The Value of Free Water: Analyzing South Africa's Free Basic Water Policy*

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Abstract

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 structurally 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 unique dataset 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 revenue unchanged. This optimal tariff would also reduce the number of households consuming low quantities of water, a desirable policy goal according to the WHO.

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"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).[1]

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, 2007), educational attainment (Gould, Lavy, and Paserman, 2009), women's empowerment (Ivens, 2008), as well as its connection to corruption (Anbarci et al., 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. 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,[2] the South African scheme, which is motivated by equity concerns and in which water is actually free, is one of a handful such policies in the world.

[1] A block rate structure is one that defines different unit prices for various quantity blocks. See Whittington (1992), World Bank (1993), Berg and Mugisha (2008), and Diakite et al. (2009) for more information on the pricing practices in these countries.

[2] For example, Gibbs (1978), Dandy et al. (1997), Castro et al. (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, e.g., to simplify billing for a vacant apartment where a minor leak or water testing produces positive consumption.

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 unique dataset 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 dataset contains rich price variation across 20 different tariff schedules, which allows the identification of structural 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 to form an optimal tariff without a free allowance, which would increase welfare while leaving the water provider's revenue 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.[3]

The dataset used in this paper is exceptional in coverage and quality. I observe individual monthly meter reading data for every household served by a local water provider from January 2002 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 monthly household income around 500 USD. About 13% of the households have running water but no sanitation, and over 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 is therefore observed without the type of measurement errors common in survey data. The dataset provides a sufficiently long purchase history and over 3 million monthly observations, which contributes to a precise estimation and circumvents the typical problems of datasets used to estimate price elasticities in developing countries.

I observe administrative data on prices, and the seven-year period I consider contains much richer price variation than datasets used in similar studies.[4] During the observed 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

[3] This goal is relevant in the South African case due to the constant threat of cholera outbreaks. As recently as 2008-09, a cholera outbreak in Zimbabwe, South Africa, Angola and Mozambique killed more than 1,000 people and affected another 32,000 (*The Weekender*, January 17-18, 2009, p1). The spread of this disease can be easily constrained with such simple measures as washing hands with clean water after using toilets or before preparing food. It is thus particularly important that the pricing policy ensure that households consume enough clean water rather than fetching water from contaminated sources such as rivers and streams.

[4] For example, Nauges and van den Berg (2006) do not observe any price variation and use the choice of vendor to estimate demand. Diakite, Semenov and Thomas (2009) study a 3-block structure which does not vary over time or in the cross-section.

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 raised the free water allowance for low-income households (from 6 to 12 kl) while removing the allowance for all other households, who therefore experienced a dramatic price increase. The rich price variation in the dataset allows me to identify the structural parameters of a demand model and perform a counterfactual analysis without free water.

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

Because the water utility uses a complex block pricing structure, reduced form estimation methods would 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 structurally 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 heterogenous 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, some of which have been overlooked in previous studies of demand estimation.[5] First, while previous studies considered systems with monotonically increasing or decreasing marginal prices, the schedules analyzed in this paper feature a combination 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. Considering these additions to previous estimation methods, this paper provides the most comprehensive demand estimation with nonlinear prices

[5] Most earlier papers use reduced form analyses, summarized in Arbues et al. (2003) and Olmstead (2009). Structural studies include Hewitt and Haneman (1995), Pint (1999), and Olmstead, Hanemann and Stavins (2007). Reiss and White (2005) and McRae (2009) use structural methods to estimate electricity demand.

in the literature. The analysis can be directly applied to other markets with similar pricing structures, including electricity and wireless phone service.

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 disadvantaged households in this area. 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 an optimal pricing problem. I assume that a social planner maximizes consumers' total expected utility subject to both the water provider's revenue and total consumption being unchanged. The latter constraint guarantees that the water provider's capacity constraint is satisfied. I consider tariff structures with the same tiers as the one currently employed, with or without a free water allowance. 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.

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 et al. (2001) asked 358 small business owners in Uganda about their willingness to pay for improved water connections, Whittington et al. (2002) surveyed 1500 households in Nepal, Pattanayak et al. (2006) surveyed 1800 households in Sri Lanka, and Akram and Olmstead (2009) report on a survey about service quality improvements of 197 households in Pakistan. Some of the disadvantages 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.[6] I am aware of two previous studies which are based on observed consumption data from a developing country. Diakite, Semenov, and Thomas (2009) study water demand in Cote d'Ivoire using aggregate consumption data at the community level. Strand and Walker (2005) have access to billing data for about 1000 households from six cities across Central America. However, these observations come from different years and different months of the year (each household is observed only once), and it is unclear what population is represented by this data. To my knowledge, my paper is the first to estimate water demand using administrative, individually metered consumption data for large numbers of low-income households.[7]

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) provide a nonparametric estimation method for nonlinear budget sets. Their method is not applicable to my dataset 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.[8] 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 optimal pricing schedule. In a recent working paper, Kowalski (2012) studies a health insurance application characterized only by non-convex budget segments. Instead of working with a closed form solution for the likelihood function, she proposes 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.

[6] 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, 49).

[7] There are two studies about South African water consumption. Jensen and Schulz (2006) estimate water demand in Cape Town for 275 households using survey data and IV estimation, and Smith and Hanson (2003) present descriptive evidence from a survey of 120 households. Neither study uses a statistical method that properly addresses the block pricing structure, nor do they offer any analysis of the Free Basic Water Policy.

[8] Blomquist and Newey suggest 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 dataset 3 out of the 10 non-convex tariff schedules have non-convexities on the last segment and 4 on the second to last segment.

In summary, this paper makes four contributions to the existing literature. First, this is the first paper to analyze the welfare effects of free water. Second, the quality and size of the dataset used to estimate water demand in a developing country, where consumption is near the WHO-recommended minimum, also makes this exercise unique. Third, my estimation handles price schedules with a combination of increasing and decreasing marginal prices and explicitly includes convexity conditions on preferences. Finally, I use the results of the structural estimation to derive optimal price schedules from a social planner's problem and I provide a structural statement about the welfare implication of the different price scenarios.[9]

The remainder of the paper is organized as follows: Section 2 describes the institutional context and introduces the dataset, Section 3 presents a reduced form analysis, Section 4 provides the demand model, and Section 5 presents the details of the structural estimation. Section 6 presents the estimation results and Section 7 provides the welfare analysis of the Free Basic Water Policy and analyzes an optimal price schedule. 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. 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 under-developed 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 13% 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. The Online Appendix illustrates some of the relevant features of this environment.

The data used in this paper comes 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.

[9] As Reiss and White (2005, 877) note, "Despite a great deal of work in the theoretical literature on efficient nonlinear pricing schemes, there are as yet few (if any) detailed empirical studies."

2.1 Water consumption data

I collected the administrative data used in this paper directly from Odi Water. This dataset 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 dataset have individually metered running water on their property.[10] Since most of the area had no running water 15 years 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, the consumption data can be considered free of measurement error. In addition, since I observe the entire population of consumers, the consumption and price data is free of the selection problems which sometimes arise with survey data.[11] The final dataset includes 3,036,871 monthly observations and detailed summary statistics appear in Table 2.[12]

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. 3.7% reported ever lending water to a neighbor, and 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 which was carried out in 2010 by the author. 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

[10] In particular, there are no shared connections.

[11] For example, the dataset of Mayer et al. (1988), widely used in the water literature, contains about 1200 households from 16 different utility areas from the US and Canada surveyed by mail. In this dataset, 28.2% of the respondents had a BA degree, 13.3% a Masters degree, and 7.1% a Doctoral degree. Not surprisingly, educated households were more likely to respond to a mail-in survey. There is a similar bias if we consider household income, home value, home size etc. since these variables are all correlated with educational attainment.

