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 of 6 kiloliters per month. 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. The dataset contains rich price variation across 20 different nonlinear tariff schedules, and includes a policy experiment which removed the free allowance. I find that without government subsidy, the mean monthly consumption would change very little. 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 below the WHO-recommended level.

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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

[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 (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

actually free, is one of a handful such policies in the world.

The goal of this paper is to analyze the welfare effects of free water and provide an optimal pricing scheme. To do this, I collected a 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 of the City of 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 below the WHO-recommended level of clean water.

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 measurement error. 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.[3] 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

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.

[3]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.

changes from increasing to decreasing marginal prices). In addition, I take advantage of a 2007 policy experiment in which, in an effort to cut costs, Tshwane's Water Department introduced a new pricing policy that 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 2011. 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 non-linear prices raises several difficulties, some of which have been overlooked in previous studies of demand estimation.[4] First, while previous studies considered systems with continuously 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

[4] 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) use structural methods to estimate electricity demand.

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 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 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. Based on this result, I conclude that the government subsidy may be an efficient way to provide a 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 the water provider's revenue and the total consumption being unchanged. The second 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 consumption less than 6 kl per month, which is the WHO-recommended minimum. 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 optimal tariff and the one currently in effect. I find that in each given period, the average utility gain among households is about 1% of their income, or 10-20% of the amount spent on water.

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.[5] 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 data 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, this is the first paper to estimate water demand using administrative, individually metered consumption data for large numbers of low-income households.[6]

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

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

[6] There are two studies about South African water consumption. Jensen and Shulz (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.

the welfare implication of the different price scenarios.[7]

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. Section 8 describes and analyzes an optimal price schedule, and Section 9 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 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 2011. Each of these data sources is described in detail below.

2.1 Water consumption data

I collected the administrative data used in this paper directly from Odi Water. This 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

[7] 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."

water on their property.[8] 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.

The final dataset includes 3,036,871 monthly observations, and was generated as follows. I dropped from the data Odi Water's commercial and institutional consumers (5.6 % of the data). I also dropped accounts showing zero consumption.[9] The employees of Odi Water inspect the water meter each month at meter-reading. If there is a problem with the meter, employees record the code of the problem which is also included in my dataset. Accordingly, I drop observations where the meter reader recorded any problems which prevented properly reading the meter.[10] In addition, the meter reader tests the tap for any water leaks and reports the problem. I drop the observations with problems reported (1.7%). Because of the regular quality checks, illegal tapping in this area is virtually non-existent, in contrast to many other developing countries or even other parts of South Africa.

Based on my conversations with Odi Water officials, the utility has difficulty distinguishing commercial and residential consumers if the consumer is running a small business from his home. These small businesses include hair salons, car washing facilities, small restaurants etc. Since Odi Water made efforts to identify these households and re-categorize them as commercial units, there are several account numbers whose status changed from domestic to commercial during the observed period. I drop the entire accounts with changing status from the sample (less than 0.2%). I also drop areas which are categorized as agricultural since water pricing and supply is different than in the rest of the supply areas (3.7%). Lastly, I drop observations where monthly consumption is higher than 50 kl, which is 4 times the average consumption (an additional 3.4 %). These consumption levels are most likely associated with either unreported leaks or with commercial activities not yet categorized as such by Odi Water. In the final dataset, average monthly consumption is 13.2 kl. Detailed summary statistics appear in Table 2.

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

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

[9] In some cases zero consumption refers to vacant land, closed accounts etc., a total of 489,959 monthly observations.

[10] These problems include the following: dirty dial, meter covered, meter stuck, meter damaged, meter dial is missing, meter tampered with, meter obstructed, water leak or meter removed.

population of consumers, the consumption and price data is free of the selection problems which sometimes arise with survey data.[11]

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 2011 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 monthly water consumption, indigent status, whether the consumer was restricted, and the supply area.[12]

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

[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] For details on the sampling, questions and additional results, please see the online appendix at www.uh.edu/~aszabo2.

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. (Of course, even though registration is based on income, there might also be behavioral differences among indigent and non-indigent households.)

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.[13] 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.[14] 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 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 2011 survey (see the Online Appendix for the full list of questions and detailed summary statistics).

[13] 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.

[14] 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.

Income. The 2011 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 16 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.[15] 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).[16] Table 16 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.[17] In addition, I include from the survey the education level of the primary wage earner and 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 all households with below-50 kl consumption.

[15] There were 48 households with no earner. The household income is solely the benefits they receive (such as unmemployement benefit). In these cases the benefits are not multiplied.

[16] 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).

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

Table 1: Summary statistics, Household survey, 2011, N=974

Variable	Mean	Std. Dev.	Min	Max
Household income*	5158.49	4397.83	224.43	64637.76
Number of flush toilets	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 kitchen 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**	1.000	0.000	0	1
Summer irrigation**	1.000	0.000	0	1
Car washing***	1.000	0.000	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 (Houshold 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? Aproximetely 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, while results that also include household characteristics from the survey cover 63,178 monthly observations.

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. The number of block tariffs, as well as the threshold quantities vary substantially in the data. 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. 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 Appendix 8.9.

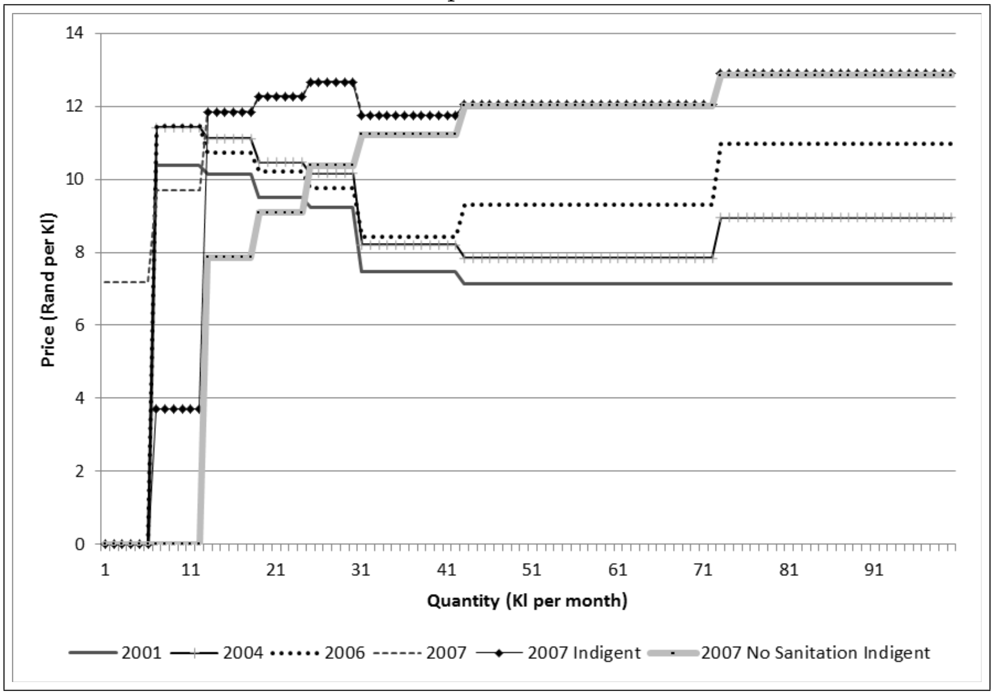
Based on my experience in the field, the local government makes extensive efforts to advertise the tariff structure and tariff changes when they occur. This includes special flyers as well as announcements in the local newspaper and at community meetings. In addition, the provider employs "education 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, all nominal values are in 2008 Rand).

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 from the first kl they consumed. Registered indigent households continued to receive 6 kl free water for sanitation and the municipality increased the free 6 kl amount to 12 kl. The tariff changes are shown on Figure 2 and 3 separately for registered and non-registered households. This policy change will provide a crucial source of identification for the counterfactual analysis under alternative price schedules, since it provides positive prices at each kiloliter, including the first 6 kl, for 88% of the population.

