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Distributional Statistics of Municipal Water Use During Cape Town's Drought

Implications for Affordability, Conservation, and Tariff Design

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Distributional Statistics of Municipal Water Use During Cape Town's Drought: Implications for Affordability, Conservation and Tariff Design

Joseph Cook, Johanna Brühl, and Martine Visser*

Abstract

We calculate the first distributional statistics for municipal water supply deliveries using 14.9 million monthly billing records for a half-million households in Cape Town, South Africa, from 2014-2018. These years span a historic drought and a multi-faceted package of conservation programs that achieved a 50% city-wide drop in consumption. We find that the top 10% of households consumed 31% of water deliveries before the drought, with the Gini coefficient showing clear seasonal peaks driven by outdoor water use. Matching billing records to fine-grained census data from 2011, we find that the correlation between income and water use in the winter was 0.08 but rose to 0.36 during outdoor watering seasons. This correlation declines before switching signs by the end of the drought. The city's increasing block tariff implied that the top 10% of users generate approximately half of utility revenues. Although before the drought these top users were more likely to be high income, the composition of top water users changed during the drought. Average income of top users during the drought was 35% lower than the average income of top users before the drought. Our results suggest that Cape Town's policy of providing a free allowance of 10.5 kL (m^3) per month to qualifying indigent households helped protect many, but not all, from multiple steep tariff increases.

Keywords: drought; water pricing; distributional analysis

JEL Codes: Q25

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1. Introduction

Municipal water utilities around the globe face a daunting set of challenges. In high-income countries, they must maintain piped networks that deliver high-quality, reliable water supply to homes and remove household waste via piped sewerage networks. In most cities in low- and middle-income countries, they must improve the quality and reliability of services, connect households to the network, and plan for large population influxes. Utilities need financial resources to attack these problems, but tariffs in many places are too low: only 35% of utilities in the World Bank's International Benchmarking Network for Water and Sanitation Utilities (IBNET) database collect enough revenue to cover operations and maintenance costs, and only 14% collect enough to cover the full economic cost of service provision, including the cost of capital (Andres et al. 2019).

Support for tariff reforms, however, depends on effectively protecting poor customers. Furthermore, "affordability" is explicitly mentioned in many of the Sustainable Development Goals, including access to "affordable" housing, energy, health care and water and sanitation services. A common policy prescription among water tariff consultants is to balance the objectives of affordability, efficiency and revenue stability with increasing-block tariffs, where the marginal price of water increases with increasing use. Because it is assumed that the highest water users are also the wealthiest, this tariff can in theory redirect revenue from wealthier households and cross-subsidize lower rates for low-income households, who are assumed to use less water. In practice, these tariff policies have been shown to do a poor job of directing subsidies to the poor in many low-income countries, in part because the correlation between income and water use is weaker than commonly believed (Fuente et al. 2016; Burger and Jansen 2014). Utilities are increasingly experimenting with other types of "customer assistance programs" to help the poor (Cook et al. 2020). These include providing a free or subsidized "lifeline" quantity of water to poor customers, a policy that many cities in South Africa have employed as part of the country's Free Basic Water program (Department of Water Affairs and Forestry (DWAF) 2001; Beck et al. 2016; Smith 2012).

At the same time, many cities are struggling to balance increasing water demands with raw water supplies that are subject to periodic drought and are shared among competing agricultural and industrial water uses (McDonald et al. 2014; Nobre et al. 2016; Tortajada 2008).

The City of Cape Town, South Africa, is in many ways emblematic of these challenges of financing, water scarcity, and affordability. The city has a high degree of income inequality and a heterogeneous housing stock, with a large fraction of free-standing residential houses using a substantial amount of water outdoors. It also has a sizeable minority of households who are not connected to the piped network and collect from public water points (Mahlanza, Ziervogel and

Scott 2016). Facing a historic four-year drought, the city instituted a battery of conservation measures that narrowly avoided a "Day Zero" in 2017 when the piped municipal system would stop nearly all deliveries. There was widespread discussion of the fairness of these water use restrictions and conservation programs during the drought (Roeland 2018; Enqvist and Ziervogel 2019; Visser and Brühl 2018; Joubert and Ziervogel 2019; Millington and Scheba 2020; Mahlanza et al. 2016). As we describe below, price and non-price tools were used to reduce water use and match supply and demand, including leveraging social norms to reduce water (Brühl and Visser 2020; Brick, De Martino and Visser 2018). In the extreme, the mayor of Cape Town publicly named the streets of the highest water users to shame them into reducing water (Brühl, Serman and Visser 2020).

