quantities, corresponding to the most common kink points in the observed tariff schedules (6, 12, 18, 24, 30, and 42 kl). Column (1) only includes the administrative variables and income from the survey, column (2) adds household demographics, and column (3) adds characteristics related to water use. In column (4), I use a subset of these control variables which will also be included in the maximum likelihood model below (the full regression table is in the Supplemental Material). The estimated price coefficients are always negative, statistically significant, and relatively stable across specifications, with values between −0.551 and −0.620. Most control variables also have the expected sign.

To explore the robustness of the estimated price coefficients, the next two rows of Table II report the results of alternative IV specifications from the literature. First, I follow the specification used by Olmstead (2009) in her comparison of IV and maximum likelihood methods, where the observed marginal price and "virtual income" are instrumented by the marginal prices at the preset quantities.[12] Second, I follow the Terza (1986) modification of a procedure attributed to McFadden, Puig, and Kirschner (1977) (see, e.g., Nieswadomy and Molina (1989)), where the instruments use predicted consumption.[13] Table II shows that these IV specifications are not always able to correct the positive OLS price coefficient, and when they do correct it, the price coefficient is sometimes insignificant. Overall, there is considerable sensitivity in the estimates both to the choice of instruments (across rows) and to the included control variables (across columns). I note that the controls included in column (4) appear to be least sensitive to the choice of instruments; I will use the same set of controls in the maximum likelihood model below.

[12]"Virtual income" is used to account for the implicit subsidy from inframarginal prices in a nonlinear tariff schedule. If consumption occurs on segment k of the schedule, virtual income is $Y_k^0 = Y - M(\bar{w}_{k-1}) + P_k \bar{w}_{k-1}$, where Y is income, P_k is the marginal price on the segment, $\bar{w}_{k-1}$ is the lower kink point of the segment, and $M(\bar{w}_{k-1})$ is total expenditure corresponding to this kinkpoint. See the next section for more details.

[13]Specifically, the first stage involves regressing observed water demand on the marginal prices at preset quantities, and using the predicted consumption to compute predicted marginal price and virtual income. In the second stage, these predicted values are used as right-hand-side variables in the demand equation.

TABLE II

PRICE COEFFICIENT ESTIMATES USING ALTERNATIVE IV SPECIFICATIONS[a]

	(1)	(2)	(3)	(4)
Baseline				
Price	−0.620	−0.608	−0.551	−0.554
	(0.024)	(0.024)	(0.023)	(0.023)
Olmstead (2009)				
Price	0.006	−0.245	−0.359	−0.500
	(0.293)	(0.427)	(0.348)	(0.268)
McFadden (1977)				
Price	−0.641	−0.561	−0.584	−0.610
	(0.038)	(0.036)	(0.033)	(0.037)

[a]The table presents coefficient estimates from (1) using various IV methods. In the first panel, the average price is instrumented by the marginal prices of consuming at the kink points 6, 12, 18, 24, 30, and 42 kl. The second panel presents specifications similar to Olmstead (2009), where the observed marginal price and virtual income are instrumented by the marginal prices at the kink points. In the third panel, following McFadden, Puig, and Kirschner (1977), the first stage regresses water consumption on the marginal prices at the kink points, and this is used to predict the marginal price and virtual income entered in the second-stage regression. As control variables, column (1) includes administrative variables and income, column (2) adds household demographics, column (3) adds water use characteristics, and column (4) uses a subset of these variables also included in the ML estimation below. See the Supplemental Material for a detailed list of variables and full regression ouptuts. Robust standard error in parentheses. $N = 63{,}178$.

In some previous applications, the IV method was found to perform quite well (Olmstead (2009)). What might account for the lack of robustness in the present case? First, IV methods should perform better when a consumer tends to stay on the same segment of the tariff schedule. Theoretically, optimizing consumers base their choices on the entire price schedule: they choose the block in which to consume based on all the marginal prices, and the quantity consumed in a specific block based on the marginal price in that block. Therefore, if the error term contains a preference shock upon which optimizing consumers base their choices, it will be correlated with not just the marginal price of the observed consumption, but also with any other characteristic of the tariff schedule. Particular features of the price schedule, such as a list of marginal prices, are therefore not valid instruments. Empirically, this problem is less severe when consumers do not switch between price segments.[14] In my data, there are many price segments and a substantial number of households switch between these over time. This suggests that any particular instrument may not be a good proxy of consumers' optimizing decision, and this could be reflected in the sensitivity of the estimates in Table II.

[14]This appears to be the case in the Mayer, DeOreo, Opitz, Kiefer, Davis, Dziegielewski, and Nelson (1999) data analyzed by Olmstead (2009), where the majority of price schedules had only two segments.

A second potential difficulty with the IV approach concerns the treatment of consumption levels around kink points. In a regression framework, these are randomly assigned the corresponding marginal prices, or in some cases are simply dropped from the regression. This will introduce an error in the estimates if these observations were in fact intended kink point consumptions. In data sets with few kink points and few consumers at the kinks, this is unlikely to be a major issue empirically. By contrast, as discussed above, the present data set features more concentration around kink point consumptions than has been previously observed in the literature. This also suggests that using any particular instrument may lead to considerable loss of information in this context.

In what follows, I estimate a textbook model of consumer choice in the face of block tariffs. While the model makes stark assumptions regarding consumer rationality, it is a useful approach in this case where consumers appear to be price sensitive, and provides a natural framework for the discussion of optimal pricing policies.

4. CONSUMER CHOICE UNDER INCREASING OR DECREASING BLOCK PRICES

Consider a general model of a consumer facing a piecewise linear budget constraint. This generalizes the treatment in Burtless and Hausman (1978) or Moffitt (1986) who focused on the case of everywhere-increasing or everywhere-decreasing prices. The consumer consumes water w and a composite good x, and his utility is $U(w, x)$, where U is strictly quasi-concave and increasing in both goods. The tariff schedule is written as $P(w)$. It is piecewise linear with a finite number K of segments, where segment k has a marginal price P_k between consumption levels $\bar{w}_{k-1}$ and $\bar{w}_k$ (referred to as "kink points"):

$$P(w) = \begin{cases} P_1 & \text{if } w \in [0, \bar{w}_1], \\ P_2 & \text{if } w \in (\bar{w}_1, \bar{w}_2], \\ \dots & \dots, \\ P_K & \text{if } w \in (\bar{w}_{K-1}, \infty). \end{cases}$$

Given income Y, the consumer solves the problem

$$\max_w U\big(w, Y - M(w)\big), \tag{2}$$

where $M(w) = \int_0^w P(u)\,du$ is total expenditure on water. While this problem is conceptually straightforward, not every solution procedure is equally amenable to estimation. The following procedure will be particularly convenient.

To solve problem (2), consider first the subproblems of maximizing utility as if the budget constraint was linear, extending each budget segment to the

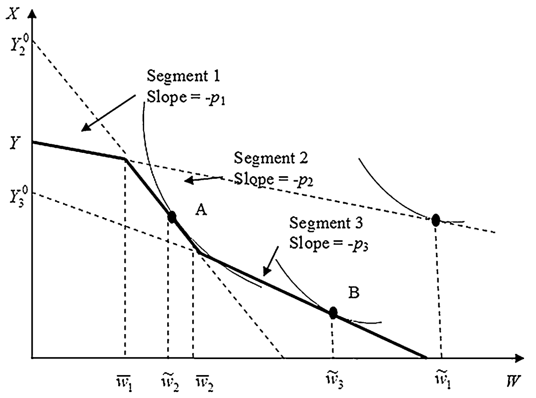

FIGURE 4.—Budget set with mixed price blocks. The consumption levels $\widetilde{w}_2$ and $\widetilde{w}_3$ are feasible, while $\widetilde{w}_1$ is not.

entire consumption set as show by the dashed lines on Figure 4. Let $Y_k^0 = Y - M(\bar{w}_{k-1}) + P_k \bar{w}_{k-1}$ denote the income corresponding to each extended segment. For each segment k, define

$$V_k = \max_w U\big(w, Y_k^0 - P_k w\big), \tag{3}$$

and let $\widetilde{w}_k$ be the solution. Thus, V_k and $\widetilde{w}_k$ are, respectively, the consumer's indirect utility function and demand function corresponding to the extended budget constraints. I will say that $\widetilde{w}_k$ is feasible if $\widetilde{w}_k \in [\bar{w}_{k-1}, \bar{w}_k]$. Next, compare the utility of the solutions which are feasible under the tariff schedule $P(w)$, and the utility of the kinks $\bar{w}_k$, to determine the consumer's demand. For each kink k, let $\bar{U}_k = U(\bar{w}_k, Y - M(\bar{w}_k))$ be the consumer's utility from consuming at kink k. Define

$$\begin{aligned} k_1^* &= \operatorname*{arg\,max}_{k \mid \widetilde{w}_k \in [\bar{w}_{k-1}, \bar{w}_k]} \{V_1, V_2, \dots, V_K\}, \\ k_2^* &= \operatorname*{arg\,max}_k \{\bar{U}_1, \bar{U}_2, \dots, \bar{U}_{K-1}\}. \end{aligned} \tag{4}$$

k_1^* is the segment giving highest utility under the tariff schedule $P(w)$, while k_2^* is the highest utility kink. Consumer demand is

$$w^*\big(P(\cdot)\big) = \begin{cases} \widetilde{w}_{k_1^*(P(\cdot))}\big(P(\cdot)\big) & \text{if } V_{k_1^*} > \bar{U}_{k_2^*}, \\ \bar{w}_{k_2^*} & \text{otherwise,} \end{cases} \tag{5}$$

where dependence of demand on the tariff is made explicit. In words, (5) says that consumer demand is either a kinkpoint, or it is the regular demand of a consumer facing a linear budget constraint with income Y_k^0 and price P_k.