Note that for indigent households, comprising 12% of the data, I never observe positive prices for the first 6 kiloliters. However, there is no evidence of different consumption patterns between indigent and non-indigent households when they are facing the same tariff structure (see Table 4).

Figure 1: Selected tariff structures. All prices are in 2008 Rand and include 14% VAT.



In the analysis below, I include a dummy variable for indigent households rather than estimate the model separately for the two groups. This ensures that the sample used for estimation always contains positive prices for all consumption levels.

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). Even though the price schedule contains different prices for 42-72, 72-90, and 90+ kiloliters, only 4.66% of all households consume more than 42 kiloliters (1.88% once above-50 kl consumers are excluded). The distribution of the consumers by consumption is shown in Table 3.

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,

Figure 2: Policy change for non-indigent households. Total Prices, 2006-2007. All prices are in 2008 Rand and include 14% VAT.

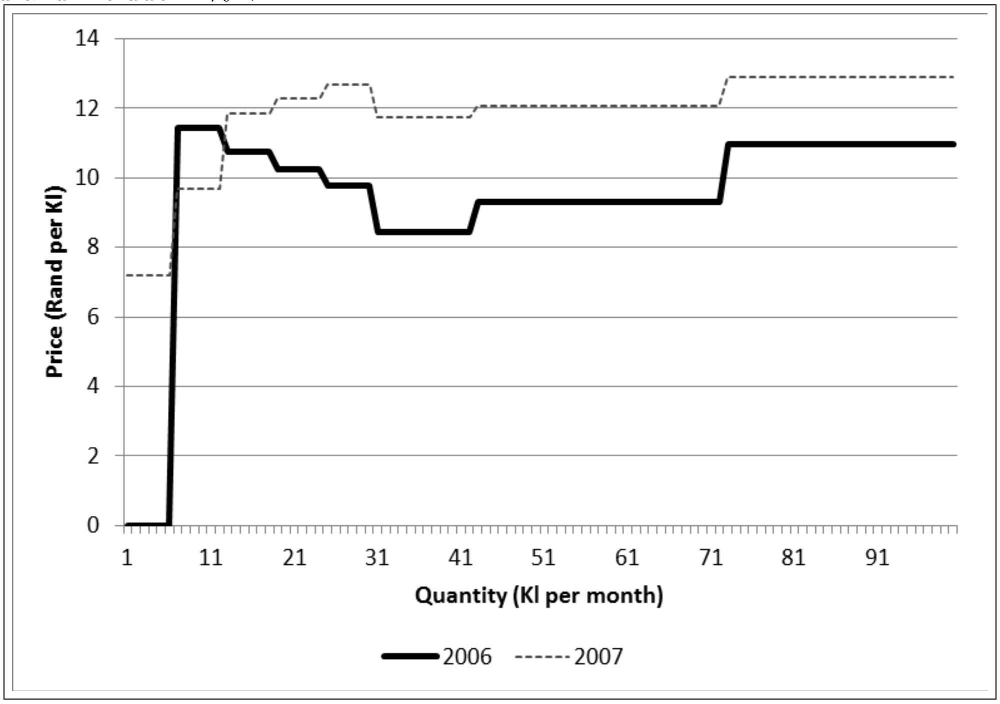


Figure 3: Policy change for indigent households, Total Prices, 2006-2007. All prices are in 2008 Rand and include 14% VAT

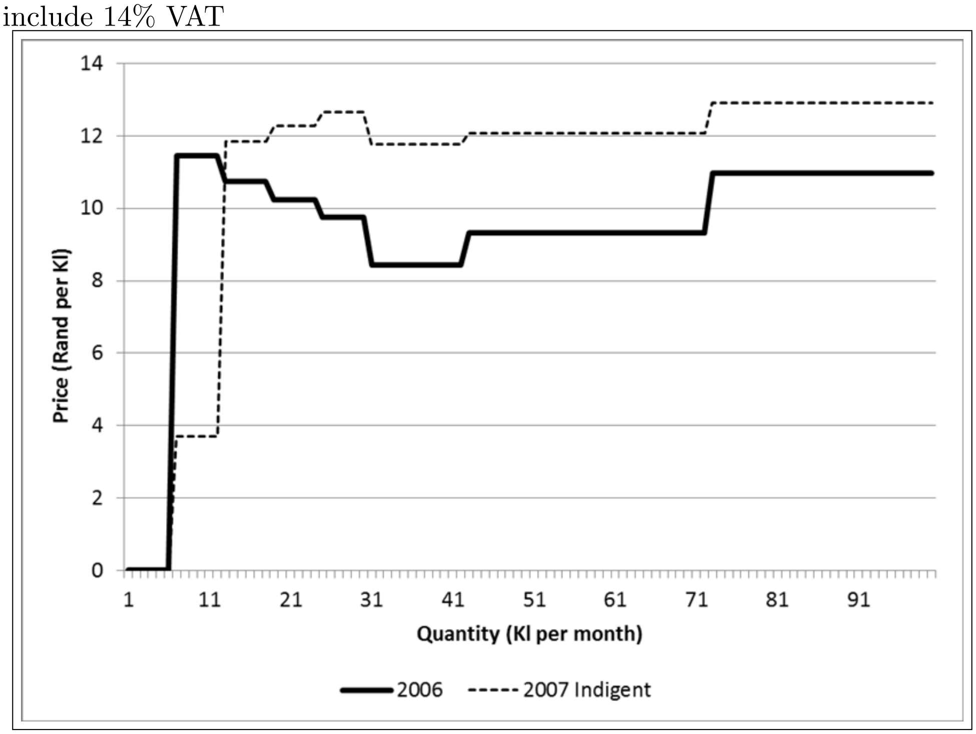


Table 3: Distribution of consumers by consumption, N=3,036,871

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

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

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 introduce a structural model for further analysis of optimal consumption in the presence of complex nonlinear tariff structures. The estimates described below are presented and discussed further in Appendix 8.8.

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 Appendix 8.8, 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 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).

The above 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. Moreover, not just the marginal prices, but also the kink points were changed. 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, the histogram of consumption levels in my dataset features some clustering around the kink points (see more on this in Section 5 below). 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 (3), I obtain the global optimum.

5 Specification and estimation

5.1 Demand specification

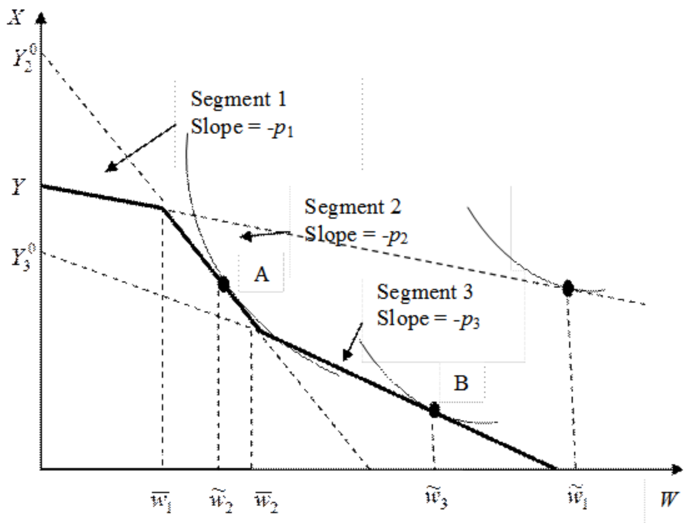
To obtain a linear demand function for convenient estimation, I assume that the consumer's direct utility function can be written as[18]

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

Here, Z represents observed consumer characteristics and contains a set of dummy variables such as the availability of water-using sanitation or indigent status, and δ is a vector of corresponding parameters. The role of the parameters $\alpha < 0$ and $\gamma > 0$ will be made clear below, and the term η

[18] A similar functional form is used by Hausman (1980).

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.



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).[19]

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

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

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

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 $V_k = V(P_k, Y_k^0)$.