Who were these high water users, and were they in fact the wealthiest households? What share of the total water supply were they consuming? Economists have used distributional statistics to measure income and wealth inequality for decades (Kuznets and Jenks 1953; Saez and Zucman 2016; Piketty, Saez and Zucman 2018) . The most well-known tool is the Lorenz curve, and the most well-known statistic is the Gini coefficient. Others report the share of wealth or income held by the top 0.1%, top 1%, bottom 50%, etc. These statistics are powerful in part because they communicate inequalities in a simple metric, but also because they allow comparisons across time and space to examine the impact of public policies on inequality (Saez 2017).

These distributional statistics have received much less attention in the water sector. The Gini coefficient was first mentioned in a basin-scale, multi-sector study of inequality in water use registrations (or rights) in South Africa (Cullis and Koppen 2007). Researchers have since used the concept to measure inequality in access to piped water supply (Yang et al. 2013; Berthe 2018) or inequality in the number of hours that the piped system supplies water (Guragai et al. 2017). The Gini coefficient has also been used as an objective in a multi-sector water allocation optimization model (Hu et al. 2016). We know of only one study that measured distributional statistics for water use among households connected to a piped municipal system. Morales et al. (Morales-Novelo, Rodríguez-Tapia and Revollo-Fernández 2018) relied on a cross-sectional survey of 689 households in Mexico City, but focused primarily on the distribution of water subsidies and relied on self-reported water volumes rather than billed consumption. Many households have difficulty reporting water volumes or water expenditures accurately (Foster 2004; Fuente et al. 2016) unless enumerators ask about usage in specific water use categories (Cheesman, Bennett and Son 2008).

Our paper contributes to the literature in five ways. First, we calculate the first set of distributional statistics, including Gini coefficients and water use shares, using approximately 15 million municipal water billing records from all free-standing residential households in Cape

Town from 2014-2018. Second, since our study period spans the historic drought, we use a panel approach to report how these distributional statistics changed as the package of conservation efforts took effect, again novel to the water supply literature. We then move to a broader investigation of how these distributional statistics, paired with information on tariffs and the income distribution, can inform policy. In a third contribution, we impute household income (by spatially matching billing records to fine-scale Census data on income) and provide what we believe are the first panel estimates of how the correlation between income and water use changes seasonally and during a drought. We find that the correlation between income and water use is positive and strongly seasonal before the drought, and reverses signs by the end of the drought, with higher-income households using less water than lower-income households. Fourth, we address the implications of distributional statistics for tariff design by simulating the share of utility revenues paid by the highest water users under the city's increasing block tariff and examining the average income of customers in those highest water use blocks. Finally, we contribute to the literature on affordability. We calculate both the percentage of households who, according to our estimates, paid more than 5% or 10% of their income towards a combined water and sewer bill, as well as the average bill paid by income quintiles. This type of affordability analysis is rarely conducted using billing data and fine-scale income data, and, to our knowledge, has not been conducted as a panel over a period of drought and multiple tariff increases. Though relatively simple, we also provide a rare counterfactual analysis of a customer assistance program (Cape Town's Free Basic Water policy) by simulating what these affordability metrics would have been were the policy not in place.

2. Background

Cape Town has a Mediterranean climate with warm, dry summers (November to February) and rainy winters (May to August). Nearly all of the region's annual rainfall arrives in the winter, contributing more than 90% of the city's water supply via six rain-fed dams (City of Cape Town 2018b). Like many cities in the western U.S., Australia and elsewhere, households in Cape Town have typically used more water during the summer months for use outdoors in yards, gardens and pools.

Residential water customers are a key component of overall water demand as city water managers match that demand to limited supplies. In 2017, 69% of water deliveries were made to domestic households, the focus of our analysis, who comprised approximately 95% of the 624,000 water accounts (City of Cape Town 2018b). The 11,000 commercial accounts and 6,000 industrial accounts accounted for 13.5% and 4.2% of water deliveries in 2017, respectively, with the remainder from city- and government-owned facilities and an unspecified "other" account type (City of Cape Town 2018b).

Our analysis focuses on domestic households who are in detached or semi-detached structures and are thus unlikely to share a water bill. Based on the most recent census data, this covers approximately 66% of the households in Cape Town: 56% live in brick or concrete structures on their own plot, and another 10% live in semi-detached houses, a second house on a plot, or a townhouse (Statistics South Africa 2012). Because we do not have data on whether individual flats in apartment buildings have separate water meters, we exclude the ten percent of households who live in this type of multifamily housing units (Statistics South Africa 2012).