The approach of solving the subproblem (3) corresponding to each segment is useful because the tariff structure is not differentiable, and not necessarily convex. The lack of differentiability prevents the use of first-order conditions at the kink points. The lack of convexity means that, on the segments, the first-order conditions of the consumer's problem (2) may yield multiple solutions. Consider, for example, Figure 4. In this example, the best choice on segment 2 (point A) is a local optimum. But it is not a global optimum. There is another local optimum on segment 3 (point B) that is preferred to segment 2. The problem arises here because the tariff is not convex. Of course, over a particular linear segment, the problem is convex, so I can use the first-order approach on a particular segment to solve subproblem (3). Then, by solving (5), I obtain the global optimum.

One aspect of the consumer's problem that is missing from the above simple model is investment in water-using appliances. In the electricity literature, such investment decisions have been shown to be important determinants of demand (e.g., Dubin and McFadden (1984), Reiss and White (2005)). However, these considerations are unlikely to be relevant in the empirical setting considered here. Washing machines are the only appliances that a household in the study area could possibly invest in (in the survey, 569 of the 1000 sampled households own a washing machine).[15] Comparing the average consumption across households with and without washing machines yields an insignificant difference of 0.023 kiloliters. Thus, instead of modeling the choice of a washing machine based on the price schedule, I treat it as an exogenous variable in the estimation below. Since this variable will enter demand nonlinearly in the estimation, I allow for any potential difference in the price elasticity of households with and without washing machines.

5. SPECIFICATION AND ESTIMATION

5.1. *Demand Specification*

To obtain a tractable demand function, I follow Hausman (1980) and assume that the consumer's direct utility function can be written as

$$U(w, x) = \frac{\gamma w + \alpha}{\gamma^2} \exp\left(\gamma \frac{\gamma x - w + Z\delta + \eta}{\gamma w + \alpha}\right). \tag{6}$$

Here, Z represents observed consumer characteristics such as the availability of water-using sanitation or indigent status, and δ is a vector of corresponding

[15] Other conservation actions, such as upgrading existing fittings, appear to be infrequent. The survey asked about various conservation actions undertaken by households in the last few years. Only 1.6% indicated installing water-efficient taps, and other conservation actions were mentioned by even fewer respondents.

parameters. The role of the parameters $\alpha < 0$ and $\gamma > 0$ will be made clear below, and the term η represents household level heterogeneity (see below). Under (6), preferences are convex if and only if $\gamma w + \alpha < 0$. Since there are two goods and two parameters (α and γ), the functional form in (6) is flexible in the sense that the two parameters can be chosen to provide a first-order approximation to an arbitrary utility function at a given point (w, x).

Given a linear budget set with income Y and price P, the indirect utility function and demand function corresponding to (6) is

$$V(P, Y) = \exp(-\gamma p)\left(Y + \frac{\alpha}{\gamma}P + \frac{\alpha}{\gamma^2} + \frac{Z\delta + \eta}{\gamma}\right), \tag{7}$$

$$\widetilde{w}(P, Y) = Z\delta + \alpha P + \gamma Y + \eta. \tag{8}$$

Equation (8) makes it clear that α and γ are, respectively, the price and income coefficients in the demand function. Using this specification, we may write demand corresponding to segment k as $\widetilde{w}_k = \widetilde{w}(P_k, Y_k^0) = Z\delta + \alpha P_k + \gamma Y_k^0 + \eta$, and the consumer's utility as $V_k = V(P_k, Y_k^0)$.

This specification gives rise to the following econometric form of the consumer's demand (5):

$$\begin{aligned} w_{it} &= w^*\big(P(\cdot)\big) + \varepsilon_{it} \\ &= \begin{cases} Z_{it}\delta + \alpha P_{it} + \gamma Y_{it} + \eta_{it} + \varepsilon_{it} & \text{if } V_{k_1^*} > \bar{U}_{k_2^*}, \\ \bar{w}_{k_2^*} + \varepsilon_{it} & \text{otherwise,} \end{cases} \end{aligned} \tag{9}$$

where k_1^* and k_2^* are defined in (4), and w_{it} is observed monthly consumption of household i in billing cycle t. Households have an individual meter on their property and they pay a monthly bill, so there are no data aggregation issues either across time or among households. Household-level heterogeneity is modeled as a time-varying term η_{it} (preference error). This is observed by the household but not by the econometrician. Finally, ε_{it} is a random optimization error not observable by either the households or the econometrician and not considered in the households' optimization problem. For example, it might represent leaks not noticed by the households or other unforeseen events causing desired consumption to differ from actual consumption.

To see why introducing the optimization error is necessary, note that, given some distribution of η, the theory predicts (i) a zero probability of consuming at non-convex kink points, and (ii) a strictly higher probability of consuming exactly at a convex kink point than in a small neighborhood around it. By contrast, the data show some clustering of consumption around the kink points. The error term ε will contribute to explaining consumption in the neighborhood of convex kinks as well as consumption at non-convex kink points.

In standard demand estimation, the distribution of η_{it} and ε_{it} cannot be separately identified, but that is not the case in the present context. When utility is maximized on a segment, observed consumption contains two error terms, as in (9). When utility is maximized at a kink point, observed consumption is equal to the kink value plus the optimization error only, since the preference error is already "included" in the kink point (Hausman (1985)). This makes it possible to separately estimate the parameters of the distributon of η and ε. Given these distributions and the estimated parameters, the model yields probabilities that desired consumption will be located on each segment or kink. The (expected) consumption predicted by the model can be computed by multiplying these probabilities with the desired consumption levels conditional on each segment and kink (see Appendix A.4).

Note that although (9) implies that the variables Z, P, and Y enter linearly in consumer demand conditional on the price segment, their effect on the choice between segments is highly nonlinear. This implies, for example, that household-level price elasticities computed from the model will be conditional on the full vector Z of household characteristics. Similarly, although the first part of (9) contains a single price parameter α regardless of which price segment k_1^* the consumer chooses to consume on, this does not imply that the consumer's sensitivity to a change in the marginal price is the same regardless of which price segment changes. For example, a change in the price on segment k affects not just the optimal choice $\widetilde{w}_k$ on that segment, but also the likelihood that the consumer will choose any of the other segments or kinks. The impact of this price change on the consumer's expected consumption can be different depending on the price segment k.

5.2. *Estimation*

Maximum likelihood estimation of the parameters of the demand schedule (9) requires the explicit derivation of demand as a function of η. As is clear from (9), this requires specifying, for all kinks and segments k, the values of η for which (i) demand $\widetilde{w}_k$ corresponding to segment k is feasible, (ii) $\widetilde{w}_k$ yields higher utility than another feasible demand $\widetilde{w}_{k'}$, (iii) $\widetilde{w}_k$ yields higher utility than a kink $\bar{w}_{k'}$, and (iv) a kink $\bar{w}_k$ yields higher utility than a kink $\bar{w}_{k'}$. We obtain the following.

PROPOSITION 1: *Let* $w_k^0 = Z\delta + \alpha P_k + \gamma Y_k^0$ *and* $\theta_{jk} = \bar{w}_j - w_k^0$. (i) $\widetilde{w}_k$ *is feasible iff* $\theta_{k-1,k} < \eta < \theta_{kk}$. (ii) *For* $\widetilde{w}_k$ *and* $\widetilde{w}_l$ *feasible*, $k < l$, $V_k > V_l$ *iff* $\eta < \eta_{kl}$, *where* η_{kl} *only depends on the data and the parameters*. (iii) $V_k < \bar{U}_j$ *iff* $\eta \in (u_{jk}^L, u_{jk}^H)$, *where* u_{jk}^L *and* u_{jk}^H *are functions of the data and the parameters*. (iv) *For* $k > j$, $\bar{U}_j > \bar{U}_k$ *iff* $\eta < \bar{\eta}_{jk}$, *where* $\bar{\eta}_{jk}$ *only depends on the data and the parameters*.

For example, for the three-segment budget constraint depicted in Figure 4, Proposition 1 can be used to rewrite observed consumption (9) as[16]

$$w = \begin{cases} w_1^0 + \eta + \varepsilon & \text{if } \eta < \theta_{11} \text{ and } (\eta < \eta_{13} \text{ when } \theta_{23} < \eta), \\ \bar{w}_1 + \varepsilon & \text{if } \eta \in (\theta_{11}, \theta_{12}) \text{ and} \\ & \big(u_{13}^L < \eta < u_{13}^U \text{ when } \theta_{23} < \eta\big), \\ w_2^0 + \eta + \varepsilon & \text{if } \eta \in (\theta_{12}, \theta_{22}) \text{ and } (\eta < \eta_{23} \text{ when } \theta_{23} < \eta), \\ w_3^0 + \eta + \varepsilon & \begin{cases} \text{if } \theta_{23} < \eta \text{ and } (\eta > \eta_{13} \text{ when } \eta < \theta_{11}) \\ \text{and } \big(\eta \notin (u_{13}^L, u_{13}^U) \text{ when } \eta \in (\theta_{11}, \theta_{12})\big) \\ \text{and } \big(\eta > \eta_{23} \text{ when } \eta \in (\theta_{12}, \theta_{22})\big). \end{cases} \end{cases} \tag{10}$$

Once a distribution for η and ε is specified, Proposition 1 can be used to write down the distribution of observed consumption levels w_{it} as a function of the parameters and the data. The model can then be estimated using maximum likelihood.

Two features of the above framework make this exercise nontrivial. First, deriving the bounds for η using Proposition 1 is computationally complex. A major difficulty is performing the required comparisons subject to the feasibility conditions; for example, in part (ii), $\eta < \eta_{kl}$ is only necessary for $\widetilde{w}_k$ to be the solution if $\widetilde{w}_l$ is feasible. This difficulty arises due to the presence of a mixture of increasing and decreasing prices.