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

This specification gives rise to the following econometric form of the consumer's demand (4):

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

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 The social planner's problem

As mentioned in the introduction, the optimal pricing of water is a major concern for governments and water providers throughout the developing world. To study this issue, I use the estimated parameters to derive an optimal pricing schedule from a social planner's problem. Specifically, I consider the problem of a social planner maximizing total consumer welfare subject to the following constraints:

1. (Revenue neutrality) The water provider should operate with the same economic loss/profit than under the current (2008/2009) price scheme, assuming a risk neutral water provider.

2. (Capacity constraint) The new tariff structure should not increase the current total consumption.

I also take as given the eight tariff tiers of the current schedule. This formulation is useful since I do not have information about the specifics of the production cost of the water provider.[20] It implies that the possible welfare changes come from the reallocation of the current consumption and payments across consumers.

In addition to the two constraints described above, I also investigate the effect of restricting the first price block (0-6 kiloliters) to have zero marginal price. Specifically, in a separate exercise, I provide optimal price schedules where the first marginal price is zero all households or for indigent households only.

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, and restrict attention to increasing price schedules.

Denote the current total revenue with $\overline{R} = \sum\limits_{i=1}^{I} \int\limits_{0}^{w_i^*(P^{08}(\cdot))} P^{08}(w)dw$ where I is the number of consumers and $P^{08}(w)$ is the current (2008/09) price schedule. Similarly, let current total consumption be $\overline{C} = \sum\limits_{i=1}^{I} w_i^*(P^{08}(\cdot))$. 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

$$\max_{P(\cdot)} E\left[\sum_{i=1}^{I} U_i(w,x)\right] = \sum_{i=1}^{I}\left[\int_{-\infty}^{\overline{\eta}_i} U_i(w_i^*(P(\cdot),\eta_i), x^*(P(\cdot),\eta_i))dF(\eta_i)\right] \tag{9}$$

[20] However, based on my conversations with Odi Water staff, a new tariff schedule satisfying the revenue neutrality and capacity constraints would be feasible to implement.

s.t.

$$\sum_{i=1}^{I} E\left[w_i^*(P(\cdot),\eta)\right] \leq \overline{C} \tag{10}$$
$$\sum_{i=1}^{I} E\left[\int_{0}^{w_i^*(P(\cdot),\eta_i)} P(w)dw\right] \geq \overline{R}.$$

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 (9) can be written as

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

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 (specified below), numerical maximization of (9) subject to (10) is straightforward.

5.3 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

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

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 (i) $\eta < \eta_{kl}$ 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 (12), demand is uniquely 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.[21] In contrast, in my dataset the average monthly consumption is 13 kiloliters, and households spend 5-10 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.

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 $\bar{\eta}_i$. Appendix 8.2 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

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

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.[22] This makes any counterfactual analysis impossible.

To derive the likelihood function based on (12), 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 the Appendix 8.3. It is continuous, but may not be everywhere differentiable in the parameters. Consistency of the MLE follows from Theorem 2' of Manski (1988). See Appendix 8.6.

Maximization of the likelihood function is implemented in MATLAB. 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 different type of quasi-Newton method was used to verify the parameter estimates. The covariance matrix of the parameter estimates is obtained by estimating the inverse of the information matrix. The model predicted values are computed using the formula given in Appendix 8.4 for expected consumption. Out of sample tests are performed and reported in Section 6.1. Appendix 8.5 contains a step-by-step summary of the estimation procedure.

6 Results

6.1 Parameter estimates and model performance

This section summarizes the results from estimating the above model. Table 19 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 done in the next section. The mean truncation point for the distribution of η is over thirty thousand, which implies that this constraint is not binding for

[22] 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.

Table 4: Model performance

Water consumption per household, in Kl	Actual mean	Predicted mean	Average error	N
All	13.39	13.33	-0.06	63178
Indigent	13.23	14.96	1.73	7534
Non-indigent	13.41	13.11	-0.30	55644
Restricted	14.98	14.07	-0.91	12231
Non-restricted	13.01	13.15	0.14	50947

Table 5: Model performance: out of sample test

Water consumption per household, in Kl	Actual mean Pre-policy	Actual mean After-policy	Model predicted MLE	Model predicted OLS	Model predicted IV
All	14.07	11.52	13.15	22.29	8.46
Indigent	13.70	11.95	13.41	8.76	16.09
Non-indigent	14.12	11.46	13.11	24.14	7.4179
Restricted	15.24	14.20	14.82	22.41	10.87
Non-restricted	13.78	10.92	12.79	22.26	7.91

the parameter vector that maximizes the likelihood function. The expected consumption predicted by the model is positive for all consumers.

Table 4 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. Looking more closely at the distribution of consumption predicted by the model, I find that the model underestimates high consumption levels (above the 95th percentile). This is due to the long right tail of the distribution of water consumption in my dataset.

To investigate the out-of-sample performance of the model, recall that the dataset contains the 2007 policy change when the free allowance was increased to 12 kl for low-income households but removed for the rest of the population. The new tariff resulted in a considerable decrease in the average price for low-income households, while other households experienced an increase in average price. I estimate the model only for a pre-policy sample, and use these parameter estimates to predict consumption after the policy change. Table 5 presents the model predicted means after the policy, which are close to the actual means observed in the data.

An important feature of the data after the 2007 policy change is a decrease in average consumption in response to an increase in the free allowance. In particular, Figure 5 suggests that some indigent households consuming more than 12 kl before the policy decreased their consumption below 12 kl after the policy was introduced to avoid paying the higher marginal prices.[23] This is of course consistent with a model of rational consumer behavior in the presence of nonlinear prices, where the consumer chooses both the price segment and water consumption on that segment. Indeed, Table 5 shows that the model used here is able to predict the decrease in consumption. Note however that, under this policy, the average price for consuming less than 27 kl actually decreased (see Figure 3). Not surprisingly, as the fifth column shows, a regression where the nonlinear price schedule is proxied by the average prices cannot explain the decrease in consumption following the policy change.

More generally, the findings reported above provide evidence that in the poor South African townships considered here consumers do take into account the nonlinearities in their price schedule, and choose the price segment on which to consume. This is in contrast to the findings 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).[24] 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.

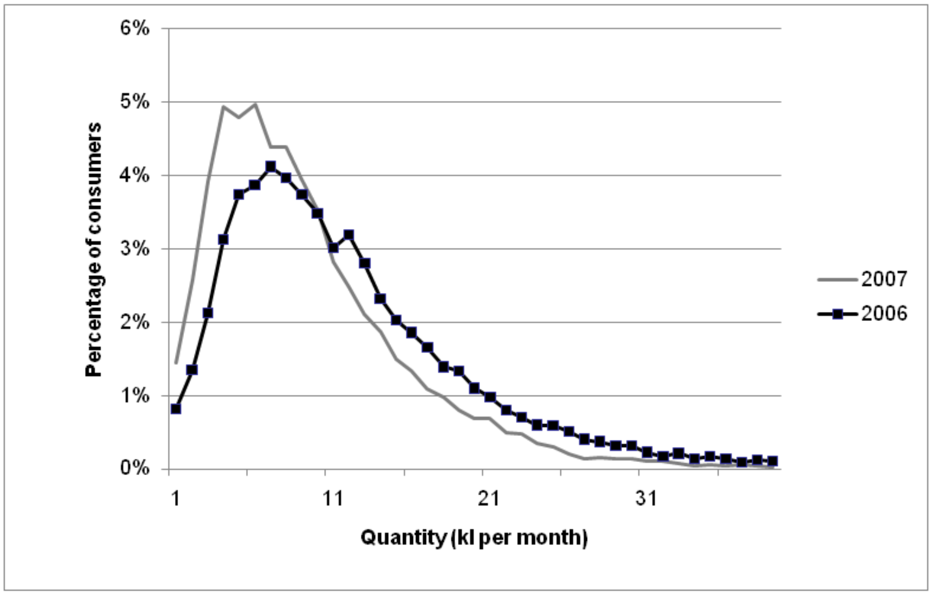
6.2 Marginal effects and price elasticities

To interpret the effect of our variables on expected consumption, marginal effects need to be calculated. 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). Marginal effects can be obtained by recalculating the model (optimal

[23] Contrary to a standard demand curve with linear pricing, demand here is measured in terms of the number of customers purchasing the q-th unit at the marginal price p. This function is called a demand profile in the literature.