[12] The Online Appendix contains further details on how the final dataset was generated.

monthly water consumption, indigent status, whether the consumer was restricted, and the supply area.[13]

Indigent status. Based on government documents, average household income is less than \$ 300 in the entire area where Odi Water provides water. 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. To qualify for indigent status, individuals must be South African citizens and own the property, and the total gross monthly income of all the members of the household must not exceed R 1700 ($\simeq$ \$170). The percentage of registered households is stable at around 12 percent for most of the 7 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. I include a dummy variable for indigent households.[14]

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. The water flow is limited using a wide range of restriction devices for these households.[15] 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.[16] These households 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

[13] Details on the survey can be found in an online appendix at www.uh.edu/~aszabo2.

[14] Although registration is based on income, which I control for, there could be behavioral differences among indigent and non-indigent households.

[15] Restriction means a water flow of around 1 liter / minute, depending on the device. At this rate, it takes about 20 minutes to fill a standard container used for bathing.

[16] 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.

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 (see the Online Appendix for details on the survey).

Income. The 2010 survey contained several questions to get a precise 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 "R20000+"). Then, we asked them to estimate how much other members of the household may earn. Based on this information, I report household income in different ways (see Table 13 in the Appendix). Household income 1 is the income reported by the respondent for the entire household. Household income 2 is the respondent's own income multiplied by the number of adults working in the household. Even though the response rate about income (57%) exceeds those typically reported in the literature, we asked a series of questions about the ownership of various appliances, which may provide further indication of a household's finances. To estimate household income, I regress household income reported by the respondent on ownership of the following items in working order: Hot running water, TV, DVD player, car, cellphone and fridge. Household income 3 is the predicted values from this regression. In the analysis, I use the reported household income (household income 1) whenever available and the estimated household income (household income 3) otherwise. The median household income is R 3,590 ($\simeq$ 359 USD).[17] Table 13 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.[18] In addition, I include from the survey the education level of the primary wage earner and the number of people living on the property. Table 1 contains summary statistics from the survey for the 974 households with consumption below 50 kl. Table 2 shows summary statistics for the administrative data for the relevant population.

[17] All monetary values in the paper are in 2008 Rand. Price index data is 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).

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

Table 1: Summary statistics, Household survey, 2010, N=974

Variable	Mean	Std. Dev.	Min	Max
Household Income*	5158.49	4397.83	224.43	64637.76
Number of flush toiletes	1.193	0.626	0	3
Number of standpipes	1.728	1.155	0	4
Number of bathtubs	0.664	0.719	0	2
Number of showers	0.106	0.308	0	1
Number of kithcen taps	0.831	0.648	0	2
Number of bathroom taps	0.877	0.981	0	3
Washing machine	0.574	0.495	0	1
Lawn area	0.528	0.499	0	1
Flower garden	0.373	0.484	0	1
Vegetable garden	0.186	0.389	0	1
Winter irrigation**	0.199	0.400	0	1
Summer irrigation**	0.416	0.493	0	1
Carwash***	0.243	0.429	0	1
Primary school or less	0.079	0.270	0	1
Some high school	0.226	0.418	0	1
High shool graduate	0.402	0.491	0	1
Some higher education	0.175	0.380	0	1
Completed higher education	0.118	0.323	0	1
Number of adults	2.832	1.321	1	7
Number of teens	0.950	0.969	0	3
Number of children	1.042	0.993	0	3
Number of people working outside the home	1.201	0.840	0	3
Number of persons on the property	4.823	2.308	1	13

Notes: *Household income is in 2008 Rand, and this is the reported household income whenever available and the estimated household income based on the ownership of various household appliances otherwise (Household income 4 as described in the text and in the Appendix). **At least once during the season. ***How often do you wash your car(s) at home using water you purchase from the utility? Approximately 30 percent of all households wash their car at home, and half of these do so once a week.

Table 2: Summary statistics, Administrative data, N=3,036,871

Variable	Mean	Std. Dev.	Min	Max
Consumption, Kl/month	13.196	9.816	1	50
Indigent	0.120	0.325	0	1
Restricted	0.187	0.390	0	1
Sanitation	0.873	0.333	0	1
Supply area 1	0.291	0.454	0	1
Supply area 2	0.194	0.396	0	1
Supply area 3	0.515	0.500	0	1
Average max daily temperature (°F)	71.420	6.220	59.133	82.750

Notes: Supply areas are created by the utility and have no special meaning other than describing a georgraphical 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.

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).

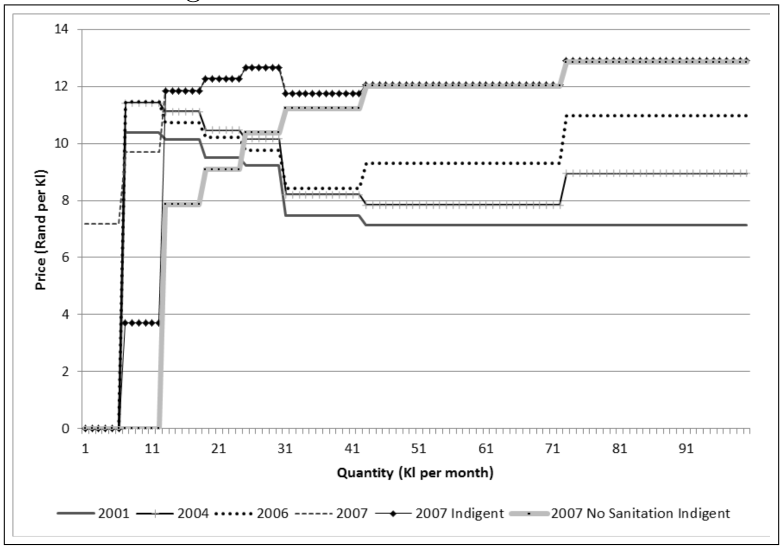
2.3 Tariff structure

The tariff structure considered in this paper has a unique feature: It contains a mixture of increasing and decreasing block tariffs. Because Odi Water 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 forms 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 contains up to 8 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. 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.

Figure 1: Selected tariff structures



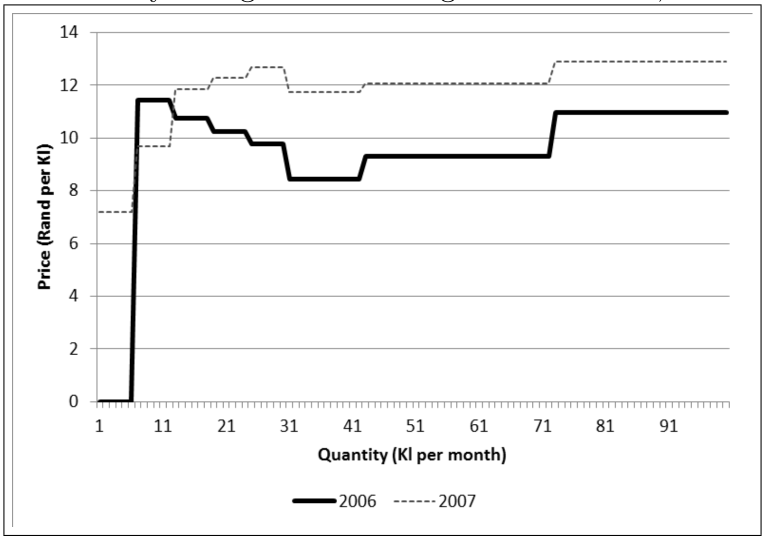
The sanitation charge consists of two different elements. First, there is a sanitation charge per kl which is a uniform price in the first 5 tariff years, a continuously decreasing block tariff structure in the sixth year, and an increasing block tariff structure in the last two years. The second component 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 Online Appendix.

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 have an adequate understanding of the prices they face.

As the above description of the tariff structures shows, Odi Water experimented with many different tariff structures over the years. Typical studies using US datasets have much less price variation, since US water tariffs are usually fixed over time after adjusting for inflation. Odi Water's frequently changing tariff structure provides another source of identification in the data (Figure 1).

The observed period includes a policy change in 2007, when the utility created separate tariff structures for low-income registered households. Previously, consumers received the first 6 kl water for free. From July 2007, Odi Water charged non-indigent households for

Figure 2: Policy change for non-indigent households, 2006-2007.



every kl they consumed. Registered indigent households continued to receive 6 kl free water as well as substantially lower prices between 6 and 12 kl.[19] The tariff changes are shown on Figure 2 and 3 separately for indigent and non-indigent households. This policy change will provide a crucial 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.