By contrast, consider the case of an everywhere-decreasing price schedule. In this case, for any extended budget segment, the unfeasible portion always lies strictly below the feasible portion of some other segment (see the extended third segment on Figure 4, which lies below the feasible portion of segment 2). Since concave kink points can never be optimal, the only conditions required for optimality are that $\widetilde{w}_k$ be feasible (as in part (i) of Proposition 1), and $\eta < \eta_{kl}$ for all l (regardless of feasibility). In this case, deriving the likelihood function simply requires computing the terms θ_{jk} and η_{kl}. The case of everywhere-increasing price schedules is even simpler. Call a kink point $\bar{w}_k$ "feasible" iff $\theta_{kk} < \eta < \theta_{k,k+1}$. (Just as in the case of $\widetilde{w}_k$, feasibility of $\bar{w}_k$ means that it is a local optimum: it provides higher utility than all consumption levels on the neighboring segments k and $k+1$.) It is easy to check that in the case of everywhere-increasing price schedules, $\widetilde{w}_k$ or $\bar{w}_k$ is the optimal solution to the consumer's problem if and only if it is feasible. In this case, deriving the Likelihood function simply requires computing the θ_{jk} terms.

The second difficulty in setting up the estimation arises from the fact that the error η affects the curvature of the indifference curves. When convexity is violated, demand may not be unique. For example, in the example in Figure 4 and (10), demand is uniquely defined only if $\theta_{11} < \theta_{12}$ or, equivalently, if $w_1^0 > w_2^0$.

[16]In the Supplemental Material, I show that, for any η, (10) uniquely defines a demanded quantity (without gaps or overlaps).

If this failed, implying non-convex preferences, for $\eta \in [\theta_{12}, \theta_{11}]$ optimal consumption could be located on the first *or* the second segment. For $w_1^0 > w_2^0$ to hold, the substitution effect of the change in price from P_1 to P_2 must not be dominated by the income effect of the extra $Y_2^0 - Y = (P_2 - P_1)\bar{w}_1$. All previous water studies that I know of simply assume that this holds. However, most of these studies use demand data either from the United States or Canada, where a typical household uses around 48 kiloliters of water per month, and spends about 0.4 percent of its monthly income on water (Mayer et al. (1999)). In contrast, in my data set the average monthly consumption is 13 kiloliters, and households spend 2–20 percent of their monthly income on water. Based on this fact, income effects might be substantial and there is no reason to expect the convexity constraint not to bind a priori.

In the framework used here, convexity can be guaranteed by performing the estimation subject to the constraint that $\gamma W + \alpha < 0$. Under (6), this is necessary and sufficient for preferences to be convex. Rewriting this constraint using (9), we get $\eta < -w_k^0 - \frac{\alpha}{\gamma}$. To guarantee that this holds for every segment, we require that $\eta < \min_k(-w_k^0) - \frac{\alpha}{\gamma}$. Note that this automatically guarantees that preferences are convex over kink points $\bar{w}_k$ for which $\bar{w}_k < w_l^0$ for all l, that is, for all the kink points at which the consumer might possibly want to consume. Since w_k^0 differs across billing periods t and consumers i, in practice I impose

$$\eta < \bar{\eta}_i \equiv \min_{tk}\left(-w_{itk}^0\right) - \frac{\alpha}{\gamma}.$$

The truncation point $\bar{\eta}_i$ differs across consumers (but is the same for a consumer in all billing cycles). I specify the distribution of η_{it} as truncated-Normal, from a Normal distribution with mean 0 and variance σ_η^2, truncated at $\bar{\eta}_i$. Appendix A.2 explains the truncation in more detail.

Truncation guarantees that demand is unique for every consumer, even for counterfactual realizations of η that would result in consumption on different segments of the budget constraint. This will allow me to perform counterfactual experiments in a consistent manner. In the literature on utilities, the only paper I know of that addresses the problem of uniqueness is the electricity demand estimation of Herriges and King (1994). However, they imposed convexity only in the neighborhood of observed consumption levels, which may lead to invalid results when performing counterfactual analysis.

To derive the likelihood function based on (10), I assume that η_{it} is i.i.d. across billing cycles t for each household. The optimization error ε_{it} is assumed to be i.i.d. across households and billing cycles and drawn independently of η_{it} from a distribution $N(0, \sigma_\varepsilon^2)$. The resulting likelihood function is given in Appendix A.3. It is continuous, but may not be everywhere differentiable in the parameters. Consistency of the MLE follows from Theorem 2′ of Manski (1988) (see the Supplemental Material for details).

Maximization of the likelihood function is implemented in MATLAB using the Nelder–Mead simplex algorithm, which can handle discontinuities in the objective function. Starting values for the maximum likelihood program are set equal to the IV parameter estimates. To make sure that the global maximum was reached, a quasi-Newton method was used to verify the parameter estimates and both methods were run from several different starting values. The covariance matrix of the parameter estimates is estimated allowing for both heteroscedasticity and correlation of error terms within a household over time. Specifically, I use the "sandwich" formula $\mathbf{H}^{-1}(\mathbf{s}'\mathbf{s})\mathbf{H}^{-1}$, where $\mathbf{H}$ is the Hessian matrix of the likelihood function and $\mathbf{s} = [\sum_t s_{it}^l]$, where s_{it}^l denotes the likelihood score around the optimal parameter vector for observation it and parameter l (both the Hessian and the scores are computed numerically). The model predicted values are computed using the formula given in Appendix A.4 for expected consumption. Standard errors for marginal effects and price elasticities are based on 100 bootstrapped samples of the same size as the estimation sample, taken with replacement. Reported standard errors are the standard deviations across these bootstraps. Because of the computational complexity, the estimation must be done on a subsample of the data. I draw a random sample of 10,000 monthly observations and the subsequent estimation is done for this sample. The Supplemental Material contains a step-by-step summary of the estimation procedure.

6. ESTIMATION RESULTS

6.1. *Marginal Effects and Price Elasticities*

This section summarizes the results from estimating the above model. I begin by discussing the estimated marginal effects and then turn to price elasticities.

Table IX in the Appendix presents the parameter estimates and corresponding marginal effects from the maximum likelihood estimation. Since the model is highly nonlinear, interpreting the effect of specific variables on expected consumption requires computing marginal effects from the parameter estimates. For continuous variables, the marginal effect is the effect of a unit increase in the variable on expected monthly consumption, holding everything else constant. To measure the marginal effect of prices, I increase all prices in the price schedule by one unit (1 Rand). For dummy variables, the marginal effect is the effect of a uniform change in the variable (from 0 to 1). These marginal effects are obtained by recalculating the model (optimal consumptions at different marginal prices with the corresponding income and the probability that the consumer will consume on that segment) for a change in each explanatory variable. For example, to obtain the effect of indigent status, I calculate expected consumption by setting this variable to 0 for every observation, then setting it equal to 1, and taking the difference. This results in household-level marginal effects, which can be averaged across households to get the average marginal effect. In the Supplemental Material, I also average these household-level effects separately for various groups (indigent/non-indigent, restricted/non-restricted). The magnitudes of the estimates seem reasonable. Having water-using sanitation increases average monthly consumption by 3.43 kl, while having a bathtub or shower in the house has an effect of +5.81 kl. To benchmark the latter effect, I note that a typical shower uses 30 liters of water, while bathing uses 90 liters. For a four-person household over 30 days, this translates to between 3.6 kl (shower) and 10.8 kl (bathing). Individuals who completed high school are estimated to use less water, all else equal.

Following the literature, I define the price elasticity under block prices as the percentage change in household consumption resulting from a one percent increase in each price block. (This allows for the possibility that a household may decide to switch consumption to a different tariff segment in response to the price changes.) Since I have zero prices in the first block in most tariff years, I change those prices from 0 to 1 Rand. Because the model is nonlinear, the price elasticity cannot be obtained directly from the price coefficient. As in the case of marginal effects, computing the price elasticity requires recalculating the model using the increased prices. Table III shows these price elasticities across all households and separately by consumer group and consumption level.

The results indicate that households respond to price changes, with an average price elasticity of −0.98. The table also highlights some differences in the price sensitivity of different groups. To interpret the magnitudes, I note that the standard deviation of the estimated household-level price elasticities in the sample is 0.45. Households with sanitation have a higher price elasticity than those without, by about half a standard deviation. This may reflect the presence of more water-using fixtures (e.g., flush toilets) and hence more possibilities for adjusting behavior, in the former group compared to the latter. Households that own a bathtub are less price sensitive, which suggests that bathtubs may proxy for income; indeed, as expected, households with above average income are less price sensitive than lower income households. I also find that indigent households are somewhat less price sensitive than non-indigent consumers, although the difference tends to be small. For all consumers, price elasticities are higher for households that use less water. One explanation of this finding is that low consumption is associated with lower income levels where the total expenditure on water is a bigger percentage of household income, and these households are therefore more price sensitive.

It is noteworthy that the price elasticities in Table III are much larger than those implied by the instrumental variables regressions in Table II. For example, the largest IV price coefficient estimate, −0.64, implies a price elasticity of −0.38 around the mean. This is in line with the discussion in Section 3.2 which suggested that in the present context the IV method may be sensitive and may not provide reliable estimates.