[24] 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. In particular, they argue that "schmeduling" is more common in the presence of nonlinear pricing when there is a potential to confuse average and marginal prices.

Figure 5: Consumption decrease among indigent households due to the price reduction



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. I do this separately for indigent non-indigent households as well as the restricted group. The results are in Table 6.

The magnitudes of the estimates are reasonable. Based on Table 6, having water-using sanitation increases average monthly consumption by 3.73 kl, while having a bathtub or shower in the house has an effect of +5.14 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 7 shows the average household level price elasticities. The results indicate that households respond to price changes, with an average price elasticity of -0.79 percent. I find that indigent households are more price sensitive than non-indigent consumers.

Table 6: Marginal effects

Explanatory variables	*Effect on kl consumed per month*				
	All	Indigent	Non-indigent	Restricted	Non-restricted
Price (0.01 Rand)	-0.185	-0.167	-0.187	-0.230	-0.174
Income (Rand)x10-4	0.351	0.319	0.355	0.364	0.348
Average max daily temperature	0.223	0.189	0.228	0.255	0.215
Number of people on the property	0.052	0.047	0.052	0.059	0.051
Outdoor water usage	0.110	0.096	0.111	0.123	0.106
Binary variables					
Indigent	0.579	0.434	0.599	0.627	0.568
Restricted	0.358	0.306	0.366	0.344	0.362
Sanitation	3.729	4.598	3.611	3.764	3.721
Washing machine	0.075	0.072	0.075	0.086	0.725
Bathtub or shower	5.135	2.261	5.524	4.478	5.229
Education, completed high-school or higher	-0.145	-0.131	-0.147	-0.168	-0.140
N	63178	7534	55644	12231	50947

Table 7: Price elasticities by group

	MLE	OLS	IV
All households	-0.795	0.152	-0.06
Indigent	-0.895	0.161	0.154
Non-indigent	-0.781	0.15	-0.065
Restricted	-0.998	0.166	0.157
Non-restricted	-0.746	0.148	-0.097

For comparison, the second column of Table 7 shows price elasticity estimates from the OLS regression specified in Section 3. As can be seen, the OLS estimates result in incorrect signs for the price effect.

Table 8 shows price elasticities by consumption level. For all consumers, price elasticities tend to be higher for households that use more water. This is similar to the patern 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

Table 8: Price elasticities by household monthly water consumption

Quartile	Quartile range	Price elasticity				
		All	Indigent	Non-indigent	Restricted	Non-restricted
1-st	1-6	-0.750	-0.916	-0.731	-1.061	-0.691
2-nd	7-10	-0.756	-0.905	-0.733	-0.978	-0.706
3-rd	11-17	-0.804	-0.883	-0.792	-1.037	-0.746
4-th	18-	-0.869	-0.878	-0.868	-0.943	-0.847

sensitive.[25] Alternatively, this finding might be a consequence of the free water allowance. In some years, indigent households receive free water until 12 kl, so the effect of a price increase on these segments is magnified.

It is difficult to compare the elasticity measures above to previous estimates as studies typically find a wide range of price elasticities. Most differences are due to the different estimation methods employed. For example, Arbues et al. (2003) report reduced-form price elasticity estimates from 65 different studies, ranging from -1.64 to +0.332. Structural estimates of Pint (1999) imply elasticities between -0.04 and -1.24, while Olmstead et al. (2007) find elasticities between -0.589 and -0.330. There are two 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 -0.816 using aggregate data from Cote d'Ivoire.

6.3 Analyzing the Free Basic Water Policy

The most interesting question from a development perspective is how consumption and expenditure would change in the absence of the free water allowance. One of the difficulties in answering this question 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.

In a counterfactual exercise, I replace zero prices from 2002-2009 with the effective price the utility reports to the government, holding everything else constant.[26] Results are shown in Table

[25] In South Africa few (if any) households use water on luxury items (e.g., swimming pools) which tend to increase price elasticity in the US among high-income consumers.

[26] Note that this counterfactual exercise is different from the actual 2007 policy change where free water was taken

Table 9: Household consumption and expenditure changes

Means per household	All	Indigent	Non-indigent	Restricted	Non-restricted
Consumption (Kl/month)					
With free water	13.39	13.23	13.41	14.98	13
Without free water	13.32	14.96	13.11	14.07	13.15
Change (%)	-0.52	13.08	-2.24	-6.07	1.15
Expenditures (2008 Rand/month)					
With free water	85.88	72.39	87.71	102.35	81.93
Without free water	109.02	120.99	107.39	118.54	106.73
Change (%)	26.94	67.14	22.44	15.82	30.27

Notes: * All monetary amounts in constant 2008 Rand. The exercise without free water replaces 0 prices with the effective price the utility reports to the government.

9. 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 scenario, consumption decreases substantially.

In this counterfactual experiment, average consumption decreased only slightly by 0.52%, even though the associated average expenditure on water increased by 26.9%. This suggests that, by itself, the subsidy does not introduce substantial distortions in households' consumption. Instead, zero prices work as a cash subsidy for the households. In this sense, subsidizing households in the form of free water might be beneficial. On the other hand, if the government's goal is to increase clean water consumption, allocating the subsidy in a different way could be more desirable. 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.[27] 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, and discourage them from supplementing their water needs by fetching water from contaminated sources such as rivers and streams. In the next section, I provide optimal tariffs which are able to increase consumption keeping the total subsidy constant.

With detailed information on the health risks associated with consuming specific quantities

away from a large number of households but the rest of the price schedule was also changed substantially.

[27] The Weekender, January 17-18, 2009, p1.

Table 10: Description of the optimal tariff structures

Optimal tariff	Description
OT 1	Eight-tier tariff. The blocks are the same as in the current price schedule. Same tariff structure for all households. All prices obtained from the optimization problem.
OT 2	OT 1 but $P_1 = 0$ for indigent households.

of clean water, it would be possible to quantify the health implications of proposed and actual policies.[28] 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. In this sense the above results regarding the impact of a free water allowance on consumption are a first step towards establishing the social value of free water. In the pricing exercise below, I restrict attention to consumer utility derived directly from water consumption.

6.4 Optimal pricing scheme

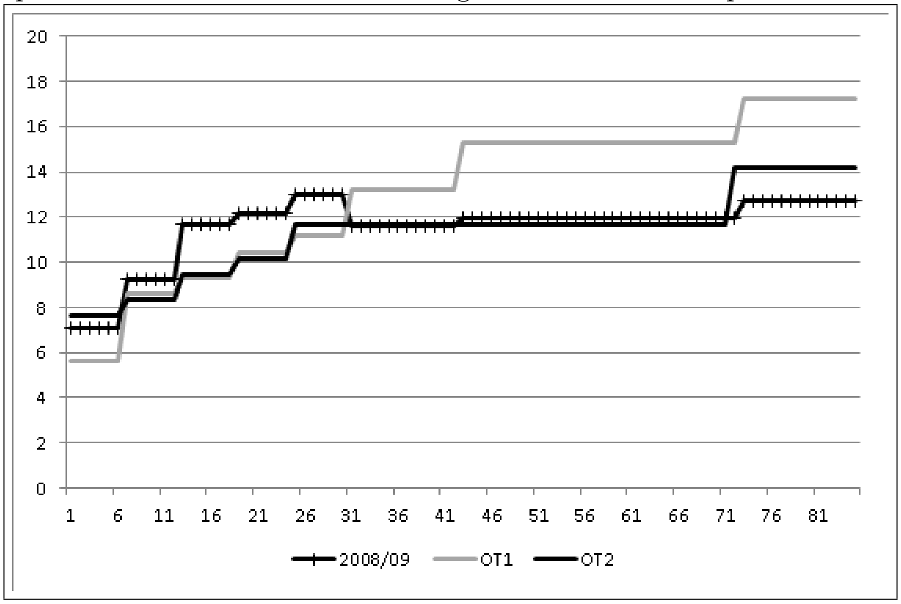
The previous section suggests that providing a government subsidy in the form of free water might be beneficial. But is a free water allowance the best way to provide such a subsidy? Or is it possible to achieve higher welfare if the same subsidy is distributed more evenly across the different segments of the price schedule? To investigate this issue, this section solves the social planner problem introduced in Section 5.2.