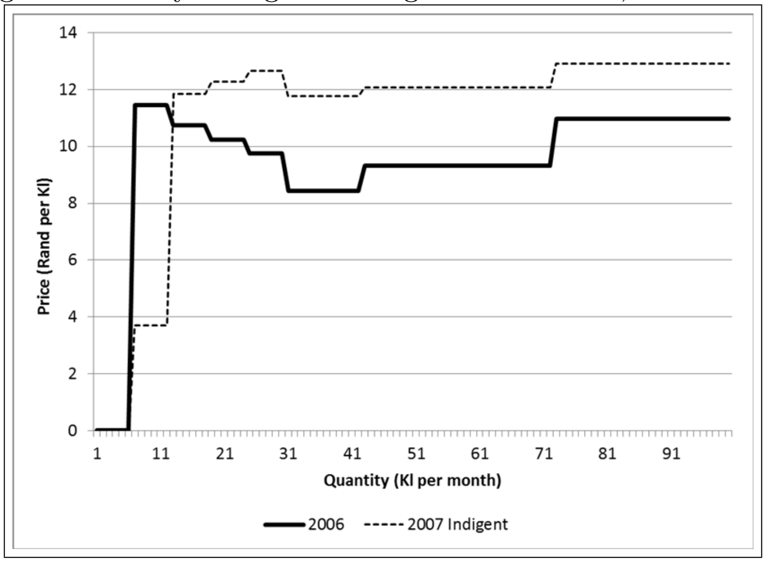
The distribution of the consumers by consumption is shown in Table 3. The mean consumption is 13.2 kiloliters. 28.3 percent of the households consume below 6 kiloliters, which is the free allowance. There is a high concentration of consumers (15.8%) around the kink point of the free allowance (between 5-7 kiloliters).

3 Reduced Form Analysis

As Olmstead (2009) notes, "... of 400 price elasticity studies of water demand produced between 1963 and 2004, only three employed [structural] models, [...] despite the fact that in at least 140 study samples, prices were either increasing or decreasing block." To relate my work to this earlier literature, this section estimates a linear demand function using a variety of reduced form methods, reviews why these estimates are likely to be biased, explains why some widely used IV methods are not able to correct this bias, and argues that it is crucial to use a structural model for further analysis of optimal consumption in the presence of

[19] 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.

Figure 3: Policy change for indigent households, 2006-2007.



complex nonlinear tariff structures. Details are in the Online Appendix.

In the reduced form regressions the dependent variable is monthly metered consumption, and the regressors are observed individual household characteristics, weather, and the price of water. 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.

The use of the average or marginal price in the OLS regression 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 Online Appendix, the OLS estimates produce an upward sloping demand curve even in regressions including household-level fixed or random effects.

Several water studies attempt to find 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, one might take, for each tariff year, the marginal prices corresponding to specific predetermined quantities (such as the kink points). The price variable is then instrumented with these characteristics of the price schedule. Essentially, this amounts to approximating the nonlinear price schedule with a

Table 3: Distribution of consumers by consumption, N=3,036,871

Quantity consumed, Kl	% of consumers	No. Observations
1-6 Kl	28.32	859,931
7-12 Kl	29.26	888,575
13-18 Kl	18.86	572,784
19-24 Kl	10.73	325,789
25-30 Kl	5.88	178,524
31-42 Kl	5.08	154,219
43 + Kl	1.88	57,049
5,6,7 Kl	15.82	480,574

Notes: The free allowance is 6 kiloliters. The last row shows the consumption around this kink point.

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).

Such instruments are unlikely to be valid in the present context. First, there is no guarantee that the price schedule can be represented in a meaningful way using marginal prices or other summary statistics. As described above, the price schedule I analyze is the sum of a separate water and sanitation charge, both of which were subject to yearly reviews during the observed period. Second, as the structural analysis below will make explicit, 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 unlikely to be valid instruments. Finally, consumption levels in my dataset feature some clustering around the kink points (see Table 3). While this follows naturally from a framework with consumer optimization, reduced form regressions would require special assumptions on the error structure to be consistent with such a pattern. Therefore, I turn to a structural model of water consumption.

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 focus 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 $\overline{w}_{k-1}$ and $\overline{w}_k$ (referred to as "kink points"):

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

Given income Y, the consumer solves the problem

$$\max_w U(w, Y - M(w)), \tag{1}$$

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 (1), consider first the sub-problems of maximizing utility as if the budget constraint was linear, extending each budget segment to the entire consumption set as show by the dashed lines on Figure 4. Let $Y_k^0 = Y - M(\overline{w}_{k-1}) + P_k \overline{w}_{k-1}$ denote the income corresponding to each extended segment. For each segment k define

$$V_k = \max_w U(w, Y_k^0 - P_k w), \tag{2}$$

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 $\widetilde{w}_k \in [\overline{w}_{k-1}, \overline{w}_k]$. Next, compare the utility of the solutions which are feasible under the tariff schedule $P(w)$, and the utility of the kinks $\overline{w}_k$, to determine the consumer's demand. For each kink k, let $\overline{U}_k = U(\overline{w}_k, Y - M(\overline{w}_k))$ be the consumer's utility from consuming at kink k. Define

$$
\begin{aligned}
k_1^* &= \underset{k|\widetilde{w}_k \in [\overline{w}_{k-1}, \overline{w}_k]}{\arg\max} \{V_1, V_2, ..., V_K\} \\
k_2^* &= \arg\max_k \{\overline{U}_1, \overline{U}_2, ..., \overline{U}_{K-1}\}.
\end{aligned} \tag{3}
$$

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

$$
w^*(P(\cdot)) = \begin{cases} \widetilde{w}_{k_1^*(P(\cdot))}(P(\cdot)) & if\ V_{k_1^*} > \overline{U}_{k_2^*} \\ \overline{w}_{k_2^*} & otherwise \end{cases} \tag{4}
$$

where dependence of demand on the tariff is made explicit. In words, (4) says that consumer demand is either a kink point, 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 (2) 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 (1) 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 (2). Then, by solving (4), I obtain the global optimum.

5 Specification and estimation

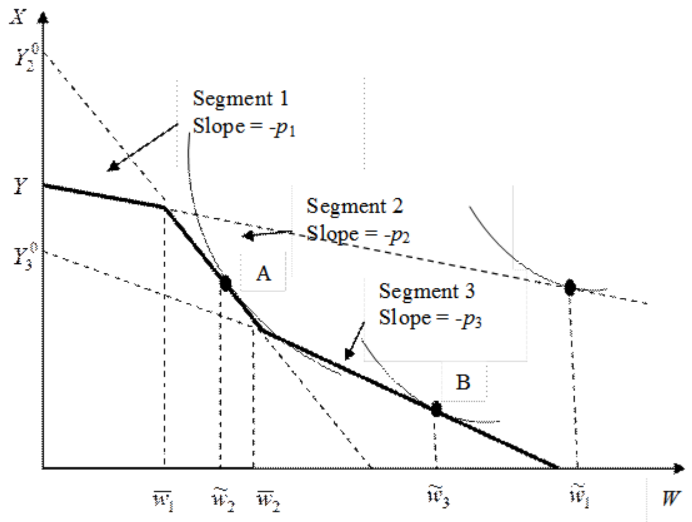
5.1 Demand specification

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

$$
U(w, x) = \frac{\gamma w + \alpha}{\gamma^2} \exp\left(\gamma \frac{\gamma x - w + Z\delta + \eta}{\gamma w + \alpha}\right). \tag{5}
$$

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

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



parameters $\alpha < 0$ and $\gamma > 0$ will be made clear below, and the term η represents household level heterogeneity (see below). Under (5), 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 (5) 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).[20]

Given a linear budget set with income Y and price P, the indirect utility function and demand function corresponding to (5) is

$$V(P, Y) = \exp(-\gamma p)\left(Y + \frac{\alpha}{\gamma}P + \frac{\alpha}{\gamma^2} + \frac{Z\delta + \eta}{\gamma}\right) \quad (6)$$

$$\widetilde{w}(P, Y) = Z\delta + \alpha P + \gamma Y + \eta. \quad (7)$$

Equation (7) 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

[20]In addition, each household characteristic Z has a corresponding parameter δ.