It is difficult to compare the elasticity measures reported above to previous estimates, as studies report a wide range of price elasticities using differ-

TABLE III

PRICE ELASTICITIES BY CONSUMER GROUPS[a]

	Consumption Quartile				
	1st (1–6 kl)	2nd (7–10 kl)	3rd (11–17 kl)	4th (18+ kl)	Overall
All	−1.022	−0.997	−0.971	−0.923	−0.976
	(0.010)	(0.009)	(0.010)	(0.008)	(0.004)
No sanitation	−0.806	−0.789	−0.762	−0.791	−0.793
	(0.008)	(0.011)	(0.016)	(0.014)	(0.006)
Sanitation	−1.084	−1.021	−0.986	−0.935	−1.000
	(0.012)	(0.009)	(0.010)	(0.010)	(0.005)
No bathtub	−1.137	−1.186	−1.186	−1.172	−1.166
	(0.011)	(0.013)	(0.016)	(0.018)	(0.008)
Bathtub	−0.838	−0.849	−0.872	−0.839	−0.851
	(0.013)	(0.009)	(0.010)	(0.011)	(0.006)
Below average income	−1.037	−1.030	−0.984	−0.957	−1.004
	(0.010)	(0.012)	(0.010)	(0.013)	(0.006)
Above average income	−0.983	−0.938	−0.954	−0.886	−0.933
	(0.019)	(0.015)	(0.015)	(0.013)	(0.007)
Indigent	−0.954	−0.964	−0.879	−0.873	−0.915
	(0.042)	(0.038)	(0.025)	(0.036)	(0.015)
Non-indigent	−1.030	−1.001	−0.984	−0.930	−0.984
	(0.010)	(0.009)	(0.011)	(0.009)	(0.005)

[a]Price elasticities reflect the percentage change in consumption in response to a 1 percent change in all marginal prices (0 prices are increased to 1 Rand). Elasticities are based on expected consumption before and after the change, computed at the household level as described in Appendix A.4, and averaged within the different consumer groups and consumption quartiles. Standard errors are based on 100 bootstrapped samples of the same size as the estimation sample, taken with replacement. Reported standard errors are the standard deviations across these bootstraps. $N =$ 10,000.

ent estimation methods and data sets. Arbues, Garcia-Valinas, and Martinez-Espineria (2003) reported reduced-form price elasticity estimates from 65 different studies, ranging from −1.64 to +0.33. Borenstein (2009) and Ito (2014) argued that consumers do not respond to marginal prices in the face of block tariffs. Structural estimates include Hewitt and Hanemann (1995), with estimates between −1.63 and −1.57, Pint (1999), who found elasticities between −1.24 and −0.04, and Olmstead, Hanemann, and Stavins (2007), who reported elasticities between −0.59 and −0.33. I know of three previous elasticity estimates for developing countries using observed consumption data. Using aggregate data, Strand and Walker (2005) found elasticities between −0.3 and −0.1 in Central American cities, and Diakite, Semenov, and Thomas (2009) reported an elasticity of −0.82 in Cote d'Ivoire. Nauges and Berg (2009) studied 1800 households in Sri Lanka and found a price elasticity of −0.15. The numbers I find tend to be on the high end of these earlier elasticity estimates from the literature. There could be several reasons for this. First, relative to

North American studies, this is a low-income population where the average household's water bill is about 7% of its income. By comparison, the average U.S. household spends less than 0.5% of its income on water (Mayer et al. (1999)), so we would expect the South African estimates to be higher.[17] Second, the South African setting differs from some previously studied developing countries in that households have a reliable water service. For example, in Strand and Walker (2005), 40% of households in the sample did not have continuous water supply; such rationing is likely to limit households' ability to respond to price changes. Third, I find that, in my setting, the IV estimates are considerably lower than those obtained from the ML model. Different estimation methods could therefore also be responsible for some of the difference relative to the previous literature.

6.2. *Model Performance*

Table IV presents actual means computed from the data and the model-predicted mean consumptions for different consumer groups. The average error is not substantial. The mean truncation point for the distribution of η is over thirty thousand, which implies that this constraint is not binding for the parameter vector that maximizes the likelihood function. The expected consumption predicted by the model is positive for all consumers.

To investigate the out-of-sample performance of the model, I use the estimated parameters to predict consumption for the 53,178 monthly observations that were not used in the estimation. Table S-X in the Supplemental Material repeats Table IV for these observations. The two tables produce very similar results; the average errors of the model's predictions are only slightly higher out of sample.

TABLE IV

MODEL PERFORMANCE[a]

	Actual mean	Predicted mean	Average error	N
All	13.353	13.071	−0.282	10,000
Indigent	13.351	13.419	0.068	1142
Non-indigent	13.353	13.026	−0.327	8858
Restricted	14.934	13.726	−1.208	1882
Non-restricted	12.986	12.919	−0.067	8118

[a]Entries in the 'Actual' and 'Predicted' columns are average household consumption levels in kl. The Predicted mean column gives the average expected consumption predicted by the model with the estimated parameter values in Table IX. Expected consumption is computed at the individual level as described in Appendix A.4. Average error is the difference between the actual and predicted means.

[17]Although Hewitt and Hanemann (1995) found very high elasticities in a U.S. data set, they attributed this to the fact that their data are from the summer months in a Texas city where lawn watering is likely to be significant.

7. ANALYZING THE FREE BASIC WATER POLICY

As mentioned in the Introduction, the optimal pricing of water is a major concern for governments and water providers throughout the developing world. What is the impact of a free water allowance, and is free water the best way to subsidize water consumption? To study these questions, I first use the estimated model to conduct a simple counterfactual experiment without free water. I then derive optimal pricing schedules from a social planner's problem.

7.1. *Counterfactual Analysis Without Free Water*

In this section, I ask what would happen to consumption and expenditure if the free water allowance was removed. Specifically, I take the estimated model, and predict consumption and expenditures for tariff years 1–6, when all consumers had a free 6 kl allowance. I then repeat this, but replacing the 0 prices with positive ones, and compare consumption and expenditure with and without free water.

One of the difficulties in analyzing a scenario without free water is to determine the unobserved positive prices which would replace the zero marginal prices. Fortunately, in the case of Odi Water, this can be done in a straightforward manner. The Free Basic Water Policy is subsidized by the central government. When the utility sets the tariff structure, it reports a positive "effective price" for the block with 0 consumer price, and this effective price forms the basis of the rebate received from the central government. Thus, according to the government, the effective prices can be interpreted as the provider's cost of providing the free water allowance. I obtained administrative data on the effective prices. Depending on the tariff year, effective prices range from 4.00–5.07 Rand for consumers with no sanitation, and 10.40–12.10 Rand for consumers with sanitation. These values are close to the first nonzero marginal prices on the tariff schedule (the second tariff block). I conduct the counterfactual experiment by replacing zero prices in the data set with these prices.[18]

Table V shows the results of the counterfactual exercise where zero prices are replaced with the effective price the utility reports to the government. Note that the change in consumption is computed keeping everything else constant. Specifically, the marginal prices of the different segments were left intact, which also means that the size of the cross-subsidies among different groups of consumers is unchanged.

In this counterfactual experiment, average consumption decreases only slightly, by less than 0.1%, even though the associated expenditure on water

[18] I only use observations from 2002–2007 for this exercise. Since after 2007 some consumers received no free water while others received 12 kl for free, the counterfactual exercise I study would have different implications for this period. Note that the counterfactual exercise described here is different from the actual 2007 policy change where free water was taken away from a large number of households but the rest of the price schedule was also changed substantially.

TABLE V

HOUSEHOLD CONSUMPTION AND EXPENDITURE CHANGES WITHOUT FREE WATER[a]

	All	Indigent	Non-Indigent	Restricted	Non-Restricted
Consumption (kl/month)					
With free water	13.307	13.408	13.293	13.826	13.183
Without free water	13.296	13.400	13.283	13.819	13.172
Change (%)	−0.077	−0.058	−0.079	−0.054	−0.082
Expenditures (Rand/month)					
With free water	77.337	80.140	76.971	85.033	75.506
Without free water	140.453	147.335	139.554	152.425	137.604
Change (%)	81.612	83.847	81.307	79.254	82.242

[a]Values reported are the model-predicted values using either the actual water tariffs ("With free water"), or the counterfactual tariffs where 0 prices were replaced with the provider's accounting prices ("Without free water"). Expected consumption is computed at the individual level as described in Appendix A.4, and averaged within the different consumer groups in each column. Expenditure is average household water spending (in 2008 Rand). $N = 7309$ (observations after the 2007 policy change are excluded from both the actual and the counterfactual computations).

increases by 81.6% on average. This is true both overall as well as for specific consumer groups. The lack of a large consumption effect may seem surprising given consumers' high price elasticity found above. However, recall that price elasticity was measured by increasing all prices along the tariff schedule. By contrast, the no-free-water counterfactual only increases prices on the first block. Thus, we would only expect a significant reduction in consumption if the expected consumption predicted by the model was within the free allowance for a substantial number of households. If this is not the case, then removing the free allowance only affects prices that are "inframarginal" from consumers' point of view. That is, it does not directly affect the price on the segment they are planning to consume on. As long as the income effect is small, there should not be large reductions in expected consumption.

With the estimated parameters, the model indeed predicts that expected consumption should be above the free allowance for most consumers. Although the model does allow for consumer satiation, the satiation points implied by the parameter estimates are above 6 kl for the overwhelming majority of consumers. Thus, optimizing consumers would not plan on consuming strictly within the free allowance and, with the estimated parameters, observations within the free allowance are instead explained by the optimization error ε. This implies that, by itself, the free water allowance acts like an inframarginal (lump-sum) cash subsidy to the households.

This finding suggests that subsidizing households in the form of free water might be an efficient (non-distortionary) policy in this environment. Whether this is the case requires comparing this policy to the optimal policy that a social planner would choose. For example, is it possible to achieve higher welfare if the same subsidy is distributed more evenly across the different segments of the price schedule? I turn to this issue below.

Clearly, care should be taken in generalizing the finding that free water has no effect on consumption, as specifics of the policy are likely to be important. For example, changing the magnitude of the subsidy would affect consumption. In the Supplemental Material, I present various alternative counterfactuals, where the free allowance is replaced with larger marginal prices. A counterfactual exercise using 30, 60, or 90 percent higher effective prices on the first block would yield, respectively, a 6.8, 25.3, or 71.1 percent reduction in mean consumption.

7.2. *The Social Planner's Problem*

In this section, I consider the problem of a social planner choosing the tariff schedule. I assume that the planner's goal is to maximize total consumer welfare subject to different profitability constraints for the provider. First, I estimate the marginal cost of water and impose the constraint that the provider's profit under the optimal tariff schedule should not be lower than under the current prices. Later, I consider a more stringent set of constraints that prevents total consumption from rising and the provider's revenue from falling. Based on my conversation with Odi Water officials, these types of profitability conditions are important feasibility considerations in the present context.