From 2015 until the beginning of 2018, Cape Town and the surrounding area experienced a dramatic and unprecedented drought (Otto et al. 2018; Wolski 2018; Wolski, Hewitson and Jack 2017). The six major surface water dams that supply the City of Cape Town dropped from 100% filled capacity in 2014 to 38.4% in 2017 (City of Cape Town 2018b). They dropped to such low levels in early 2018 that Cape Town was at risk of becoming the first major city world-wide to face a "Day Zero" when the municipal piped system would essentially stop delivering water to homes and businesses. To curb demand, the local municipality implemented a variety of demand side management tools (Parks et al. 2019; Brühl and Visser 2020; Sinclair-Smith and Winter 2019; Muller 2019; Taing et al. 2019; Booysen, Visser and Burger 2019; Brick et al. 2018). Households faced increasingly stringent controls on water usage, forbidding watering gardens or pools in earlier stages and restricting residents to 50 liters of water per person per day by February 2018. Households who repeatedly failed to comply with water restrictions had water-limiting devices attached to their water line (Sinclair-Smith and Winter 2019). Water prices also increased substantially throughout the drought, increasing overall by 175% in February 2018, with rates in the highest consumption tiers of the increasing block tariff increasing the most (Brühl and Visser 2020). At the same time, the City increased its efforts to raise water conservation awareness and to inform the public about the severity of the drought (Ziervogel 2018; Sinclair-Smith et al. 2018; Booysen et al. 2019). All interventions combined led to a more than 50% decrease in consumption in less than three years (Brühl and Visser 2020; Muller 2019). Decomposing the marginal impacts of each type of demand-side policy in a causal framework is not our focus, but Suppl. Appendix Figure S1 shows the dramatic overall decline in water deliveries to domestic customers during the time period, and Figure S2 shows the importance of reducing household demand in avoiding Day Zero.

According to Statistics South Africa's 2011 Census, the most recent available, the average household in Cape Town has 3.3 members. Wealthier households are on average smaller than poorer households (Table 1): the correlation between household size and annual household income is -0.55 in our sample. Average annual household income was R161,762 in 2011 (11,094 US$) (Statistics South Africa 2012). Matching a household's monthly water use from the billing data to the average income in the Small Area Layer (SAL) in which they live, Table 1 also shows a positive correlation between household income and water use before the drought. We return to this point in the next section.

Table 1. Income, Household Size, and Pre-drought Water Consumption, by Income Quintile

Income Quintile	**First Mean (sd)**	**Second Mean (sd)**	**Third Mean (sd)**	**Fourth Mean (sd)**	**Fifth Mean (sd)**
Average monthly household income (2011 ZAR)	3,101 (696)	5,756 (1023)	11,010 (2264)	20,628 (3559)	37,789 (10676)
Average household size	3.6 (0.58)	4.2 (0.5)	3.9 (0.53)	3.2 (0.66)	2.8 (0.43)
Average property value (2011 ZAR)	122,718 (91,189)	251,216 (130,384)	464,833 (225,438	871,348 (461,639)	1,887,764 (1,669,806)
Average monthly water consumption pre-drought (kL)					
Summer months (Nov-Feb)	15.9 (21.1)	16.7 (16.3)	18.6 (14.7)	21.5 (16.1)	31.8 (25.8)
Winter months (Mar-Sept)	14.8 (22.0)	15.1 (16.6)	16.4 (13.8)	15.9 (12.3)	18.0 (14.4)

Notes: Source = 2011 Census (Statistics South Africa). ZAR = South African Rand. Income, household size and property value are averaged at the Small Area Layer (SAL) level, and not observed for each household. Water use statistics, observed at the household level, are averaged over the period 2014 to 2015 and matched to income quintiles via the Small Area Layer (SAL) the household is in.

Around a third of the population is eligible for the indigent support program (approximately 213,424 households), which provides free 10.5kL (m^3) of water and 7.35kL of sanitation, refuse removal rebates, free "basic" electricity and property rates rebates (Department of Water and Sanitation 2018). Any water use above 10.5kL is charged at the prevailing water tariff for that volume. This can mean that an indigent household sees an extremely large jump in the marginal price of water after 10.5kL[*]. Households are automatically enrolled in the indigent support program in Cape Town if their municipal property value is lower than R300,000

[*] The tariff blocks in Cape Town are: <6 kL, 6-10.5kL, 10.5 -20kL, 20-35kL, 35-50kL and >50kL. An indigent household who exceeded the "free" lifeline block would face a marginal price for the third tariff block that increased from ZAR 12.54 per kL in January 2015 to ZAR 100 in February 2018.