In this problem, total expected consumer welfare is maximized subject to a revenue and a capacity constraint. I consider two different optimal tariff structures. The first is an eight-tier tariff structure with the same kink points as in the actual tariff, where all eight prices follow from an optimization problem as in (9)-(10). The second structure modifies this benchmark to include the 6 kl free allowance for indigent households, while the other prices follow from the social planner's problem. Table 10 summarizes these two cases.[29] For this exercise, I ignore households without sanitation, since they have a separate water schedule without sanitation prices. The calculations below are performed using a random sample of 1000 households.

[28] It should be noted that the 2007 policy change which removed the free allowance for non-indigents also led to a substantial increase in the fraction of households consuming less than 6 kl water (from 27.3 to 37.1%).

[29] I also ran the optimalization routine assuming price structures where every household receives 6 kiloliters for free. There were no feasible solutions. The reason is that the provider's revenue significantly increased after the 2007 policy change and this increased revenue cannot be guaranted with the reintroduction of free water.

Figure 6: Optimal tariff schedules for non-indigent households. All prices are in 2008 Rand.



The resulting optimal tariff structures are shown in Figures 6 and 7. In contrast to the current tariff structure, the prices in the optimal tariff schedules are lower in the first five blocks and higher in upper blocks. The price difference between blocks is also higher than in the current schedule.

Table 11 shows the change in mean consumption among different consumer groups under the three different optimal tariff structures. Since the optimization was done under the constraint that total consumption should not exceed the current total consumption, there is little change in the total mean consumption among tariff structures. However, there are large differences in the distribution of consumption. Both OT 1 and OT 2 reduce the proportion of consumers under 6 kiloliters. In particular, under OT 1, only 6.5% of households consume under the WHO-recommended 6 kiloliters despite the fact that the free allowance has been removed. In this price structure, the price for the first 30 kiloliters is lower than under the current tariff. The consumption increase is the consequence of the marginal price decrease on these segments. Relative to OT 1, introducing the free allowance in OT 2 not only reduces welfare, but also raises substantially the proportion of consumers under 6 kl.

I calculate the compensating variation to measure the change in consumers' welfare as a consequence of the introduction of the new tariff structures. Specifically, I calculate the change in a consumer's income that equates utility under the current (2008/09) price schedule and expected

Figure 7: Optimal tariff schedules for indigent households. All prices are in 2008 Rand.

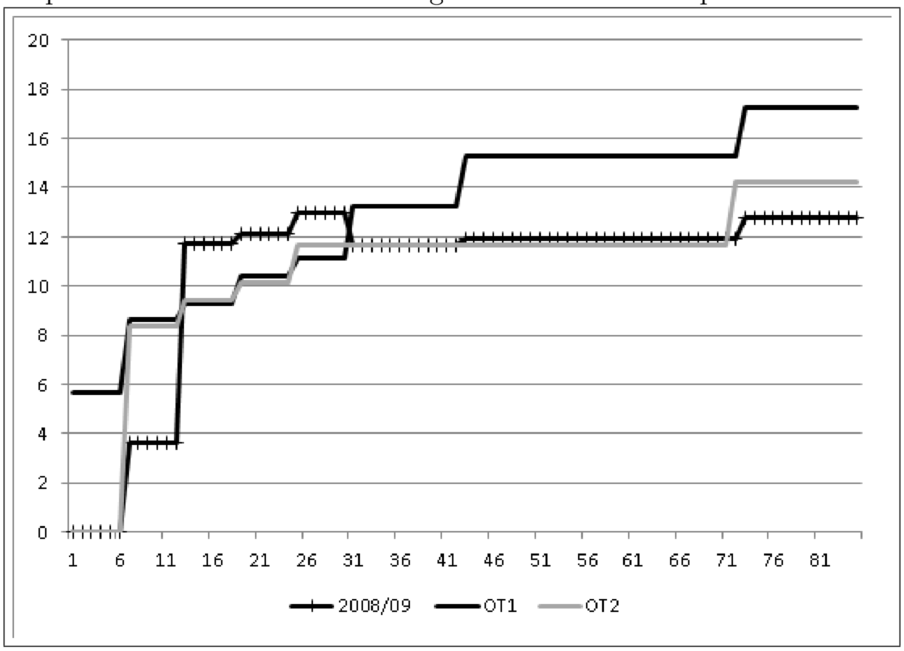


Table 11: Consumption under the optimal price schedules

Consumption distribution (%)	2008/2009	OT 1	OT 2
0-6	36.6	6.5	22.2
7+	68.6	93.5	77.8
Mean consumption			
All	7.74	8.8	7.74
Indigent	14.72	6.92	7.95
Non-indigent	6.71	9.07	7.71
Restricted	8.99	9.17	7.98
Non-restricted	7.37	8.68	7.67

Table 12: Change in expenditure under the optimal tariff structures

Expenditure	2008/2009	OT 1	OT 2
All	50.60	58.07	55.00
Indigent	54.48	42.19	17.99
Non-indigent	50.03	60.40	60.43
Restricted	56.24	61.49	53.02
Non-restricted	48.93	57.05	55.58
Compensating variation (in 2008 Rand)			
All		-31.33	-14.47
Indigent		39.94	19.42
Non-indigent		-37.18	-23.15
Restricted		-11.03	-1.55
Non-restricted		-32.12	-18.31

utility under the alternate price schedules (OT 1 or OT 2). For example, for two price segments (11) implies that the compensating variation C is defined implicitly by

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

where U_0 is the baseline utility level. A negative value of C indicates that the consumer is better off than under the baseline.

Expenditure changes and the compensating variation are in Table 12. Introducing any of the tariff structures would induce substantial expenditure differences among consumers based on consumption level. Under OT 1, indigent households would decrease their consumption, resulting in a lower bill, while non-indigent households would slightly increase their consumption and experience an average increase of 14% in their monthly bill. Average consumer welfare increases under OT 1 and OT 2. Since indigent households currently receive 12 kiloliters of water for free, the welfare change is negative for them under these optimal price scenarios. Non-indigent households benefit the most under OT 1. The overall compensating variation of 31 Rand per household per month under OT1 corresponds to 5 kiloliters of water and is equal to about 0.6-1 percent of household income.

In summary, an optimal tariff structure with no free allowance raises welfare, and substantially lowers the proportion of households under the WHO-recommended 6 kl.

7 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 3 million household level observations and the price variation in the period covered allow the precise estimation of the parameters of interest.

The results have three main implications. First, the paper asks how consumption and welfare would change in the absence of free water. As part of a counterfactual exercise, I replace zero prices from 2002-2009 with the effective prices the provider reports to the government, holding everything else constant. I find that consumption does not change substantially, suggesting that the free water allowance might function as an efficient cash transfer, causing little distortion in household behavior on average.

Second, I find that the optimal tariff schedule does not contain zero marginal prices, but rather divides the government subsidy more evenly across blocks. The continuously increasing eight-tier tariff structure I derive also reduces the percentage of consumers below 6 kl, improving the situation of those who consume the least water.