Because of the random taste parameters η_{it}, consumer welfare in a given year is a random variable. The optimal tariff will be one which maximizes the expected welfare of consumers subject to the profitability constraints holding in expectation. Denote the current total revenue with $\bar{R} = \sum_{i=1}^{I} \int_0^{w_i^*(P^0(\cdot))} P^0(w)\,dw$, where I is the number of consumers and $P^0(w)$ is the currently observed price schedule. Similarly, let current total consumption be $\bar{C} = \sum_{i=1}^{I} w_i^*(P^0(\cdot))$. Let F_i denote the c.d.f. of η_i and E the expectation operator over $(\eta_1, \dots, \eta_I)$. The objective of the social planner is

$$\max_{P(\cdot)} E\left[\sum_{i=1}^{I} U_i(w, x)\right] = \sum_{i=1}^{I}\left[\int_{-\infty}^{\bar{\eta}_i} U_i\big(w_i^*\big(P(\cdot), \eta_i\big), x^*\big(P(\cdot), \eta_i\big)\big)\,dF(\eta_i)\right]. \tag{11}$$

As above, $F_i(\eta)$ is assumed to be truncated-Normal, where the truncation $\bar{\eta}_i$ depends on individual consumer characteristics. For example, for the case of two price segments with $P_1 > P_2$, each term in (11) can be written as

$$\int_{-\infty}^{\theta_{11}} V_i(P_1, Y)\,dF(\eta_i) + \int_{\theta_{11}}^{\theta_{12}} U_i(\bar{w}_1, Y - P_1\bar{w}_1)\,dF_i(\eta_i) + \int_{\theta_{12}}^{\bar{\eta}_i} V_i\big(P_2, Y_2^0\big)\,dF_i(\eta_i). \tag{12}$$

Here, the three terms correspond to the utility the consumer achieves from consuming on the first segment, the kink, or the second segment, respectively.

I consider the problem of maximizing (11) subject to the following "profit neutrality" constraint:

$$\sum_{i=1}^{I} E\left[\int_0^{w_i^*(P(\cdot),\eta_i)} P(w)\,dw - b w_i^*\big(P(\cdot),\eta_i\big)\right] \geq \bar{R} - b\bar{C}, \tag{13}$$

where b is the marginal cost of water. I compute b in two alternative ways, the details of which are in the Supplemental Material. In the first case, b is the price of the bulk water purchased by Odi Water from a national bulk water supplier. In the second case, I also include in b some of the operational expenses reported by the provider. The first calculation yields 4 Rand per kiloliter, the second 8.2 Rand per kiloliter. Results in the main text are computed using the higher marginal cost value, and the Supplemental Material presents the corresponding results using the lower value.

As an alternative to the above formulation, I replace the constraint (13) by a "capacity" and a "revenue neutrality" constraint:

$$\sum_{i=1}^{I} E\big[w_i^*\big(P(\cdot),\eta\big)\big] \leq \bar{C}, \tag{14}$$

$$\sum_{i=1}^{I} E\left[\int_0^{w_i^*(P(\cdot),\eta_i)} P(w)\,dw\right] \geq \bar{R}.$$

The revenue neutrality constraint says that the water provider should obtain at least the same revenue as under the current price scheme (assuming risk neutrality), while the capacity constraint states that the new tariff structure should not increase the total consumption above its current level. This formulation is useful for several reasons. First, it imposes a more stringent set of constraints, ensuring that costs do not rise while revenues do not fall under the alternative price schedules. This may be advantageous for practical feasibility. Second, the constraints in (14) do not require estimating the marginal cost of water provision. Third, welfare maximization under a capacity constraint is an interesting exercise because it implies that the possible welfare changes come from the reallocation of the current consumption and payments across consumers, rather than from increased consumption.[19]

Using the parameter estimates together with the functional forms in (6) and (7) and the distribution of η, numerical maximization of (11) subject to (13) or

[19]Note that in general, the revenue and capacity constraints are difficult to satisfy simultaneously unless demand is very inelastic. Since we found this not to be the case in the present context, it is far from obvious a priori that the existing price schedule can be improved upon.

(14) is straightforward. Note that the social welfare function (11) assumes that each household receives equal weight in the planner's problem. Rather than assuming different arbitrary weights, I will present the change in welfare separately for various consumer groups. This can be used to evaluate the welfare impact of the proposed tariffs under any weighted Utilitarian social welfare function.

An important consideration missing from either formulation of the planner's problem is the health effects of water. With detailed information on the health risks associated with consuming specific quantities of clean water, it would be possible to quantify the health implications of actual price schedules as well as those of the tariffs derived from the social planner's problem. Clearly, the valuation of these effects, including the externalities associated with any diseases, is important to assess the overall welfare implications of water pricing policies. However, I am unaware of measures that could be applied in this context.[20] Thus, the tariffs I refer to as "optimal" simply maximize consumer utility derived directly from water consumption and they do not include health effects. In this sense, my results regarding the impact of tariffs on consumption are a first step toward establishing the social value of these pricing policies.

7.3. *Optimal Tariffs*

First, I consider optimal tariff schedules relative to a situation where the government subsidy to the provider covers the provision of free basic water to all households (as was the case under the original Free Basic Water policy before 2007). Thus, I set consumption ($\bar{C}$) and revenue ($\bar{R}$) equal to their actual 2006/2007 values in the profit neutrality constraint (13). This helps answer the question whether passing along the government subsidy to households in the form of universal free basic water is the most efficient policy. I consider both an "unrestricted" tariff schedule where all marginal prices are set optimally, as well as a schedule where indigent households receive 6 kl for free (in line with the revealed policy preference of the post-2007 period).[21]

To keep the exercise computationally feasible, I keep the same kink points as in the actual tariff and require that marginal prices be non-decreasing (as in the actual water tariff without sanitation). Note that this allows for a wide range of schedules: any schedule with at most seven blocks, with one or more

[20]While a large literature in economics and epidemiology discusses the health effects of *access* to clean water (see Zwane and Kremer (2007) for a survey), I am not aware of any estimates on the health impacts of marginal increases of clean water consumption. These effects seem particularly hard to measure, especially at the relatively high levels of water use characterizing my sample.

[21]I ignore households without sanitation, since they have a separate water schedule without sanitation prices. The calculations below are performed for all households with survey data in the given tariff years. The number of observation is 8385 for tariff year 2006/2007 and 5660 for tariff year 2008/2009.

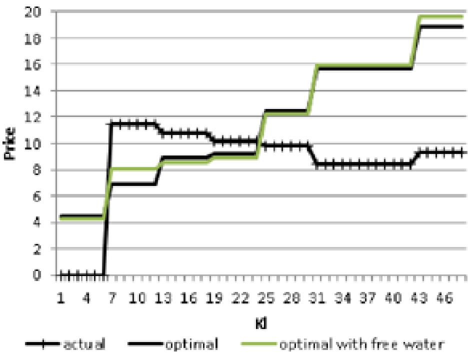

FIGURE 5.—Optimal and actual 2006/2007 tariff schedules. *Notes*: The figure shows the actual 2006/2007 tariff and the corresponding optimal tariffs with and without 6 kl free water for indigent households. The marginal cost is set to 8.2 Rand. The "optimal with free water" schedule shown is for non-indigent households.

kinks at any of the six kink points considered here. This includes, for example, a uniform price (where all marginal prices are the same), or a two-block schedule with a kink point at either 6, 12, 18, 24, 30, or 42 kl. Thus, while establishing whether the optimal tariffs considered here provide the highest welfare over the set of *all* price schedules is not computationally feasible, the problem considered here does allow for a reasonably large set of tariff schedules.

The 2006/2007 optimal tariff structures are shown in Figure 5 along with the actual tariff (highlighted with markers). The dark line is the optimal unrestricted tariff schedule, while the lighter line is the optimal price schedule for non-indigent households when indigent households receive free 6 kl and face the same schedule thereafter.[22] In contrast to the current tariff schedule, the prices in the optimal schedules are lower in the first three blocks and higher in upper blocks. The welfare-maximizing price schedule involves no free water. Instead, consumers pay a low positive marginal price for the first kiloliters and a price for the second block that is substantially lower than under the actual schedule. This encourages a higher consumption for consumers who use low amounts of water. The intuition for this is twofold. First, without a large price jump between the first and second blocks, there is no important incentive for households to reduce consumption in order to stay below the free allowance. Second, removing the free water allows a large price decrease on the second block, where the modal consumption is located. The magnitude of this decrease is between 30% (when free water is retained for indigent households) and 40% (when all free water can be removed). This price decrease further encourages an increase in low end consumption.

[22]For the sake of clarity, in this case the indigent tariff is not shown on the figure. It is identical to the non-indigent tariff, except for a price of 0 for the first 6 kl. Optimal tariffs under the lower marginal cost are very similar (see Supplemental Material).

Under the optimal tariffs, marginal prices starting from the fourth block (where quantity consumed is over twice the mean) show large price increases. The intuition behind this is that high marginal prices generate more revenue which pays for the decrease in prices on the lower blocks. The graph also shows that the 6 kl free water for indigent households can be reinstated by increasing the second block price slightly without changing the main characteristics of the tariff structure.

Next, I consider optimal tariffs relative to the post-2007 period, when free water provision was focused on the indigent households. As mentioned above, this policy change substantially increased the utility's revenue (and reduced the government subsidy). Here, I set consumption and revenue equal to their actual 2008/2009 values. As before, I consider both a tariff schedule where all marginal prices are set optimally, as well as a schedule where indigent households receive 6 kl for free.

Optimal and actual 2008/2009 tariffs are shown on Figure 6. Relative to the actual tariff schedule, the optimal tariffs exhibit similar features as those discussed above for the 2006/2007 benchmark. In particular, for the majority of households, prices should be reduced for the lower blocks and increased for the higher blocks. Using the lower marginal cost again yields broadly similar patterns: the main difference is that the lower marginal cost allows for lower prices on the highest segments (see Supplemental Materail). Note that on the first four segments, where over 85% of observed consumption is located, the actual 2008/2009 tariffs are much closer to the optimal tariff than is the case for 2006/2007 tariffs. In this sense, the policy change implemented in 2007 may have moved the tariff schedule closer to the optimal (this is confirmed by the welfare analysis below).