(approximately US$21,000). Though few do, households can also apply for indigent status if their property value is higher than R300,000 but their total monthly household income is less than R6,000 (approximately US$400). Most participating households were enrolled automatically.

Finally, note that the increasing-block tariff structure in Cape Town included a free block of 6 kL for all households, regardless of income, until the increasing severity of the drought forced the city to end this free allowance for non-indigent households in July 2017 (City of Cape Town 2018a).

3. Methods

We used monthly water consumption data from June 2014 to May 2018 for all free-standing households with a water meter that received their bill via post (not via email). This is 507,579 domestic free-standing households with access to water supply metered by a credit meter. We lack consumption data on the 20% of residential customers who receive an electronic bill, as this data is stored in a separate billing database. It is possible that these "e-bill" customers are systematically different (e.g., wealthier) than customers who receive bills in the mail, but we have no data to make this comparison and acknowledge this as a possible limitation.

We include only actual water meter readings. Every month, water meters are read manually using a handheld computer terminal. If a meter reader cannot access the meter, an account holder's bill will be estimated based on their past consumption. We drop estimated readings because they are often much higher than a household's actual consumption. Observations with very large billing periods of more than 45 days were dropped. Furthermore, we dropped the bottom 1% of water users in each month to remove zero consumption values and households that were likely vacant homes, either permanently or because of vacations. This leaves us with 14,945,343 monthly water observations.

How we treat households with a major water leak from a burst pipe or fitting may affect our distributional calculations. A simple approach of trimming the top 1% of the distribution in every month would bias our distributional statistics downward (less unequal) if some of those 1% of households are those with high ongoing water use. Instead, we use an algorithm to detect observations that are very likely to be leaks. After splitting the data into nine wet and dry seasons over the four-year period, we calculate median seasonal water use for each household. If a household's monthly water use is four times higher than its seasonal median water use, we assume that a major leak occurred that month and drop it from the distributional calculations. This approach drops 53,312 monthly observations (<1% of the total). Our final sample comprises

14,892,031 observations. The supplementary appendix repeats our main calculations without dropping possible leaks to explore the importance of this assumption.

The main distributional measure we use is the Gini coefficient, calculated in the conventional manner as:

$$G = \frac{2\sum_{i=1}^{n} i\, W_i}{n\sum_{i=1}^{n} W_i} - \frac{n+1}{n} \qquad (1)$$

where W_i is household i's billed water consumption in month i, and the *n* total households are ordered from lowest to highest consumption. We also display Lorenz curves, which plot the cumulative distribution of municipal water use against a distribution assuming perfect equality. The Gini coefficient is equivalently calculated as the area under this line of perfect equality minus the area under the empirical Lorenz curve. Gini coefficients and Lorenz curves were calculated for each month using the Stata package *ineqdeco*. Finally, we also report water delivery shares: the share of total water deliveries in our sample that go to the top 0.1% of water users, to the top 1%, the top 10%, and the bottom 50%. These groups are re-calculated each month such that a household could be in the top 10% in 2015, fail to reduce municipal water use in response to the drought in 2016, and be included in the top 1% in 2017.

To calculate the impact of tariff increases and changing water use on household affordability and overall utility revenue, we simulate each household's combined bill for water and sanitation services. We use the simulated bill rather than actual billed amounts to avoid complications with accounts that are in arrears because of fines and unpaid past bills, which would carry forward and inflate the current month's bill. As tariffs changed multiple times during the study period, we calculate each household's monthly bill based on the tariff structure in place during that month. Each monthly billing record states whether or not a household is registered as indigent and receives bill reductions.