(4):

$$w_{it} = w^*(P(\cdot)) + \varepsilon_{it} = \begin{cases} Z_{it}\delta + \alpha P_{it} + \gamma Y_{it} + \eta_{it} + \varepsilon_{it} & if\ V_{k_1^*} > \overline{U}_{k_2^*} \\ \overline{w}_{k_2^*} + \varepsilon_{it} & otherwise \end{cases}, \tag{8}$$

where k_1^* and k_2^* are defined in (3), 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. 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, my data shows 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, η_{it} and ε_{it} cannot be distinguished, 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 (8). 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).

5.2 Estimation

Maximum Likelihood estimation of the parameters of the demand schedule (8) requires the explicit derivation of demand as a function of η. As is clear from (8), this requires specifying, for all kinks and segments k, the values of η for which (i) demand $\tilde{w}_k$ corresponding to segment k is feasible, (ii) $\tilde{w}_k$ yields higher utility than another feasible demand $\tilde{w}_{k'}$, (iii) $\tilde{w}_k$ yields higher utility than a kink $\bar{w}_{k'}$, and (iv) for which 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 $\theta_{jk} = \overline{w}_j - w_k^0$. (i) $\tilde{w}_k$ is feasible iff $\theta_{k-1,k} < \eta < \theta_{kk}$. (ii) For $\tilde{w}_k$ and $\tilde{w}_l$ 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 3-segment budget constraint depicted in Figure 4, Proposition 1 can be used to rewrite observed consumption (8) as[21]

$$w = \begin{cases} w_1^0 + \eta + \varepsilon & \text{if } \eta < \theta_{11} \text{ and } (\eta < \eta_{13} \text{ when } \theta_{23} < \eta); \\ \overline{w}_1 + \varepsilon & \text{if } \eta \in (\theta_{11}, \theta_{12}) \text{ and } (u_{13}^L < \eta < u_{13}^U \text{ when } \theta_{23} < \eta); \\ w_2^0 + \eta + \varepsilon & \text{if } \eta \in (\theta_{12}, \theta_{22}) \text{ and } (\eta < \eta_{23} \text{ when } \theta_{23} < \eta); \\ w_3^0 + \eta + \varepsilon & \begin{cases} \text{if } \theta_{23} < \eta \text{ and } (\eta > \eta_{13} \text{ when } \eta < \theta_{11}) \\ \text{and } (\eta \notin (u_{13}^L, u_{13}^U) \text{ when } \eta \in (\theta_{11}, \theta_{12})) \\ \text{and } (\eta > \eta_{23} \text{ when } \eta \in (\theta_{12}, \theta_{22})). \end{cases} \end{cases} \tag{9}$$

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 $\tilde{w}_k$ to be the solution if $\tilde{w}_l$ 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 is that $\tilde{w}_k$ 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 $\tilde{w}_k$, 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, $\tilde{w}_k$ 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 equation (9), demand is uniquely

[21] In the Online Appendix I show that, for any η, (9) uniquely defines a demanded quantity (without gaps or overlaps).

defined only if $\theta_{11} < \theta_{12}$ or, equivalently, if $w_1^0 > w_2^0$. 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 $Y_2^0 - Y = (P_2 - P_1)\overline{w}_1$. All previous water studies that I know of simply assume that this holds. However, most of these studies use demand data either from the US 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.[22] In contrast, in my dataset 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 (5), this is necessary and sufficient for preferences to be convex. Rewriting this constraint using (8), 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 $\overline{w}_k$ for which $\overline{w}_k < w_l^0$ for all l, i.e., 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

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

The truncation point $\overline{\eta}_i$ 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 $\overline{\eta}_i$. Appendix 9.2 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, their solution amounts to imposing convexity only in the neighborhood of observed consumption levels. This is problematic because if uniqueness of demand is not guaranteed for all possible values of the preference error, expected consumption cannot be computed.[23] This makes any

[22] E.g., Mayer at al. (1988).

[23] The authors compute expected consumption by restricting the distribution of η to put 0 probability on values yielding multiple optima (p429). Thus, they use different distributions to estimate the parameters and to compute expected consumption given those parameters.

counterfactual analysis impossible.

To derive the likelihood function based on (9), 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 9.3. 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 Online Appendix 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 using the robust "sandwich" formula $\mathbf{H}^{-1}\left(\sum \mathbf{ss}'\right)\mathbf{H}^{-1}$, where $\mathbf{H}$ is the Hessian matrix of the likelihood function and $\sum \mathbf{ss}'$ denotes the outer product of the likelihood scores around the optimal parameter vector (both of these are computed numerically). The model predicted values are computed using the formula given in Appendix 9.4 for expected consumption. 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. Out of sample tests are performed and reported in Section 6.2. The Online Appendix 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. Table 14 in the Appendix presents the parameter estimates from the maximum likelihood estimation. Since the model is highly non-linear, interpreting the effect of specific variables on expected consumption requires computing the marginal effects. This is the effect of a unit increase in a given explanatory variable on monthly consumption, holding everything else constant. For dummy variables, it is the effect of a uniform change in the variable (from 0 to 1). The 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. I calculate household level marginal effects, and then average across households to get the average marginal effect.

Table 4: Marginal effects

Explanatory variables	*Effect on kl consumed per month*				
	All	Indigent	Non-indigent	Restricted	Non-restricted
Price (Rand)	-0.823	-0.833	-0.822	-0.856	-0.816
Income x 10^4 (Rand)	0.345	0.349	0.345	0.416	0.329
Average max daily temperature (°F)	0.237	0.189	0.243	0.275	0.228
Number of people on the property	0.059	0.049	0.060	0.065	0.058
Outdoor water usage	0.112	0.092	0.115	0.123	0.110
Binary variables					
Indigent	0.437	0.336	0.450	0.475	0.429
Restricted	0.415	0.341	0.424	0.392	0.420
Sanitation	3.849	4.623	3.749	3.932	3.829
Washing machine	0.091	0.079	0.093	0.096	0.090
Bathtub or shower	5.224	2.494	5.576	4.804	5.322
Education, completed high school or higher	-0.141	-0.118	-0.144	-0.171	-0.134
N	10000	1142	8858	1882	8118

Notes: For continuous variables, the marginal effect reflects the impact of a unit increase in the variable on expected consumption. For categorical variables, it is the impact of an increase by one category (e.g., 0 to 1). Expected consumption is computed at the individual level as described in Appendix 8.4, and averaged within the different consumer groups in each column.

I do this separately for indigent non-indigent households as well as the restricted group.[24] The results are in Table 4.

The magnitudes of the estimates are reasonable. Based on Table 4, having water-using sanitation increases average monthly consumption by 3.849 kl, while having a bathtub or shower in the house has an effect of +5.224 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. Since I have zero prices in the first block in most tariff years, I change those prices from 0 to 1 Rand. The first column of Table 5 shows the average household level price elasticities. The results indicate that households respond to price changes, with an average price elasticity of -

[24] For the indigent group, the marginal effect of the Indigent variable measures the effect of being indigent relative to the counterfactual of not being indigent. For the non-indigent group, it measures the effect of becoming indigent relative to not being indigent.

Table 5: Price elasticities by group

	MLE	OLS	IV
All households	-0.888	0.152	-0.06
Indigent	-0.910	0.161	0.154
Non-indigent	-0.885	0.15	-0.065
Restricted	-0.982	0.166	0.157
Non-restricted	-0.866	0.148	-0.097

Notes: Price elasticities are computed as the percentage change in consumption resulting from a 1 percent increase in the marginal price of all tariff blocks. The MLE column gives the elasticities from the estimated structural model, using the percentage change in expected consumption. Expected consumption is computed at the individual level as described in Appendix 8.4, and averaged within the different consumer groups in each row. For blocks with a 0 price, the price was increased to 1 Rand. The OLS elasticities were estimated by regressing log(Consumption) on log(Price) and its interactions with Indigent and Restricted (as well as the control variables). IV elasticites were estimated similarly, instrumenting ln(Price) with the marginal prices in the tariff schedule.