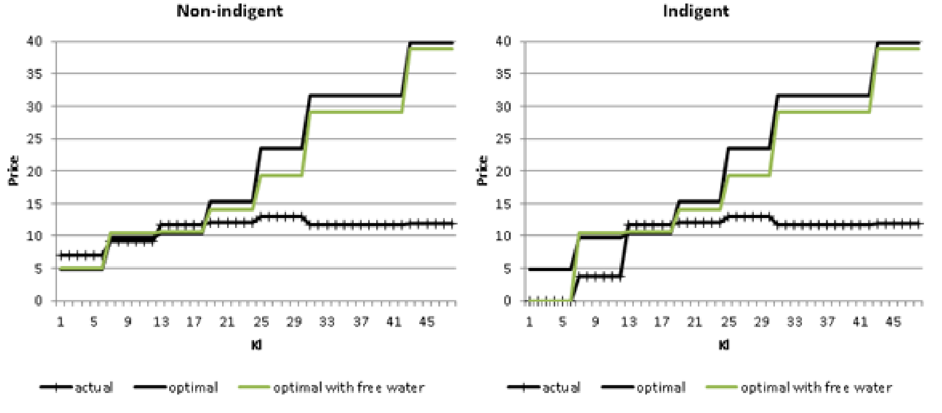

FIGURE 6.—Optimal and actual 2008/2009 tariff schedules. *Notes*: The figure shows the actual 2008/2009 tariff and the corresponding optimal tariffs with and without 6 kl free water for indigent households. The marginal cost is set to 8.2 Rand.

7.4. *Compensating Variation*

To quantify the gain in consumer welfare that can be achieved as a result of the optimal tariff schedules derived above, I calculate the compensating variation. This is the change in a consumer's income that equates utility under the actual (2006/2007 or 2008/2009) price schedule and expected utility under the optimal price schedule. For example, for two price segments, (12) implies that the compensating variation CV_i for consumer i is defined implicitly by

$$\begin{aligned} U_0 = &\int_{-\infty}^{\theta_{11}} V_i(P_1, Y + CV_i)\, dF(\eta_i) \\ &+ \int_{\theta_{11}}^{\theta_{12}} U_i(\bar{w}_1, Y + CV_i - P_1\bar{w}_1)\, dF_i(\eta_i) \\ &+ \int_{\theta_{12}}^{\bar{\eta}_i} V_i\big(P_2, Y_2^0 + CV_i\big)\, dF_i(\eta_i), \end{aligned}$$

where U_0 is the baseline utility level under the current prices. A negative value of CV_i indicates that the consumer is better off than under the baseline, while a positive value of CV_i indicates that he is worse off.

Table VI shows the compensating variation achieved by the above tariff schedules (with or without free water for indigent households) relative to the respective 2006/2007 or 2008/2009 benchmark. The table presents the mean and median of the household-level compensating variation both overall and in specific consumer groups. In the Supplemental Material, I also compute the corresponding expenditure changes. For the "unrestricted" 2006/2007 optimal prices, the welfare gains would be very similar among groups, with a median gain of 6.6 Rand each month. Over a year, this would mean a saving approximately equal to a typical monthly water bill. When the marginal cost of water is set lower, the optimal tariff results in a threefold increase in the welfare gains (see Supplemental Material). The second column of Table VI shows that welfare gains are possible even when the 6 kl free water is kept in place for indigent households. Relative to the unrestricted optimal tariff, this tariff yields a substantial median welfare gain for indigent households ($28.48 - 6.27 = 22.21$ Rand per month) at a cost of only 3.19 Rand ($= 6.62 - 3.43$) for the median non-indigent household.

The negative compensating variation that can be achieved relative to the universal free water policy of 2006/2007 shows that welfare can be improved by removing the free allowance for all households. In this sense, the 2007 policy change that removed the free allowance for the majority of households can be considered a step in the right direction. However, as Table VI shows, considerable welfare improvement is possible by making further changes to the tariff schedule relative to the 2008/2009 benchmark. In particular, under the optimal schedule without free water, the median compensating variation is 12.54 Rand

TABLE VI

COMPENSATING VARIATION UNDER THE OPTIMAL TARIFFS (MEAN/MEDIAN)[a]

	2006/2007 Optimal Tariff			2008/2009 Optimal Tariff		
	Without Free Water	With Free Water	*N*	Without Free Water	With Free Water	*N*
Compensating variation						
All	−3.98/−6.59	−3.61/−5.00	8385	−1.96/−12.54	−1.04/−7.51	5660
Indigent	−3.75/−6.27	−25.66/−28.48	1021	61.59/61.79	37.35/37.61	877
Non-indigent	−4.01/−6.62	−0.55/−3.43	7364	−13.62/−12.79	−8.09/−8.07	4783
Consumption						
Consumption (kl)	15.87/16.57	16.04/17.02	8385	13.36/14.11	12.85/13.87	5660
Low consumption (%)	19.11	15.56	–	41.27	41.48	–
Medium consumption (%)	49.48	49.83	–	58.66	58.52	–
High consumption (%)	31.41	34.61	–	0.07	0.00	–
Actual consumption						
Consumption (kl)	13.36/14.49		8385	12.76/12.60		5660
Low consumption (%)	55.60		–	65.44		–
Medium consumption (%)	21.13		–	17.91		–
High consumption (%)	23.27		–	16.75		–

[a]The top part of the table reports the compensating variation corresponding to the optimal tariffs. If the provider switched from the actual (2006/2007 or 2008/2009) tariff to the optimal tariff, this is the change in income that would leave a consumer as well off as he was before the switch. Negative numbers indicate an increase in consumer utility from the switch. In each cell, the first entry is the mean, the second entry is the median compensating variation. All entries are in 2008 Rand. The middle part of the table shows consumption under the different optimal tariff schedules, including the fraction consuming Low (0–12 kl), Medium (12–18 kl), or High (above 18 kl) quantities. The bottom part of the table shows the corresponding consumption values under the actual tariff schedules observed in the data (2006/2007 and 2008/2009).

per month, which is more than the price of 1 kiloliter of water and equal to about 13% of the average monthly expenditure on water. Over a year, the median savings is about 3.5 percent of monthly household income. Since indigent households currently receive 12 kiloliters of water for free, the welfare change is negative for them under the optimal tariffs.

Table VI also shows the distribution of consumption under the actual and optimal tariff structures. It is noteworthy that the optimal tariff schedules substantially reduce the proportion of low consumers (below 12 kl, the current free allowance for indigent households). For the 2006/2007 tariff year, the reduction is 35–40 percentage points relative to the corresponding actual schedule, while for 2008/2009, it is around 24 percentage points. This is in line with the stated WHO policy of increasing clean water consumption among households on the low end of the distribution (World Health Organization (2003)). Another desirable feature of the 2008/2009 optimal tariffs is to promote conservation on the high end of the distribution by increasing the marginal price on these blocks.

7.5. *Separate Tariffs for Indigent and Non-Indigent Households*

The provider's more recent pricing policy indicates a desire to treat indigent and non-indigent households separately. To better understand the welfare impacts of these tariffs, I now derive separate optimal tariffs for the non-indigent and indigent groups. Specifically, I compute the provider's profit from each group separately, and solve the planner's problem restricting attention to the given group. Note that this keeps in place the indigent group's current subsidy, which is paid by non-indigent households in order to finance the free water allowance for the indigent group (currently, indigent households account for 16% of total consumption but pay only 5% of the provider's revenue). The exercise asks whether there is a better allocation of this subsidy along the tariff schedule; it does not say anything about the desirability of having the subsidy to begin with.

The resulting tariffs are shown on Figure 7. The tariff on the left hand panel is the non-indigent group's optimal tariff subject to the provider obtaining at least as much profit from this group as it currently does. The tariff on the right hand panel is the indigent group's optimal tariff under a similar constraint. The fist column of Table VII shows the corresponding compensating variation and consumption that would result.

As in the previous cases, the welfare-maximizing tariff does not include free water. For non-indigent households, the optimal schedule again features higher prices for large consumption, which allows the prices on lower segments to decrease. As shown in Table VII, using this schedule it is possible to provide higher welfare to the non-indigent group even if pricing for indigent households is kept unchanged. For indigent households, gradually increasing tariffs also increase welfare compared to the actual prices with free water. This is possible because under the current prices, this group pays a small fraction of the

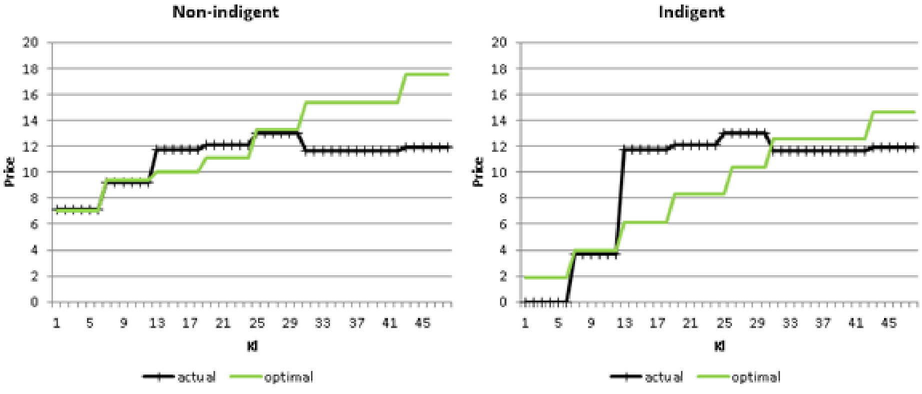

FIGURE 7.—Separate optimal and actual 2008/2009 tariff schedules for non-indigent and indigent households. *Notes*: The figure shows the optimal and actual 2008/2009 tariff when the social planner sets the tariff for the non-indigent group only (left hand side) or the indigent group only (right hand side). Optimal tariffs maximize welfare subject to a profit neutrality constraint for the given group. The marginal cost is set to 8.2 Rand.