Finally, 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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8 Appendix

8.1 Proof of 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.

(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 $\eta < \bar{\eta}_{jk} \equiv \frac{\frac{1}{\gamma}\ln(\frac{\gamma\bar{w}_j+\alpha}{\gamma\bar{w}_k+\alpha}) + \frac{\gamma Y_j^0 - \bar{w}_j(1+\gamma P_j)+Z\delta}{\gamma\bar{w}_j+\alpha} - \frac{\gamma Y_k^0 - \bar{w}_k(1+\gamma P_k)+Z\delta}{\gamma\bar{w}_k+\alpha}}{\frac{1}{\gamma\bar{w}_k+\alpha} - \frac{1}{\gamma\bar{w}_j+\alpha}}$.

8.2 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 :

$$\begin{aligned}
F_{\eta_i}(x) &= \Phi\left(\frac{x}{\sigma_\eta}\right)/\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right) \text{ if } x < \overline{\eta}_i, \text{ 1 otherwise} && (14)\\
f_{\eta_i}(x) &= \phi\left(\frac{x}{\sigma_\eta}\right)/\left[\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)\sigma_\eta\right] \text{ if } x < \overline{\eta}_i, \text{ 0 otherwise} && (15)\\
E(\eta_i) &= -\phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)/\left[\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)\right]\sigma_\eta && (16)\\
Var(\eta_i) &= \sigma_\eta^2\left[1-\frac{\phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}{\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}\left(\frac{\overline{\eta}_i}{\sigma_\eta}+\frac{\phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}{\Phi\left(\frac{\overline{\eta}_i}{\sigma_\eta}\right)}\right)\right] && (17)
\end{aligned}$$

8.3 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 (12), for each observed monthly consumption level W, the contribution to the likelihood may be written as

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

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

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

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

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

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

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

8.4 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

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

8.5 Estimation procedure

The demand estimation procedure described in Section 5 is computationally complex. The following describes the step by step instructions to estimate the demand function in the case of a mixture of increasing and decreasing tariffs. The procedure can be implemented in MATLAB or using similar software.

The following steps should be iterated from initial starting values for the parameters $(\alpha, \gamma, \delta, \sigma_\eta, \sigma_\varepsilon)$ using any minimization procedure until convergence is achieved.

1. Compute the following for each individual:

(a) For each tariff segment k: Y_k^0, $w_k^0 = Z\delta + \alpha P_k + \gamma Y_k^0$, and $\theta_{jk} = \overline{w}_j - w_k^0$, as well as $\bar{\eta} \equiv \min_k(-w_k^0 - \frac{\alpha}{\gamma})$.

(b) *Compare segments to segments.* For each pair of segments i and j : η_{ij}^s which solves $V(P_i, Y_i^0) = V(P_j, Y_j^0)$. Given the functional forms, η_{ij}^s has a closed form solution and is unique.

(c) *Compare convex kink points to convex kink points.* For each pair of convex kink points i and $j : \eta^k_{ij}$ which solves $U(\overline{w}_i) = U(\overline{w}_j)$. Given the functional forms, η^k_{ij} has a closed form solution and is unique.

(d) *Compare segments to convex kink points.* For each convex kink i and segment $j \neq i \pm 1$: $u^L_{ij} < u^U_{ij}$ which are the two roots of the equation $U(\overline{w}_i) = V(P_j, Y^0_j)$ in η. Given the functional forms, for given i and j, there are a maximum of two roots which can be computed numerically (no closed form solution).

To make sure that a root exists, I first compute the value of η for which $\partial V/\partial\eta = \partial U/\partial\eta$. Equation $U(\overline{w}_i) = V(P_j, Y^0_j)$ has two roots iff at this value of η, $V_j < U_i$, in which case I proceed to compute the roots numerically starting the search from a sufficiently low or from a sufficiently large starting point. If $V_j > U_i$ for this value of η, then $U(\overline{w}_i) \leq V(P_j, Y^0_j)$.

2. Establish the feasibility conditions for each segment and kink as described in (12) using θ_{jk} calculated in 1(a).

3. Combine the feasibility and optimality conditions for each segment and kink, as described in Section 5.1, by taking the maximum of the lower bounds and the minimum of the upper bounds. Denote these values (L_k, H_k) and (l_k, h_k) for segments and kinks, respectively.

4. Substitute in the likelihood function as described in Appendix 8.3.

5. Choose $\delta, \alpha, \gamma\ \sigma_\eta$ and σ_ε to minimize the objective function. Iterate.

8.6 Consistency of the MLE

Let $W = (W_1, ..., W_N) \in \Theta$ denote the sequence of observations on the data and let G_N bet the empirical distribution of W. Let $L(b, W)$ denote the the log likelihood function derived in Section 8.3, where $b = (\delta, \alpha, \gamma, \sigma_\eta, \sigma_\varepsilon) \in B$ denotes the vector of parameters to be estimated.

Manski (1988, Theorem 2') shows that the maximum likelihood estimator of b is consistent provided the following conditions hold:

Condition 2 *There is a unique $b \in B$ for which $b = \arg\max_{c \in B} \int_\Theta L(c, W) dG$.*

Condition 3 *$L(\cdot, W)$ is continuous on B for all $W \in \Theta$.*

Condition 4 *There exists an integrable function $D : \Theta \rightarrow [0, \infty)$ for which $|L(c, W)| \leq D(W)$ for all $(c, W) \in B \times \Theta$.*

Condition 5 *B is compact.*

Condition 6 *The observations W_i, $i = 1, ..., \infty$ are independent realizations from G.*

Condition 1 states that the parameters $(\delta, \sigma_\varepsilon, \sigma_\eta)$ are identified. This requires the assumption that the model (hence the conditional densities in the likelihood function) is well-specified. If this holds, as explained in the text σ_ε and σ_η are identified from variation in consumption within and across segments (or kinks). Note that if the distribution of η is well-specified, it contains household-level heterogeneity without incurring an incidental parameters problem. In particular, household-level fixed effects are not estimated.

Condition 2 states that the likelihood function is continuous. In fact, as Manski (1988, Chapter 7.3) shows, this assumption can be relaxed to requiring that points of discontinuity have zero probability. Inspection of (20) shows that continuity of the likelihood function is satisfied.

Condition 3 is the condition for the Lebesgue dominated convergence theorem. In the standard case when the likelihood function is differentiable, this theorem guarantees that integration and differentiation of the likelihood function can be interchanged, which is used to show that the expected score is zero under the true parameters (e.g., Greene, 2000, p475) An important class of problems for which this condition fails is when the support of the dependent variable depends on the parameters. In my case, this might appear to be a problem because the support of η depends on the parameters due to the assumed truncation. However, note that the dependent variable also contains the optimization error ε which is distributed normally. Thus, the support of W is $(-\infty, +\infty)$ regardless of the parameters.

Finally, Conditions 4 and 5 are conditions on the parameter space and the sample which we assume to hold. Note that this theorem does not require the differentiability of the likelihood function.

8.7 Uniqueness of the demanded quantity for any η

As long as preferences are convex, we know that demand exits and is unique for any kinked budget. (More precisely, uniqueness is true 'almost surely', ignoring the case when a convex indifference curve has two tangency points with a non-convex part of the budget. Not to deal with this situation is standard.). This means that demand is unique for any η, and it is either w_1^0, $\overline{w}_1, w_2^0$, or w_3^0, since these are all the possibilities under the specific 3-part budget considered here. The conditions given in (21) are necessary for each of these cases to obtain.