0.888. I find that indigent households are more price sensitive than non-indigent consumers.[25]

Table 6 shows price elasticities by consumption level. For all consumers, price elasticities tend to be higher for households that use more water. This is consistent with the patterns typically found in developed countries. I also find, however, that for indigent households the reverse pattern holds: these consumers become less sensitive at higher consumption levels. One explanation of this finding is that high consumption is associated with higher income levels where the total expenditure on water is a smaller percentage of household income, and these households are therefore less price sensitive.[26] Alternatively, this finding might be a consequence of the free water allowance. In some years, indigent households receive free water or lower prices until 12 kl, so the effect of a price increase on these segments is magnified.[27]

[25] For comparison, the second and third columns of Table 5 show price elasticity estimates from the OLS and IV regressions specified in Section 3. As can be seen, these estimates often result in incorrect signs for the price effect.

[26] In South Africa few (if any) households use water on items such as swimming pools that tend to increase price elasticity in the US among high-income consumers.

[27] It is difficult to compare the elasticity measures above to previous estimates as studies typically find a wide range of price elasticities. For example, Arbues et al. (2003) report reduced-form price elasticity esti-

Table 6: Price elasticities by household monthly water consumption

Quartile	Quartile range	Price elasticity				
		All	Indigent	Non-indigent	Restricted	Non-restricted
1-st	1-6	-0.868	-0.951	-0.859	-1.021	-0.840
2-nd	7-10	-0.878	-0.953	-0.867	-0.979	-0.856
3-rd	11-17	-0.874	-0.852	-0.877	-1.019	-0.841
4-th	18-	-0.933	-0.879	-0.940	-0.926	-0.935

Notes: Reported price elasticities are the individual price elasticities computed from the structural model, averaged within the various consumption quartiles and consumer groups. See Appendix 8.4 for the computation of expected consumption at the individual level.

Table 7: Model performance

	Actual mean	Predicted mean	Average error	N
All	13.353	13.340	-0.013	10000
Indigent	13.351	14.881	1.530	1142
Non-indigent	13.353	13.141	-0.212	8858
Restricted	14.934	14.168	-0.766	1882
Non-restricted	12.986	13.148	0.162	8118

Notes: The Predicted mean column gives the average expected consumption predicted by the model with the estimated parameter values in Table 14. Expected consumption is computed at the individual level as described in Appendix 8.4. Average error is the difference between the actual and predicted means.

6.2 Model performance

Table 7 presents actual means computed form the data and the model-predicted mean consumptions for different consumer groups. The average error is not substantial, the model performs well. 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

mates from 65 different studies, ranging from -1.64 to +0.33. Differences are due to the different estimation methods and the different datasets. Structural estimates include Pint (1999), who finds elasticities between -0.04 and -1.24, and Olmstead et al. (2007), who find elasticities between -0.59 and -0.33. There are three previous elasticity estimates for developing countries using observed consumption data: Strand and Walker (2005) find elasticities between -0.1 and -0.3 in Central American cities, and Diakite et al. (2009) report an elasticity of -0.82 in Cote d'Ivoire. Both of these studies use aggregate data. Nauges and Berg (2009) study 1,800 households in Sri Lanka and find that a price elasticity of -0.15. The numbers I find make sense given these previous studies.

Table 8: Model performance: out of sample

	Actual mean	Predicted mean	Average error	N
All	13.395	13.358	-0.038	53178
Indigent	13.206	14.907	1.701	6392
Non-indigent	13.421	13.146	-0.275	46786
Restricted	14.990	14.145	-0.844	10349
Non-restricted	13.010	13.167	0.157	42829

Notes: The Predicted mean column gives the average expected consumption predicted by the model with the estimated parameter values in Table 14. Expected consumption is computed at the individual level as described in Appendix 8.4. Average error is the difference between the actual and predicted means. Values in the table are for the 53,178 monthly observations that were not used in estimating the parameters in Table 14.

estimation.[28] Table 8 repeats Table 7 for these observations. As can be seen, the two tables produce very similar results. The average errors of the model's predictions are only slightly higher out of sample.

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

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, they report 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.[29] I obtained administrative data on the effective prices, and I conduct

[28] Recall that the estimation was run on 10,000 observations due to computational constraints.

[29] Depending on the tariff year, effective prices range from 7.8 Rand to 10.7 Rand. They are close to the first nonzero marginal prices (the second tariff block) charged to the consumers.

Table 9: Household consumption and expenditure changes

	All	Indigent	Non-indigent	Restricted	Non-restricted
Consumption (Kl/month)					
With free water	13.358	13.448	13.346	13.867	13.236
Without free water	13.349	13.442	13.337	13.862	13.227
Change (%)	-0.067	-0.045	-0.067	-0.036	-0.068
Expenditures (2008 Rand/month)					
With free water	77.868	80.584	77.513	85.477	76.057
Without free water	141.001	147.797	140.114	152.898	138.170
Change (%)	81.077	83.407	80.762	78.876	81.666

Notes: 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 8.4, 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).

a counterfactual experiment by replacing zero prices in the dataset with these prices.[30]

Table 9 shows the results of the counterfactual exercise where zero prices are replaced with the effective price the utility reports to the government.[31] 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 are unchanged.

In this counterfactual experiment, average consumption decreases only slightly, by less than 0.1%, even though the associated expenditure on water increases by 81.1% on average. This is true both overall as well as for specific consumer groups. This suggests that, by itself, the free water allowance mimics a lump sum-cash subsidy to the households. In this sense, 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

[30] Note that this counterfactual exercise 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.

[31] I only use observations from 2002-2007 for this exercise. Since after 2007 some consumers received no free water while others received 12kl for free, the counterfactual exercise I study would have different implications for this period.

magnitude of the subsidy would affect consumption. Currently, the effective prices assigned to the first price block average 9.20 Rand. A counterfactual replacing this with 18 Rand would yield a 17% reduction in mean consumption, while for 20 Rand, the reduction would be 38%.

7.2 The social planner's problem

I consider the problem of a social planner maximizing total consumer welfare subject to two constraints: (1) The water provider should operate with the same economic loss/profit as under the current price scheme, assuming a risk neutral water provider (Revenue neutrality); (2) The new tariff structure should not increase the current total consumption (Capacity constraint).

This formulation is useful since I do not have information about the specifics of the production cost of the water provider. It implies that the possible welfare changes come from the reallocation of the current consumption and payments across consumers. Based on my conversations with Odi Water officials, both of these constraints are important feasibility considerations in the present context.[32]

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 revenue and capacity constraints holding in expectation. (I assume that the marginal cost of water distribution is zero).

Denote the current total revenue with $\overline{R} = \sum_{i=1}^{I} \int_{0}^{w_i^*(P^0(\cdot))} P^0(w)dw$ where I is the number of consumers and $P^0(w)$ is the currently observed price schedule. Similarly, let current total consumption be $\overline{C} = \sum_{i=1}^{I} w_i^*(P^0(\cdot))$. Let F_i denote the cdf of η_i and E the expectation operator over $(\eta_1, ..., \eta_I)$. The problem of the social planner is

$$\max_{P(\cdot)} E\left[\sum_{i=1}^{I} U_i(w,x)\right] = \sum_{i=1}^{I}\left[\int_{-\infty}^{\overline{\eta}_i} U_i(w_i^*(P(\cdot),\eta_i), x^*(P(\cdot),\eta_i))dF(\eta_i)\right] \tag{10}$$

s.t.

$$\begin{aligned} \sum_{i=1}^{I} E\left[w_i^*(P(\cdot),\eta)\right] &\leq \overline{C} \\ \sum_{i=1}^{I} E\left[\int_{0}^{w_i^*(P(\cdot),\eta_i)} P(w)dw\right] &\geq \overline{R}. \end{aligned} \tag{11}$$

[32] Note that in general, these two constraints are difficult to satisfy simultaneously unless demand is very inelastic. Thus, it is far from obvious a priori that the existing price schedule can be improved upon.