TABLE VII

COMPENSATING VARIATION AND CONSUMPTION UNDER INDIGENT-ONLY AND NON-INDIGENT-ONLY OPTIMAL TARIFFS[a]

	Separate Tariffs for Indigent and Non-Indigent	Optimal Tariffs Under Revenue and Capacity Constraints		N
		Without Free Water	With Free Water	
Compensating variation				
All	−2.73/−2.03	−0.40/−11.88	−0.94/−7.41	5660
Indigent	−2.66/−7.14	63.52/63.14	37.69/38.01	877
Non-indigent	−2.74/−2.00	−12.05/−12.04	−8.03/−8.03	4783
Consumption (kl)				
All	14.17/14.69	12.76/13.00	12.76/13.74	5660
Indigent	16.63/18.00	12.72/12.99	12.64/13.74	877
Non-indigent	13.72/14.75	12.77/13.00	12.79/13.74	4783

[a]The first column reports the compensating variation corresponding to the indigent-only and non-indigent-only optimal tariffs, as well as the consumption resulting from these tariffs. If the provider switched from the actual (2008/2009) tariff to the optimal tariff for the given group, the compensating variation is the change in income that would leave a consumer in this group as well off as he was before the switch. Negative numbers indicate an increase in consumer utility from the switch. The second and third columns show the compensating variation and consumption corresponding to the optimal tariffs under revenue and capacity constraints. If the provider switched from the actual (2006/2007 or 2008/2009) tariff to the optimal tariff, the compensating variation is the change in income that would leave a consumer as well off as he was before the switch. In each cell, the first entry is the mean, the second entry is the median. Compensating variation entries are in 2008 Rand.

provider's revenue. The gradually increasing price schedule shown on Figure 7, in contrast to the actual prices that feature a large jump after the second segment, gives consumers an incentive to use more water. The resulting increase in consumption leads to higher welfare (Table VII).

7.6. *Optimal Tariffs Under Revenue and Capacity Constraints*

In this section, I consider strengthening the feasibility constraint on the welfare-maximizing tariffs by replacing the profit neutrality constraint (13) with the capacity and revenue neutrality constraints in (14). This exercise asks the question whether the current water pricing can be improved upon without increasing total consumption *and* without lowering the provider's revenue.

The optimal tariff schedules resulting from the planner's problem in this case are shown in Figure 8. This shows a similar pattern to the optimal prices derived above, with non-indigent households receiving lower prices on the low segments than their current prices, and much higher prices on the upper segments. Compensating variation and consumption under these tariff schedules are given in the second and third columns of Table VII. Even under these stricter constraints, total consumer welfare can be improved relative to the current prices. Given the capacity constraint, this increase in welfare is achieved solely by redistributing the current water subsidy without an increase in total consumption. The detailed distribution of consumption and changes in expenditure under these optimal tariff schedules are reported in the Supplemental Material. In particular, these tariffs also generate a reduction in both the fraction of very low and very high consumers.

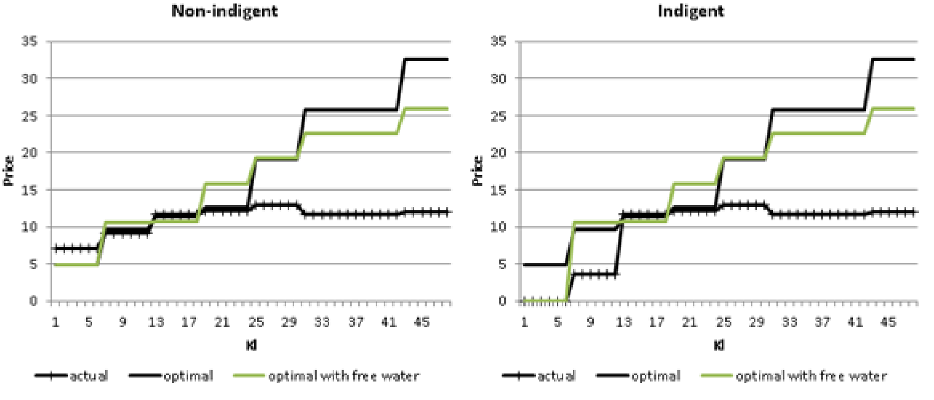

FIGURE 8.—Optimal and actual 2008/2009 tariff schedules under capacity and revenue neutrality constraints. *Notes*: The figure shows the actual 2008/2009 tariff and the corresponding optimal tariffs with and without 6 kl free water for indigent households. Optimal tariffs maximize welfare subject to revenue neutrality and a capacity constraint.

In summary, there exist price schedules capable of raising social welfare relative to the actual prices while satisfying different profitability constraints for the provider. In addition, these schedules appear to move the distribution of consumption levels in a desirable direction.

8. CONCLUSION

This paper analyzes the welfare effects of free water using the South African Free Basic Water Policy. It provides a comprehensive demand estimation under nonlinear prices with increasing and decreasing segments, and derives optimal pricing schedules using these estimates. The results are based on a large administrative data set of household-level observations on a low-income population. This is complemented with survey data, and features rich price variation over the period of study.

To study the Free Basic Water policy, I first conduct a counterfactual exercise, replacing zero prices from 2002–2009 with the effective prices the provider reports to the government, holding everything else constant. I find that consumption does not change substantially, suggesting that in this environment, the free water allowance acts as a lump-sum cash transfer to indigent households. To study whether this is efficient, I derive optimal price schedules from a social planner's problem. I find that the optimal tariff schedule does not contain zero marginal prices, but rather divides the government subsidy more evenly across blocks. Under the Free Basic Water policy, zero prices on the lowest quantities are subsidized by higher prices for remaining consumption, even at low levels. To obtain enough revenue, the provider charged very high prices for consumption between 6 and 12 kl, where many consumers were located. Welfare can be improved if, instead of this, positive prices are charged on all consumption. In fact, removing the free allowance can improve welfare even for the indigent households, who were likely the target of the free water policy to begin with. The gradually increasing seven-tier tariff structure I derive also reduces the percentage of households consuming low quantities of water, which is a desirable policy goal according to the World Health Organization.

Under block prices, economic theory suggests that consumers should take into account the marginal prices on different segments. However, some empirical studies find that consumers respond to average prices or total expenditure rather than marginal prices. The data used here provide evidence that in a setting where spending on water is a large fraction of their income, consumers are responsive to marginal prices even in the face of complicated price schedules. From a policy perspective, this suggests that complex prices are an effective tool to regulate consumption in this context.

APPENDIX

A.1. *Proof of Proposition 1*

(i) This follows directly from the definition of feasibility.

(ii) Using (7),

$$V_k > V_l \quad \text{iff} \quad \eta < \eta_{kl} \equiv \frac{\gamma\left(V_k^0 - V_l^0\right)}{e^{-\gamma p_l} - e^{-\gamma p_k}}, \quad \text{where}$$

$$V_k^0 = e^{-\gamma p_k}\left(Y_k^0 + \frac{\alpha}{\gamma}P_k + \frac{\alpha}{\gamma^2} + \frac{Z\delta}{\gamma}\right).$$

(iii) Direct utility (6) is increasing and concave in η while indirect utility (7) is increasing and linear. Therefore the equation $\bar{U}_j - V_k = 0$ has at most two roots. When it has fewer than two, $\bar{U}_j \geq V_k$ for all values of η. When it has two, $\bar{U}_j > V_k$ iff $\eta \in (u_{jk}^L, u_{jk}^H)$, where u_{jk}^L and u_{jk}^H are the roots.

(iv) Using (6),

$$\begin{aligned} &\bar{U}_j > \bar{U}_k \quad \text{iff} \\ &\eta < \bar{\eta}_{jk} \\ &\quad \equiv \left(\frac{1}{\gamma}\ln\left(\frac{\gamma\bar{w}_j + \alpha}{\gamma\bar{w}_k + \alpha}\right) + \frac{\gamma Y_j^0 - \bar{w}_j(1+\gamma P_j) + Z\delta}{\gamma\bar{w}_j + \alpha}\right. \\ &\qquad \left. - \frac{\gamma Y_k^0 - \bar{w}_k(1+\gamma P_k) + Z\delta}{\gamma\bar{w}_k + \alpha}\right) \Big/ \left(\frac{1}{\gamma\bar{w}_k + \alpha} - \frac{1}{\gamma\bar{w}_j + \alpha}\right). \end{aligned}$$

A.2. *Truncation*

For a demanded quantity W^*, the utility function in (6) is quasi-concave around W^* only if

$$\gamma W^* + \alpha < 0.$$

If this fails, demand may not be uniquely defined for a given set of parameter values, and we cannot proceed with the estimation. Assume that demanded quantity falls on segment k: $W^* = w_k^0 + \eta$. Then demand is unique iff $\eta < -w_k^0 - \frac{\alpha}{\gamma}$. To guarantee that this holds for every segment, we require that $\eta < \min_k(-w_k^0) - \frac{\alpha}{\gamma}$. Note that this automatically guarantees that preferences are convex over kink points $\bar{w}_k$ for which $\bar{w}_k < w_l^0$ for all l, that is, for all the kink points at which the consumer might possibly want to consume. Since w_k^0 differs across billing periods t and consumers i, in practice I impose

$$\eta < \bar{\eta}_i \equiv \min_{tk}\left(-w^0_{itk}\right) - \frac{\alpha}{\gamma}. \tag{15}$$

The truncation point $\bar{\eta}_i$ differs across consumers (but is the same for a consumer in all billing cycles). As is clear from (15), restricting the distribution of η is the only way to guarantee that demand is uniquely defined for all possible realizations of the data. For example, if η has full support on $(-\infty, +\infty)$, (15) will fail with positive probability for any $-\frac{\alpha}{\gamma} < \infty$.