$$w = \begin{cases} w_1^0 \quad if & \begin{cases} \text{(i) } w_1^0 < \overline{w}_1 \text{ and} \\ \text{(ii) } V(P_1, Y) \geq V(P_3, Y_3^0) \text{ if } w_3^0 > \overline{w}_2. \end{cases} \\ \overline{w}_1 \quad if & \begin{cases} \text{(i) } w_2^0 < \overline{w}_1 < w_1^0 \text{ and} \\ \text{(ii) } U(\overline{w}_1) \geq V(P_3, Y_3^0) \text{ if } w_3^0 > \overline{w}_2. \end{cases} \\ w_2^0 \quad if & \begin{cases} \text{(i) } w_2^0 \in [\overline{w}_1, \overline{w}_2] \text{ and} \\ \text{(ii) } V(P_2, Y_2^0) \geq V(P_3, Y_3^0) \text{ if } w_3^0 > \overline{w}_2. \end{cases} \\ w_3^0 \quad if & \begin{cases} \text{(i) } w_3^0 > \overline{w}_2 \text{ and} \\ \text{(ii) } V(P_1, Y) < V(P_3, Y_3^0) \text{ if } w_1^0 < \overline{w}_1 \text{ and} \\ \text{(ii') } V(P_2, Y_2^0) < V(P_3, Y_3^0) \text{ if } w_2^0 \in [\overline{w}_1, \overline{w}_2] \text{ and} \\ \text{(ii") } U(\overline{w}_1) < V(P_3, Y_3^0) \text{ if } w_2^0 < \overline{w}_1 < w_1^0. \end{cases} \end{cases} \tag{21}$$

Each condition has two parts: (i) feasibility (consumption on the budget), and (ii) optimality (higher utility than the 3 other possibilities if they are feasible). In most cases, (ii) can be simplified, as done in (21). For example, w_1^0 is demanded iff it is feasible and yields higher utility than $\overline{w}_1, w_2^0$ and w_3^0. In this case, feasibility of w_1^0 implies that neither $\overline{w}_1$ nor w_2^0 is feasible, so optimality simplifies to $V(P_1, Y) \geq V(P_3, Y_3^0)$. Clearly, these conditions are mutually exclusive (because of the optimality conditions). Therefore they are also sufficient for each case to obtain.

I now illustrate this with the specific functional forms resulting in (12). That is, I show that, for any η, (12) uniquely defines a demanded quantity (without gaps or overlaps). Under convexity, we know that

$$\theta_{11} < \theta_{12} < \theta_{22},$$

where the second inequality follows from $\overline{w}_1 < \overline{w}_2$, and the first from the fact that $w_2^0 - w_1^0 =$

$(P_2 - P_1)(\alpha + \gamma\overline{w}_1) < 0$ since $P_2 > P_1$ and $\alpha + \gamma\overline{w}_1 < 0$ from convexity. We don't know anything about θ_{23}, since w_3^0 can be anywhere on the extended budget constraint with P_3. Thus, there are 4 possible scenarios:

$$\begin{aligned}
\theta_{23} &< \theta_{11} < \theta_{12} < \theta_{22} \\
\theta_{11} &< \theta_{23} < \theta_{12} < \theta_{22} \\
\theta_{11} &< \theta_{23} < \theta_{12} < \theta_{22} \\
\theta_{11} &< \theta_{12} < \theta_{22} < \theta_{23}.
\end{aligned}$$

Consider the first one, and check that, for each possible η (12) gives exactly one solution (and we can do the same for the other three scenarios). Denote the conditions in (12) for demand to be on the first segment, the kink, or the two other segments S1, K1, S2 and S3.

When $\theta_{23} < \theta_{11} < \theta_{12} < \theta_{22}$, we have the following possibilities (summarized in Figure 8).

If $\eta < \theta_{23}$: Only S1 holds (and since $\theta_{23} < \eta$ does not hold the value of η_{13} is irrelevant). Observed consumption is predicted to be $w_1^0 + \eta + \varepsilon$.

If $\theta_{23} < \eta < \theta_{11}$: First part of S1 and S3 holds. If $\eta < \eta_{13}$, observed consumption is $w_1^0 + \eta + \varepsilon$. If $\eta > \eta_{13}$,observed consumption is $w_3^0 + \eta + \varepsilon$. Note that the second and third "and" in S3 are irrelevant since $\eta < \theta_{11}$.

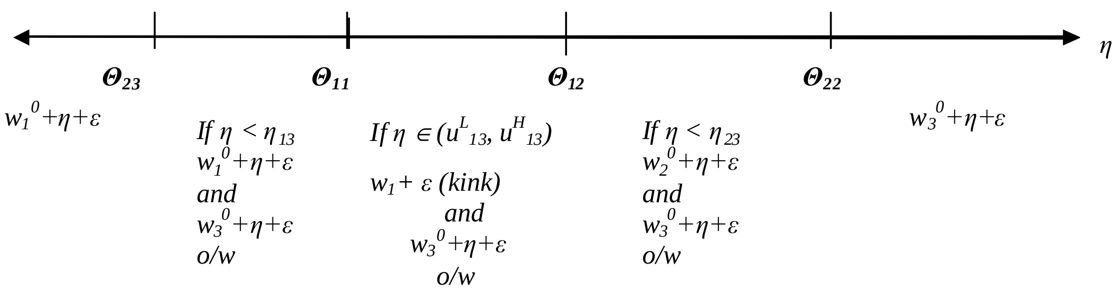
If $\theta_{11} < \eta < \theta_{12}$: First part of K1 and S3 holds. Observed consumption is $\overline{w}_1 + \varepsilon$ if $\eta \in (u_{13}^L, u_{13}^U)$ and $w_3^0 + \eta + \varepsilon$ otherwise. The first and third "and" in S3 are irrelevant.

If $\theta_{12} < \eta < \theta_{22}$: First part of S2 and S3 holds. Observed consumption is $w_2^0 + \eta + \varepsilon$ if $\eta < \eta_{23}$ and $w_3^0 + \eta + \varepsilon$ otherwise. The first and second "and" in S3 are irrelevant.

If $\eta > \theta_{22}$: Only the first part of S3 holds, i.e. $\theta_{23} < \eta$. The other parts of S3 are irrelevant. Observed consumption is $w_3^0 + \eta + \varepsilon$.

Figure 8 summarizes the consumer's observed consumption as a function of η for this scenario. The other 3 scenarios can easily be checked in the same way.

Figure 8: Uniqueness of the demanded quantity for any η.



8.8 Reduced form estimates

Table 13 presents OLS and IV regressions for the entire population of residential consumers using the average price paid by each household (spending on water divided by quantity consumed). The dependent variable is monthly household consumption in kiloliters. The regressions include the household characteristics observed in the administrative data, and Column (2) includes random effects, while Columns (3) and (4) include household-level fixed effects. In Column (4), the average price is instrumented by the marginal prices of consuming 6 preset quantities, corresponding to the most common kinkpoints in the observed tariff schedules (6, 12, 18, 24, 30, and 42 kl).

Table 14 presents the corresponding regressions for the 974 households on whom more information is available from the survey and who form the sample for the structural estimation. Over the eight-year period, this results in 63178 monthly observations. As can be seen, these estimates are very similar to those obtained for the entire population.

Table 15 replaces the household fixed effects with the detailed household characteristics available from the survey in the IV regression (corresponding to Column (4) of Table 14). Column (1) only includes the administrative variables and income from the survey. Column (2) adds characteristics related to water use, Column (3) adds household demographics, and (4) includes all these variables simultaneously. As can be seen the estimated price coefficient changes very little.

As described in the main text, including these 27 control variables in the structural estimation is computationally not feasible. I use 9 variables, and Column (5) of Table 15 presents the IV regression including only these 9 controls (as well as average price, which is treated as endogenous). Comparing the price coefficient in Columns (4) and (5) suggests that limiting the set of controls

Table 13: Reduced form estimates, Administrative data, N=3,036,871

Variables	OLS	Random effects	Fixed effects	IV fixed effect
Price	2.001***	1.488***	1.471***	-0.364***
	(0.001)	(0.002)	(0.002)	(0.003)
Indigent	2.470***	3.490***	3.705***	-1.333***
	(0.011)	(0.028)	(0.033)	(0.051)
Sanitation	-3.319***	-3.280***	-6.569***	-1.956***
	(0.017)	(0.072)	(0.156)	(0.161)
Average max daily temperature	0.103***	0.096***	0.095***	0.098***
	(0.001)	(0.001)	(0.001)	(0.001)
Area 1	-1.086***	-2.221***	-	-
	(0.01)	(0.048)		
Area 2	-1.994***	-2.311***	-	-
	(0.015)	(0.067)		
Restricted	0.754***	-0.929***	-1.136***	-0.679***
	(0.012)	(0.016)	(0.017)	(0.018)
Constant	-0.851***	1.763***	4.722***	9.969***
	(0.052)	(0.086)	(0.142)	(0.15)

Notes: The dependent variable is monthly consumption in kl. Supply areas are created by the utility and has no significant meaning other than describing a georgraphic 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.

does not lead to a substantial loss of information.