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 (10) can be written as

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

Here, the three terms correspond to the utility the consumer achieves from consuming on the first segment, the kink, or the second segment, respectively. Using the parameter estimates together with the functional forms in (5) and (6) and the distribution of η, numerical maximization of (10) subject to (11) is straightforward.

The social welfare function (10) 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.

7.3 Optimal tariffs

First, I consider optimal tariff structures 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 the revenue and capacity constraints equal to their actual 2006/07 values. This helps answer the question whether passing along the subsidy to households in the form of universal free basic water is the most efficient policy. 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 the revenue and capacity constraints equal to their actual 2008/09 values. For both of these scenarios I consider 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.[33] Table 10 summarizes these four cases.[34]

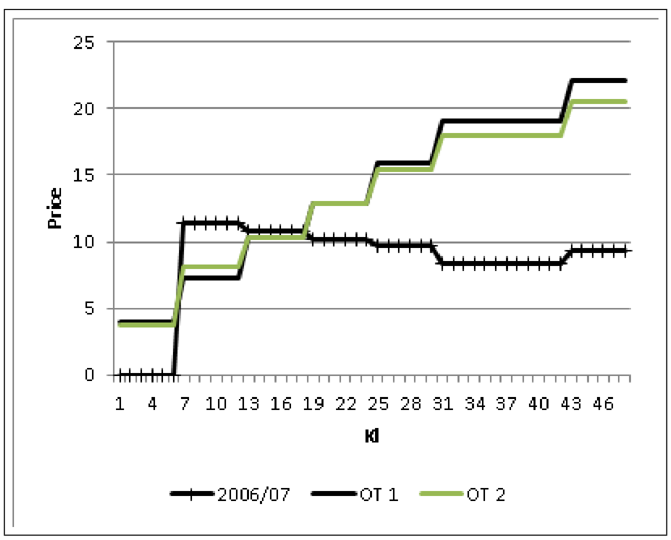
[33] To keep the exercise computationally feasible, I keep the same kink points as in the actual tariff and require that marginal prices be non-decreasing (as in the actual water tariff without sanitation). Note that this includes uniform pricing as a special case. I ignore households without sanitation, since they have a separate water schedule without sanitation prices. Since there are no households consuming on the highest tariff block (above 72 kl) in the dataset, I ignore this block and work with a 7-block tariff. The calculations below are performed for all households with survey data in the given tariff years. The number of observation is 8,385 for tariff year 2006/07 and 5,660 for tariff year 2008/09.

[34] I also ran the optimalization routine assuming price structures where every household receives 6 kiloliters for free. There were no feasible solutions: such a schedule cannot simultaneously satisfy both the revenue

Table 10: Description of the optimal tariff structures

Optimal Tariff	Description
OT 1	Seven tier tariff with the same blocks as in the 2006/07 price schedule (the last price schedule before the 2007 policy change). The revenue and capacity constraints are set equal to the actual 2006/07 total revenue and consumption. Same tariff structure for all households. All prices are obtained from the optimization problem.
OT 2	OT 1 but P1=0 (until 6 Kl) for indigent households.
OT 3	Seven tier tariff with the same blocks as in the 2008/09 price schedule (the latest tariff). The revenue and capacity constraints are set equal to the actual 2008/09 total revenue and consumption. Same tariff structure for all households. All prices are obtained from the optimization problem.
OT 4	OT 3 but P1=0 (until 6 Kl) for indigent households.

Figure 5: Optimal tariff schedules OT 1 and OT 2



Notes: The 2006/07 schedule is the actual tariff observed in the data. OT 1 is the fully optimized schedule (subject to the constraints described in the text). OT 2 is the optimized schedule under the aditional constraint that indigent households should face 0 prices for the first 6 kiloliters. The figure shows the tariff schedule for non-indigent households. For indigent households, the only difference is that OT 2 is 0 up to 6 kl.

The resulting optimal tariff structures are shown in Figure 5.[35] 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. Both OT 1 and OT 2 (for non-indigent households) show that changing the current tariff is advantageous if nobody receives free water, but pays a low positive marginal price for the first kiloliters and a price for the second block that is substantially lower than under the current 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, there is about a 60 percent price decrease on the second block (where the mean and median consumption are located) which further encourages an increase in low end consumption.

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 discourage high consumption (helping to satisfy the capacity constraint) and generate more revenue which pays for the decrease in prices on the lower blocks (given the revenue constraint). The graph also shows that the 6 kl free water for indigent households can be reinstated by increasing the second block prices slightly and decreasing higher blocks (to increase consumption and generate more revenue) without changing the main characteristics of the tariff structure.

OT 3 and OT 4 are shown on Figure 6 for non-indigent and Figure 7 for indigent households together with the actual 2008/09 tariff. Relative to the actual tariff schedule, OT 3 and OT 4 exhibit similar features as those discussed above for OT1 and OT2. In particular, for the majority of households prices should be reduced for the lower blocks and increased for the higher blocks. It is reassuring that the optimal tariffs exhibit these similarities despite the different revenue and capacity constraints used to derive them. Note that OT 3 and OT 4 are much closer to the actual 2008/09 tariff than OT 1 and 2 to the actual 2006/07 tariff. In this sense, the policy change implemented in 2007 moved the tariff schedule closer to the optimal.

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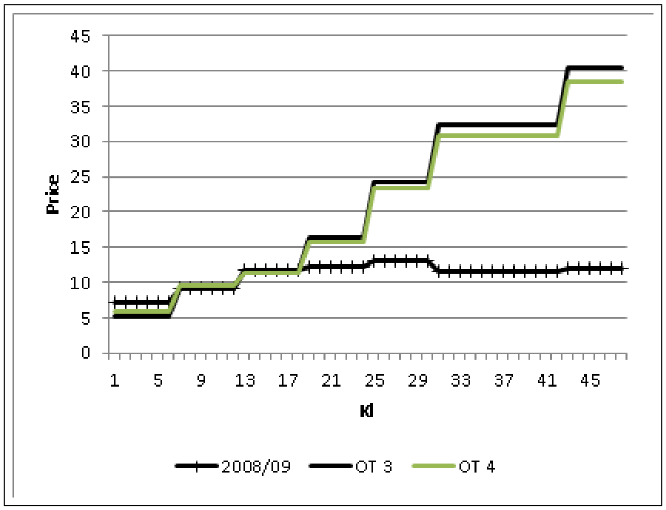
and the capacity constraint. I also tried simple 2-block schedules with various kink points, and was never able to obtain higher welfare than with OT 1-4. While establishing whether the OT schedules provide the highest welfare over the set of *all* price schedules is not computationally feasible, this does suggest that there are no obvious, simple schedules that would dominate them.

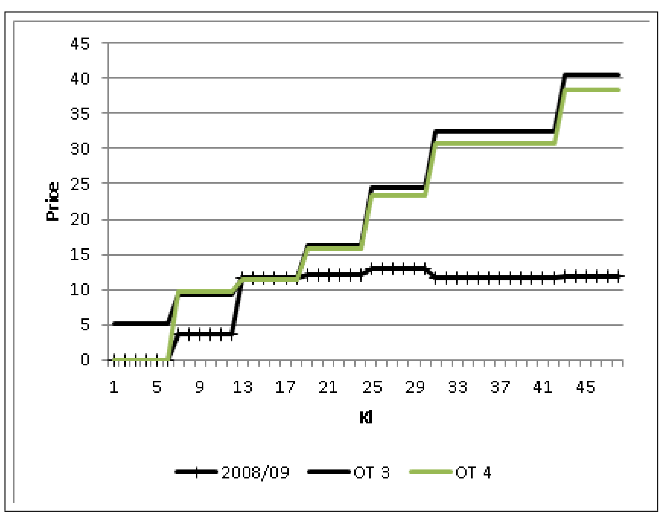
[35] For the sake of clarity, the indigent tariffs are not shown on the Figure. They are identical to the non-indigent tariffs, except that they face a price of 0 for the first 6 kl under OT 2.