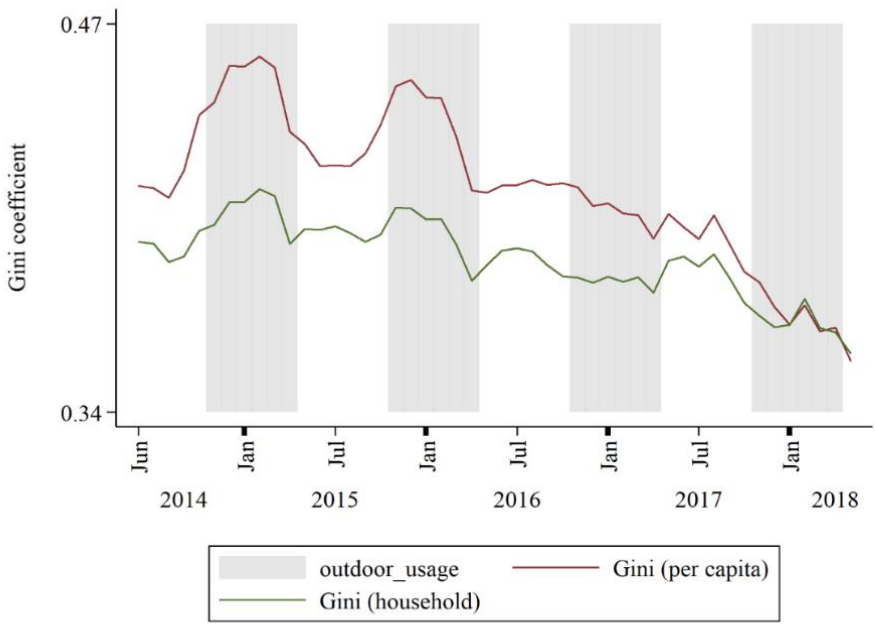
Finally, we spatially joined billing accounts to data from the most recent South African Census (2011). This decennial survey provides basic population and housing statistics, including annual household income (including social support grants, investments and rentals) and household size. We observe average demographic statistics at the most detailed geographic level for research purposes, the Small Area Layer (SAL). The City of Cape Town contains 5,339 SALs, each of which has a minimum of 300 people. We calculated per-capita water use assuming a household had the average number of members as the SAL-level average. Because the affordability calculations use nominal water tariffs in the numerator (the bill), we inflated income in the denominator from 2011 levels to the appropriate timeframe using general inflation rates from Statista (Statista 2020).

4. Results

4.1 Distributional Statistics

We highlight three results from Figure 1, which plots the monthly Gini coefficient from June 2014 to May 2018. The coefficient is equal to zero under perfect equality and one under perfect inequality.

Figure 1. Gini Coefficient in Municipal Water Deliveries: per household usage (green line) and per capita usage (red line), Cape Town (June 2014 to May 2018).



Notes: The grey shading marks months that generally correspond to outdoor water usage.

First, outdoor water use before the drought drove increases in municipal water use inequality during summer months. Figure 1 shows two distinct seasonal peaks in inequality in summer 2014-2015 and 2015-2016, where increases in the Gini coefficients indicate more unequal water use distributions. Summer seasons are shaded grey. Second, the various demand-side measures employed by the government to deal with the drought caused a substantial increase in municipal water use equality (decreasing Gini coefficient) across households. These policies were clearly successful at reducing the effect of outdoor water use, as the seasonal peaks in the Gini coefficients disappear. Third, imputing a customer's household size based on census data, household water use per person (red line) was more unequal than per account (green). This suggests that households with higher water use per account tend to have fewer members. This would be consistent with a situation where higher-income households both use more water overall and have smaller household sizes. We discuss the connection between water use and income in more detail below. It appears that the conservation measures were more effective on these high-use households with fewer members: the Gini coefficients for per-capita and per-account water consumption converge by 2018. Appendix Figure S3 shows that these results do not change when we include consumption data that we consider leaks (see Methods). Appendix Figure S4 presents parallel Lorenz curves for water use during February (a representative summer month) in 2014 through 2018, and shows the distribution slightly flattening (more water use equality) during the drought.

Table 2 reports distributional shares and average water use among share groups. In 2015, before the drought, the bottom half of water users consumed 24% of all water delivered to residential households in our subset. Note that this calculation excludes apartments and households whose members travel outside the home to collect water, both of which almost certainly use even less water per capita. The top 10% of users received 31% of all deliveries, the top 1% of users received 7.7% of deliveries, and the highest 0.1% of water users received 1.7% of deliveries. Although these shares were not substantially affected by the drought, average water use declined substantially among all customers (Table 2, Panel B). Moreover, the composition of these share classes (which types of households are in the top 1%) changed substantially, as we describe below.