There are several options for choosing the distribution of η_i to be consistent with (15). The most natural extension of the previous literature, and one that makes computation of the likelihood function tractable, is to let η_i be drawn from a truncated normal distribution with truncation point $\bar{\eta}_i$ for each consumer. To economize on the number of parameters to be estimated, I assume that the un-truncated "parent" distribution of η_i is the same for everyone: $N(0, \sigma^2_\eta)$. Denoting ϕ and Φ the standard normal density and c.d.f., respectively, this yields the following specification of the c.d.f., p.d.f., mean, and variance of η_i:

$$F_{\eta_i}(x) = \Phi\left(\frac{x}{\sigma_\eta}\right) \Big/ \Phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right) \quad \text{if} \quad x < \bar{\eta}_i, \quad 1 \quad \text{otherwise}, \tag{16}$$

$$f_{\eta_i}(x) = \phi\left(\frac{x}{\sigma_\eta}\right) \Big/ \left[\Phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right)\sigma_\eta\right] \quad \text{if} \quad x < \bar{\eta}_i, \quad 0 \quad \text{otherwise}, \tag{17}$$

$$E(\eta_i) = -\phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right) \Big/ \left[\Phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right)\right]\sigma_\eta, \tag{18}$$

$$\operatorname{Var}(\eta_i) = \sigma^2_\eta \left[1 - \frac{\phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right)}{\Phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right)} \left(\frac{\bar{\eta}_i}{\sigma_\eta} + \frac{\phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right)}{\Phi\left(\frac{\bar{\eta}_i}{\sigma_\eta}\right)}\right)\right]. \tag{19}$$

A.3. *Likelihood Function*

Let $\nu = \eta + \varepsilon$ and let F_x and f_x denote, respectively, the c.d.f. and p.d.f. of the random variable x. Based on (10), for each observed monthly consumption level W, the contribution to the likelihood may be written as

$$\begin{aligned} &\sum_k f_\nu\left(W - w^0_k\right)\left[F_{\eta|\nu=W-w^0_k}(H_k) - F_{\eta|\nu=W-w^0_k}(L_k)\right] \\ &\quad + \sum_k f_\varepsilon(W - \bar{w}_k)\left[F_\eta(h_k) - F_\eta(l_k)\right]. \end{aligned} \tag{20}$$

The first sum in (20) is the probability that W is observed given that desired consumption was located on one of the segments $k = 1, 2, \ldots$. Each term in the sum is the density of ν at $W - w_k^0$ times the probability that desired consumption was located on segment k: H_k and L_k are the upper and lower bounds of η for which this is the case. The second sum is the probability that W is observed given that desired consumption was at one of the kink points $k = 1, 2, \ldots$. h_k and l_k are the bounds on η corresponding to kink k. The log-likelihood function is the sum, for each observed monthly consumption level W, of the logarithms of the corresponding expressions (20).

Terms in the second sum in (20) corresponding to the kink points may be rewritten using (16) and the fact that

$$f_\varepsilon(W - \bar{w}_k) = \phi\left(\frac{W - \bar{w}_k}{\sigma_\varepsilon}\right)\frac{1}{\sigma_\varepsilon} \tag{21}$$

since $\varepsilon \sim N(0, \sigma_\varepsilon^2)$. For the first sum in (20) corresponding to the segments, we need to find f_ν and $F_{\eta|\nu}$. To find f_ν, use the convolution of f_ε in (21) and f_η in (17) to get

$$\begin{aligned} f_\nu(x) &= \int_{-\infty}^{\bar{\eta}} f_\varepsilon(x - \eta) f_\eta \, d\eta \\ &= \int_{-\infty}^{\bar{\eta}} \phi\left(\frac{x-\eta}{\sigma_\varepsilon}\right)\phi\left(\frac{\eta}{\sigma_\eta}\right) d\eta \frac{1}{\sigma_\eta \sigma_\varepsilon \Phi\left(\frac{\bar{\eta}}{\sigma_\eta}\right)}. \end{aligned}$$

After some algebra, this can be shown to equal

$$\Phi\left(\frac{\bar{\eta}/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{x}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right)\frac{\phi\left(\frac{x}{\sigma_\nu}\right)}{\sigma_\nu \Phi\left(\frac{\bar{\eta}}{\sigma_\eta}\right)},$$

where $\sigma_\nu = \sqrt{\sigma_\eta^2 + \sigma_\varepsilon^2}$ and $\rho = \frac{\sigma_\eta}{\sigma_\upsilon}$.

To find $F_{\eta|\nu}$, use the fact that if for two random variables x_1 and x_2,

$$x_1, x_2 \sim N\left[\begin{matrix}\mu_1 \\ \mu_2\end{matrix}, \Sigma = \begin{bmatrix}\sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2\end{bmatrix}\right],$$

then

$$x_1|_{x_2=a} \sim N(\bar{\mu}, \bar{\sigma}^2),$$

where

$$\bar{\mu} = \mu_1 + \frac{\sigma_{12}}{\sigma_2^2}(a - \mu_2),$$

$$\bar{\sigma}^2 = \sigma_1^2 - \frac{\sigma_{12}^2}{\sigma_2^2}.$$

Assume for a moment that η is not truncated, that is, $\eta \sim N(0, \sigma_\eta)$. Since $v = \eta + \varepsilon$, we then have $\eta|\nu \sim N(\rho^2\nu, \sigma_\varepsilon^2\rho^2)$. Truncating this distribution at $\bar{\eta}$ gives

$$F_{\eta|\nu}(x) = \Phi\left(\frac{x/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{\nu}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right) \Big/ \Phi\left(\frac{\bar{\eta}/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{\nu}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right).$$

To summarize, for each observed monthly consumption level W, the contribution to the likelihood (20) is

$$\sum_k \frac{\phi\left(\frac{W - w_k^0}{\sigma_\nu}\right)}{\sigma_\nu \Phi\left(\frac{\bar{\eta}}{\sigma_\eta}\right)} \left[\Phi\left(\frac{H_k/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{W - w_k^0}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right) - \Phi\left(\frac{L_k/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{W - w_k^0}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right)\right] + \sum_k \frac{\phi\left(\frac{W - \bar{w}_k}{\sigma_\varepsilon}\right)}{\sigma_\varepsilon \Phi\left(\frac{\bar{\eta}}{\sigma_\eta}\right)} \left[\Phi\left(\frac{h_k}{\sigma_\eta}\right) - \Phi\left(\frac{l_k}{\sigma_\eta}\right)\right]. \tag{22}$$

A.4. *Expected Consumption*

Expected consumption can be written as

$$E(W) = \sum_{k=1}^{K} \left(w_k^0 + E\left(\eta|\eta \in [L_k, H_k]\right)\right)\left(F_\eta(H_k) - F_\eta(L_k)\right) + \sum_{k=1}^{K-1} \bar{w}_k\left(F_\eta(h_k) - F_\eta(l_k)\right),$$

where the first sum is the expected consumption on the segments times the probability that each segment is chosen, and the second sum is each kink times the probability that it is chosen (0 if the kink is concave). These probabilities can be computed using the c.d.f. of η in (16). The expected value $E(\eta|\eta \in [L_k, H_k])$ is

$$\frac{\phi(L_k/\sigma_\eta) - \phi(H_k/\sigma_\eta)}{\Phi(H_k/\sigma_\eta) - \Phi(L_k/\sigma_\eta)}\sigma_\eta.$$

A.5. *Household Income Measures*

Estimated household income is computed by running the following regression for the 576 households with non-missing household income reported in the survey:

$$\ln HIncome = \alpha + \boldsymbol{\beta}\mathbf{X} + u,$$

where $\mathbf{X}$ includes the following variables and all their interactions: appliances owned by households (TV, DVD player, car, cellphone, refrigerator, hot running water), last grade of formal education of the primary wage earner (5 dummies), number of adults employed. I predict *HIncome* from this regression for all 1000 households. Note that the explanatory variables in $\mathbf{X}$ have no missing values in the sample. Detailed summary statistics of the resulting measure appear in Table VIII together with summary statistics of reported income from the survey.

As a robustness check, in the Supplemental Material I present estimates of the maximum likelihood model using alternative income measures.

TABLE VIII

INCOME MEASURES[a]

	Reported Individual Income $N = 576$	Reported Household Income $N = 576$	Estimated Household Income $N = 576$	Estimated Household Income $N = 1000$
Mean	3981.69	5205.98	4578.14	4772.50
St. Dev.	3853.81	5340.25	3832.85	3815.84
Percentiles				
5%	897.75	897.75	990.21	919.92
10%	969.57	987.52	1569.06	1103.34
25%	1795.49	1997.5	2483.04	2403.93
50%	3142.11	3590.99	3278.27	3653.22
75%	5386.48	6733.1	5450.43	6704.17
90%	7181.97	10,772.96	9620.22	9146.56
95%	9426.34	14,453.72	12,472.74	12,472.74

[a]Entries in the table are in 2008 Rand. The first two columns refer to income as reported in the survey. The third column is estimated based on the ownership of various household appliances, as described in the text. The fourth column uses these estimates to calculcate an income measure for all 1000 sampled households.

A.6. *Parameter Estimates and Marginal Effects*

TABLE IX

MAXIMUM LIKELIHOOD PARAMETER ESTIMATES AND MARGINAL EFFECTS[a]

Variable	Parameter	SE	Marginal effect	SE
Price	−1.139	0.002	−1.124	0.003
Income	0.358×10^{-4}	0.046×10^{-4}	0.366×10^{-4}	0.004×10^{-4}
Avg. max daily temperature (°F)	0.197	0.000	0.205	0.001
Number of people on the property	0.053	0.003	0.055	0.0005
Outdoor water usage	0.097	0.007	0.102	0.001
Indigent	0.364	0.142	0.377	0.001
Restricted	0.344	0.033	0.357	0.001
Sanitation	4.787	0.038	3.428	0.027
Washing machine	0.091	0.014	0.093	0.001
Bathtub or shower	6.261	0.013	5.814	0.013
Completed high school	−0.120	0.044	−0.125	0.001
Constant	2.111	0.011	–	–
σ_η	0.005	0.006	–	–
σ_ϵ	9.233	0.163	–	–

[a]Parameter estimates: Robust standard errors reported in the SE column. Marginal effect estimates: For continuous variables, the marginal effect is the impact of a unit increase in the variable on expected consumption (in kl). For categorical variables, it is the impact of an increase by one category (e.g., 0 to 1). For price, all marginal prices in the schedule are increased by 1 Rand. Expected consumption before and after the change is computed at the individual level as described in Appendix A.4 and averaged. Standard errors are based on 100 bootstrapped samples of the same size as the estimation sample, taken with replacement. Reported standard errors are the standard deviations across these bootstraps. $N = 10{,}000$.

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Manuscript received September, 2013; final revision received February, 2015.