Figure 6: Optimal tariff schedules OT 3 and OT 4 for non-indigent households



Notes: The 2008/09 schedule is the actual tariff observed in the data. OT 3 is the fully optimized schedule (subject to the constraints described in the text). OT 4 is the optimized schedule under the aditional constraint that indigent households should face 0 prices for the first 6 kiloliters. The figure shows the tariff schedule for non-indigent households.

Figure 7: Optimal tariff schedules OT 3 and OT 4 for indigent households



Notes: The 2008/09 schedule is the actual tariff observed in the data. OT 3 is the fully optimized schedule (subject to the constraints described in the text). OT 4 is the optimized schedule under the aditional constraint that indigent households should face 0 prices for the first 6 kiloliters. The figure shows the tariff schedule for indigent households.

Table 11: Compensating variation under the optimal tariffs (mean / median)

	Compared to 2006/07		N	Compared to 2008/09		N
	OT 1	OT 2		OT 3	OT 4	
All	-0.24 / -2.20	0.72 / 1.33	8385	-0.41 / -11.86	-0.14 / -6.12	5660
Indigent	-0.28 / -2.10	-18.95 / -20.67	1021	63.31 / 63.67	34.31 / 34.67	877
Non-indigent	-0.23 / -2.21	3.45 / 1.63	7364	-12.10 / -11.98	-6.46 / -6.44	4783
Restricted	-0.78 / -2.36	-1.48 / 0.9	2011	6.94 / -11.87	3.79 / -6.10	1208
Non-restricted	-0.06 / -2.16	1.42 / 1.50	6374	-2.41 / -11.86	-1.20 / -6.13	4452

Notes: The table reports the compensating variation corresponding to the optimal tariffs OT 1-4. If the provider switched from the actual (2006/07 or 2008/09) 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 number 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.

7.4 Compensating variation

I calculate the compensating variation to measure the change in consumers' welfare as a result of the proposed tariff structures. Specifically, I calculate the change in a consumer's income that equates utility under the current 2006/07 (2008/09) price schedule and expected utility under the alternate price schedules, OT 1 or OT 2 (OT 3 or OT 4). For example, for two price segments (12) implies that the compensating variation C_i for consumer i is defined implicitly by

$$U_0 = \int_{-\infty}^{\theta_{11}} V_i(P_1, Y + C_i) dF(\eta_i) + \int_{\theta_{11}}^{\theta_{12}} U_i(\overline{w}_1, Y + C_i - P_1\overline{w}_1) dF_i(\eta_i) + \int_{\theta_{12}}^{\overline{\eta}_i} V_i(P_2, Y_2^0 + C_i) dF_i(\eta_i),$$

where U_0 is the baseline utility level under the current prices. A negative value of C_i indicates that the consumer is better off than under the baseline, while a positive value of C_i indicates that he is worse off.[36]

Table 11 shows the compensating variation and the resulting expenditure changes are in the Online Appendix. Under OT 1, the welfare effects would be very similar among groups, with a median welfare increase of 2.2 Rand each month. Over a year, this would mean a saving of 30 percent on a typical monthly water bill. OT 2 seems particularly well suited to support indigent households, a goal which seems consistent with the more recent tariff policy observed in practice. Relative to the current tariff, OT 2 yields a substantial median welfare gain for indigent households (20.67 Rand per moth), at a cost of only 1.63 Rand for the median non-indigent household.

The negative average compensating variation under OT 1 demonstrates that, relative to

[36] Of course, because OT 1-4 maximize the social welfare function, they always yield higher *total* welfare than the tariffs observed in practice.

Table 12: Distribution of consumption under actual and optimal tariff schedules

Tariff schedule	Consumption Low	Medium	High	Total
2006/07 actual	55.6	21.13	23.27	100
2008/09 actual	65.44	17.81	16.75	100
OT 1	34.32	65.45	0.23	100
OT 2	33.91	65.68	0.41	100
OT 3	41.41	58.59	0	100
OT 4	41.41	58.59	0	100

Notes: Each row in the table presents the fraction of consumers consuming Low (0-12kl), Medium (12-18kl), or High (above 18kl) quantities of water under the tariff schedule indicated in the first column.

the universal free water policy of 2006/07, 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 11 shows, considerable welfare improvement is possible by making further changes to the tariff schedule. In particular, under OT 3, the median compensating variation is 11.86 Rand per month, which is equivalent to at least 1 kiloliter of free water and 13% of the average monthly expenditure on water. Over a year, the median savings is about 3.5 percent of monthly household income. This is quite substantial, especially considering that the gain is coming from the redistribution of the current government subsidy without any increase in total consumption. Since indigent households currently receive 12 kiloliters of water for free, the welfare change is negative for them under OT 3 and OT 4.

Table 12 shows the distribution of consumption under the actual and optimal tariff structures. Since the optimization was done under the constraint that total consumption should not exceed actual total consumption, there is little change in mean consumption among the tariff structures. However, there are large differences in the distribution of consumption. In particular, the optimal tariff schedules substantially reduce the proportion of low consumers (below 12 kl, the current free allowance for indigent households). Under OT 1 and OT 2, the reduction is 21-22 percentage points relative to the corresponding actual schedule, while under OT 3 and OT 4 it is 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.[37] Another desirable feature of the optimal tariffs is to promote conservation on the high end

[37] With detailed information on the health risks associated with consuming low quantities of clean water, it would be possible to quantify the health implications of proposed and actual policies. 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.

of the distribution by increasing the marginal price on these blocks (by a factor of 4 in the case of OT 3 and OT 4).

In summary, there exist price schedules capable of raising social welfare relative to the actual prices while satisfying both the provider's capacity and revenue constraints. In addition, these schedules appear to move the distribution of consumption levels in a desirable direction. More generally, these findings provide evidence that in the poor South African townships considered here, consumers respond to price changes in their nonlinear price schedules. This is in contrast to the results of most US studies. For example, Borenstein (2008) writes that "it seems likely that the vast majority of [electricity] customers in California not only do not know what tier their consumption puts them on, but even that the rate structure is tiered at all" (page 25).[38] To the extent that my findings generalize to other developing countries, they have two main implications. First, in these environments, complex pricing schedules may have an impact, and consequently changes in prices or in the amount of free water provided can have substantial welfare effects. Second, future studies analyzing demand under nonlinear price schedules should choose the estimation method taking into account this potential difference between developed and developing countries. In particular, modelling the block choice seems to be especially important in the latter case.

8 Conclusion

This paper analyzes the welfare effects of free water using the South African Free Basic Water Policy. It provides the most comprehensive demand estimation with nonlinear prices in the literature on public utilities and derives optimal pricing schedules using the structural estimates. The dataset stands out in quality and coverage among usual datasets used to estimate water demand from developing countries. The large number of administrative household level observations, complemented with survey data and rich price variation over the period of study allow the precise estimation of the parameters of interest.

To study the Free Basic Water policy, I first conduct a counterfactual exercise, replacing zero prices from 2002-2007 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

[38] Similarly, Liebman and Zeckhauser (2005) argue that people are likely to fail to perceive the true prices that they face when pricing schedules are complex. They argue that such "schmeduling" is more common in the presence of nonlinear pricing when there is a potential to confuse average and marginal prices.

marginal prices, but rather divides the government subsidy more evenly across blocks. The monotonically 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. My results provide evidence that consumers are rational in their decisions in this setting. This result underscores the importance of estimation methods that are able to capture utility-maximizing behavior and, from a policy perspective, justifies the application of complex price schedules in this setting.