Table 14: Reduced form estimates, Administrative data, N=63,178

Variables	OLS	Random effects	Fixed effects	IV fixed effect
Price	1.957***	1.366***	1.341***	-0.417***
	(0.009)	(0.01)	(0.011)	(0.019)
Indigent	2.433***	3.019***	3.216***	-1.529***
	(0.075)	(0.195)	(0.233)	(0.345)
Sanitation	-3.305***	-2.632***	-2.227***	1.534
	(0.12)	(0.479)	(0.704)	(2.012)
Average max daily temperature	0.104***	0.099***	0.098***	0.105***
	(0.005)	(0.004)	(0.004)	(0.005)
Area 1	-1.524***	-2.998***	-	-
	(0.07)	(0.301)		
Area 2	-2.260***	-3.048***	-	-
	(0.099)	(0.433)		
Restricted	1.150***	0.017	-0.164	-0.218*
	(0.079)	(0.111)	(0.115)	(0.121)
Constant	-0.541	2.040***	1.279*	6.853***
	(0.356)	(0.57)	(0.683)	(1.817)

Notes: The dependent variable is monthly consumption in kl. Supply areas are created by the utility and has no significant meaning other than describing a georgraphic 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.

Table 15: Instrumental variable regressions, Administrative data complemented with the survey data, N=63,178

Variables	(1)	(2)	(3)	(4)	(5)
Price	-0.617***	-0.559***	-0.602***	-0.551***	-0.553***
	(0.024)	(0.023)	(0.024)	(0.023)	(0.023)
Income	0.00019***	0.00019**	0.00014***	0.00003***	0.00008***
	(9.39e-06)	(9.18e-06)	(0.00001)	(0.00001)	(9.35e-06)
Indigent	-2.118***	-1.137***	-2.328***	-1.498***	-1.247***
	(0.143)	(0.138)	(0.141)	(0.137)	(0.134)
Sanitation	-0.309*	-1.729***	0.025	-1.083***	2.541***
	(0.176)	(0.172)	(0.177)	(0.175)	(0.157)
Average max daily temperature	0.105***	0.105***	0.105***	0.104***	0.104***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Area 1	-1.984***	-1.525***	-1.700***	-1.440***	
	(0.1)	(0.099)	(0.099)	(0.098)	
Area 2	-6.192***	-5.049***	-5.783***	-4.745***	
	(0.143)	(0.145)	(0.142)	(0.145)	
Restricted	1.168***	1.387***	0.942***	1.179***	1.405***
	(0.118)	(0.114)	(0.116)	(0.113)	(0.114)
Number of flush toiletes		1.073***		0.641***	
		(0.094)		(0.095)	
Number of standpipes		-0.340***		-0.468***	
		(0.045)		(0.046)	
Number of bathtubs		1.708***		1.562***	
		(0.093)		(0.094)	
Number of showers		0.433***		0.684***	
		(0.14)		(0.141)	
Number of kithcen taps		-0.708***		-0.426***	
		(0.094)		(0.093)	
Number of bathroom taps		1.355***		1.375***	
		(0.068)		(0.069)	
Washing machine		0.478***		0.666***	0.746***
		(0.091)		(0.093)	(0.091)
Lawn area		1.026***		1.070***	
		(0.105)		(0.104)	
Flower garden		-0.564***		-0.549***	
		(0.099)		(0.100)	
Vegetable garden		0.940***		1.100***	
		(0.117)		(0.118)	
Winter irrigation*		0.407***		0.337***	
		(0.058)		(0.058)	
Summer irrigation*		-0.247***		-0.230***	
		(0.049)		(0.050)	
Carwash**		-0.080		-0.087*	
		(0.049)		(0.049)	

Table 15 continued

Variables	(1)	(2)	(3)	(4)	(5)
Some high school			1.497***	1.919***	
			(0.171)	(0.166)	
High shool graduate			0.867***	1.011***	
			(0.162)	(0.156)	
Some higher education			1.191***	0.905***	
			(0.182)	(0.176)	
Completed higher education			2.929***	2.022***	
			(0.203)	(0.195)	
Number of adults			1.131***	0.994***	
			(0.036)	(0.036)	
Number of teens			-0.149***	0.101**	
			(0.047)	(0.048)	
Number of children			-0.048	-0.104**	
			(0.046)	(0.046)	
Number of people working outside the home			-0.127**	-0.484***	
			(0.062)	(0.062)	
Number of persons on the property					0.403***
					(0.020)
Outdoor water usage***					0.426***
					(0.044)
Bathtub or shower****					4.080***
					(0.094)
Education, completed high school or higher					-0.409***
					(0.094)
Constant	9.860***	7.838***	5.506***	4.111***	0.841*
	(0.531)	(0.519)	(0.546)	(0.533)	(0.506)

Notes: The dependent variable is monthly consumption in kl. Supply areas are created by the utility and has no significant meaning other than describing a georgraphic 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. *At least once during the season. **How often do you wash your car(s) at home using water you purchase from the utility? Aproximetely 30 percent of all households wash their car at home, and half of these do so once a week. ***Outdoor water usage variable is 0 to 3 depending whether the household has either a vegetable garden, flower garden, or a lawn area. ****Bathtub or shower is 1 if the household has either a bathtub or shower or both and 0 otherwise.

8.9 Data

8.9.1 Income

Table 16: Income measures, 2008 Rand

	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.

8.9.2 Tariff

Table 17: Sanitation multiplier, 2002-2009

Water consumption in kl	Sanitation multiplier
0-6	0.98
7-12	0.9
13-18	0.75
19-24	0.6
25-30	0.52
31-42	0.1
42 >	0.01

Table 18: Summary statistics, Tariff structure, 2002-2009, 2008 Rand

Variable	Units	Mean	Std. Dev.	Min	Max
Marginal price in block 1	Kl/R	1.59	2.89	0	7.18
Marginal price in block 2	Kl/R	9.96	1.93	3.67	11.78
Marginal price in block 3	Kl/R	10.54	1.34	6.47	11.86
Marginal price in block 4	Kl/R	10.38	1.37	6.53	12.28
Marginal price in block 5	Kl/R	10.39	1.53	6.61	12.99
Marginal price in block 6	Kl/R	9.10	1.72	6.69	12.02
Marginal price in block 7	Kl/R	9.17	1.97	6.76	12.86
Marginal price in block 8	Kl/R	11.32	1.46	8.96	12.91
Water quantity at kink 1	Kl	6.00	0.05	6	12
Water quantity at kink 2	Kl	12.00	0.05	12	18
Water quantity at kink 3	Kl	18.00	0.05	18	24
Water quantity at kink 4	Kl	24.83	3.77	24	42
Water quantity at kink 5	Kl	31.93	8.80	30	72
Water quantity at kink 6	Kl	42.00	0.24	42	72
Water quantity at kink 7	Kl	75.68	7.26	72	90

Table 19: Parameter estimates, ML

Variables	Parameters	t-value
Constant	2.002	0.288
Indigent	0.470	0.994
Restricted	0.320	0.638
Sanitation	4.604	0.220
Average max daily temperature	0.199	0.004
Washing machine	0.077	0.060
Number of people on the property	0.049	0.021
Outdoor water usage	0.102	0.089
Bathtub or shower	6.134	0.053
Education, completed high school or higher	-0.138	0.033
Price	-1.117	0.002
Income	0.3×10^{-4}	0.000
σ_ε	3.028	0.007
σ_η	0.063	0.215

Figure 9: Water-using sanitation for a typical household in the data