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9 Appendix

9.1 Proof of Proposition 1

(i) This follows directly from the definition of feasibility.
(ii) Using (6), $V_k > V_l$ iff $\eta < \eta_{kl} \equiv \frac{\gamma(V_k^0 - V_l^0)}{e^{-\gamma p_l} - e^{-\gamma p_k}}$, where $V_k^0 = e^{-\gamma p_k}(Y_k^0 + \frac{\alpha}{\gamma}P_k + \frac{\alpha}{\gamma^2} + \frac{Z\delta}{\gamma})$.
(iii) Direct utility (5) is increasing and concave in η while indirect utility (6) is increasing and linear. Therefore the equation $\bar{U}_j - V_k = 0$ has at most two roots. When it has less 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 (5), $\bar{U}_j > \bar{U}_k$ iff $\eta < \bar{\eta}_{jk} \equiv \frac{\frac{1}{\gamma}\ln(\frac{\gamma\bar{w}_j+\alpha}{\gamma\bar{w}_k+\alpha})+\frac{\gamma Y_j^0-\bar{w}_j(1+\gamma P_j)+Z\delta}{\gamma\bar{w}_j+\alpha}-\frac{\gamma Y_k^0-\bar{w}_k(1+\gamma P_k)+Z\delta}{\gamma\bar{w}_k+\alpha}}{\frac{1}{\gamma\bar{w}_k+\alpha}-\frac{1}{\gamma\bar{w}_j+\alpha}}$.

9.2 Truncation

For a demanded quantity W^*, the utility function in (5) is quasiconcave 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 $\overline{w}_k$ for which $\overline{w}_k < w_l^0$ for all l, i.e., 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

$$\eta < \overline{\eta}_i \equiv \min_{tk}(-w_{itk}^0) - \frac{\alpha}{\gamma}. \tag{13}$$

The truncation point $\overline{\eta}_i$ differs across consumers (but is the same for a consumer in all billing cycles). As is clear from (13), 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 $(-\infty, +\infty)$, (13) 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 (13). 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 $\overline{\eta}_i$ 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: $N(0, \sigma_\eta^2)$. Denoting ϕ and Φ the standard normal density and cdf, respectively, this yields the following specification of the cdf, pdf, mean and variance of η_i :

$$F_{\eta_i}(x) = \Phi\left(\frac{x}{\sigma_\eta}\right)/\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right) \text{ if } x < \overline{\eta}_i, \text{ 1 otherwise} \tag{14}$$

$$f_{\eta_i}(x) = \phi\left(\frac{x}{\sigma_\eta}\right)/\left[\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)\sigma_\eta\right] \text{ if } x < \overline{\eta}_i, \text{ 0 otherwise} \tag{15}$$

$$E(\eta_i) = -\phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)/\left[\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)\right]\sigma_\eta \tag{16}$$

$$Var(\eta_i) = \sigma_\eta^2\left[1 - \frac{\phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}{\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}\left(\frac{\overline{\eta}_i}{\sigma_\eta} + \frac{\phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}{\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}\right)\right] \tag{17}$$

9.3 Likelihood function

Let $\nu = \eta + \varepsilon$ and let F_x and f_x denote, respectively, the cdf and pdf of the random variable x. Based on (9), for each observed monthly consumption level W, the contribution to the likelihood may be written as

$$\sum_k f_\nu(W - w_k^0)[F_{\eta|\nu=W-w_k^0}(H_k) - F_{\eta|\nu=W-w_k^0}(L_k)] + \sum_k f_\varepsilon(W - \bar{w}_k)[F_\eta(h_k) - F_\eta(l_k)]. \tag{18}$$

The first sum in (18) is the probability that W is observed given that desired consumption was located on one of the segments $k = 1, 2, ...$ 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 $k = 1, 2, ...$ 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 (18).

Terms in the second sum in (18) corresponding to the kink points may be rewritten using (14) and the fact that

$$f_\varepsilon(W - \bar{w}_k) = \phi(\frac{W - \bar{w}_k}{\sigma_\varepsilon})\frac{1}{\sigma_\varepsilon} \tag{19}$$

since $\varepsilon \sim N(0, \sigma_\varepsilon^2)$. For the first sum in (18) 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 (19) and f_η in (15) to get

$$f_\nu(x) = \int_{-\infty}^{\overline{\eta}} f_\varepsilon(x - \eta)f_\eta d\eta = \int_{-\infty}^{\overline{\eta}} \phi(\frac{x-\eta}{\sigma_\varepsilon})\phi(\frac{\eta}{\sigma_\eta})d\eta\frac{1}{\sigma_\eta\sigma_\varepsilon\Phi(\frac{\overline{\eta}}{\sigma_\eta})}$$

After some algebra, this can be shown to equal

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

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

$$x_1, x_2 \sim N\left[\begin{array}{c}\mu_1\\ \mu_2\end{array}, \sum = \left[\begin{array}{cc}\sigma_1^2 & \sigma_{12}\\ \sigma_{12} & \sigma_2^2\end{array}\right]\right]$$

then

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

where

$$\begin{aligned}\overline{\mu} &= \mu_1 + \frac{\sigma_{12}}{\sigma_2^2}(a-\mu_2)\\ \overline{\sigma}^2 &= \sigma_1^2 - \frac{\sigma_{12}^2}{\sigma_2^2}.\end{aligned}$$

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

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

To summarize, for each observed monthly consumption level W, the contribution to the likelihood (18) is

$$\begin{aligned}&\sum_k \frac{\phi(\frac{W-w_k^0}{\sigma_\nu})}{\sigma_\nu\Phi(\frac{\bar{\eta}}{\sigma_\eta})}\left[\Phi\left(\frac{H_k/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{W-w_k^0}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right) - \Phi\left(\frac{L_k/\sigma_\eta}{\sqrt{1-\rho^2}} - \frac{W-w_k^0}{\sigma_\nu}\frac{\rho}{\sqrt{1-\rho^2}}\right)\right] \qquad (20)\\ &+\sum_k \frac{\phi(\frac{W-\bar{w}_k}{\sigma_\varepsilon})}{\sigma_\varepsilon\Phi\left(\frac{\bar{\eta}}{\sigma_\eta}\right)}\left[\Phi\left(\frac{h_k}{\sigma_\eta}\right) - \Phi\left(\frac{l_k}{\sigma_\eta}\right)\right].\end{aligned}$$

9.4 Expected consumption

Expected consumption can be written as

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

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 cdf of η in (14). The expected value $E(\eta | \eta \in [L_k, H_k])$ is

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

9.5 Additional tables

Table 13: Income measures

	Income of the respondent	Household income 1	Household income 2	Household income 3	Household income 4
Mean	3981.69	5205.98	6051.91	5143.55	5143.546
St. Dev	3853.81	5340.25	7956.275	2481.542	4371.674
Min	224.4367	224.4367	224.4367	750.52	224.4367
Max	58353.53	64637.76	1160707	9015.66	64637.76
Percentiles					
5%	897.7466	897.7466	897.7466	2256.233	969.5664
10%	969.5664	987.5213	987.5213	2506.161	1458.838
25%	1795.493	1997.486	2064.817	3134.82	2506.161
50%	3142.113	3590.987	3703.205	5136.675	3590.987
75%	5386.48	6733.1	7181.973	6326.384	6418.889
90%	7181.973	10772.96	12568.45	8956.898	8956.898
95%	9426.34	14453.72	17954.93	8956.898	11670.71
N	576	576	576	974	974

Notes: Household income 1 is the income reported by the respondent for the entire household. Household income 2 is the respondent's own income multiplied by the number of adults working in the household. Household income 3 is the predicted values from the regression described in the text. Household income 4 is household income 1 whenever available and the estimated household income (household income 3) otherwise.

Table 14: Parameter estimates, ML

Variables	Parameters	SE
Constant	2.091	1.743
Indigent	0.361	0.024
Restricted	0.354	0.455
Sanitation	4.780	1.279
Average max daily temperature (°F)	0.198	0.001
Washing machine	0.089	0.028
Number of people on the property	0.050	0.030
Outdoor water usage	0.097	0.064
Bathtub or shower	6.211	0.066
Education, completed high school or higher	-0.124	0.246
Price	-1.134	0.020
Income	0.359×10^{-4}	1×10^{-4}
σ_ϵ	9.249	0.049
σ_η	0.005	0.011