Table 2. Distributional Statistics of Single-Family Residential Water Deliveries, Cape Town 2014-2018

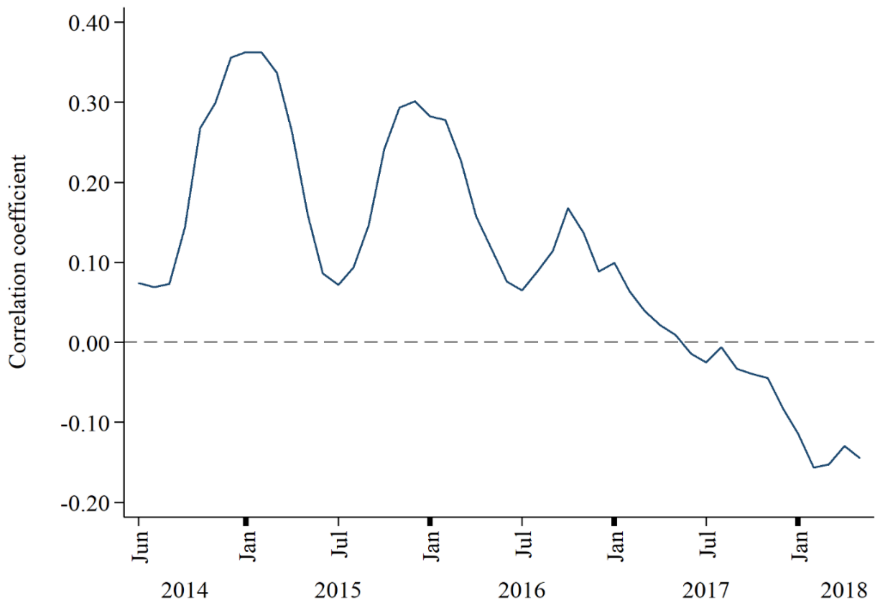
	Apr15-Sep15	**Oct15-Mar16**	**Apr16-Sep16**	**Oct16-Mar17**	**Apr17-Sep17**	**Oct17-Mar18**	**after Mar18**
Conservation measures:		*Irrigation restrictions and tariff increase*	*Tariff increase*	*Water garden with bucket, tariff increase*	*Disaster declaration, household use restrictions*	*Disaster Plan; 50L pcpd; tariff increase, Day Zero announced*	*Day Zero cancelled*
Panel A. Percent of all[a] water deliveries to…							
Top 0.1%[b]	1.7%	1.5%	1.7%	1.7%	1.8%	1.8%	1.6%
Top 1%[b]	7.7%	7.2%	7.5%	7.3%	7.3%	6.9%	6.4%
Top 10%[b]	30.6%	30.8%	29.9%	29.6%	29.4%	28.2%	27.6%
Bottom 50%[b]	24%	23.7%	24.9%	24.8%	24.5%	25.7%	26.9%
Panel B. Average household water usage (kL per day) of… (mean (std))							
Top 0.1%	9.25	9.35	8.57	8.47	6.99	5.68	4.27
	(1.86)	(1.93)	(2.09)	(2.06)	(2.14)	(2.29)	(2.07)
Top 1%	4.26	4.52	3.76	3.70	2.86	2.19	1.74
	(2.01)	(1.96)	(1.96)	(1.93)	(1.66)	(1.44)	(1.12)
Top 10%	1.70	1.94	1.49	1.49	1.15	0.91	0.74
	(1.12)	(1.13)	(1.01)	(0.99)	(0.81)	(0.65)	(0.50)
Bottom 50%	0.26	0.30	0.25	0.25	0.19	0.16	0.14
	(0.10)	(0.11)	(0.10)	(0.10)	(0.08)	(0.07)	(0.06)

Notes: [a] Total water deliveries to free-standing residential houses in our subset – does not include users in apartment buildings or those without a piped connection at home. [b] Percentiles calculated separately in each period such that a household could be in the top 10% in 2015, fail to reduce water use in response to the drought in 2016, and be in the top 1% in 2017.

4.2 Income and Water Use

Are the highest water users also the wealthiest? Figure 2 plots the correlation between monthly water use and a household's income. Like household size, income is imputed based on the average income in their SAL from the 2011 Census, and is therefore static in our data over the study period (see Methods). The correlation between income and water use is low (0.07) during winter months before the drought, when most or all water use is indoors. The correlation increases substantially, however, to 0.36 during the pre-drought summer months of 2014-2015. The dominant link between income and water use is the fact that higher-income households are more likely to own larger properties and use water outside. Figure 2 also shows that the drought and conservation policies reduced the correlation between income and water use, particularly outdoor water use. By the winter of 2017, the correlation had become negative, with wealthier households using *less* municipal water than lower-income households.

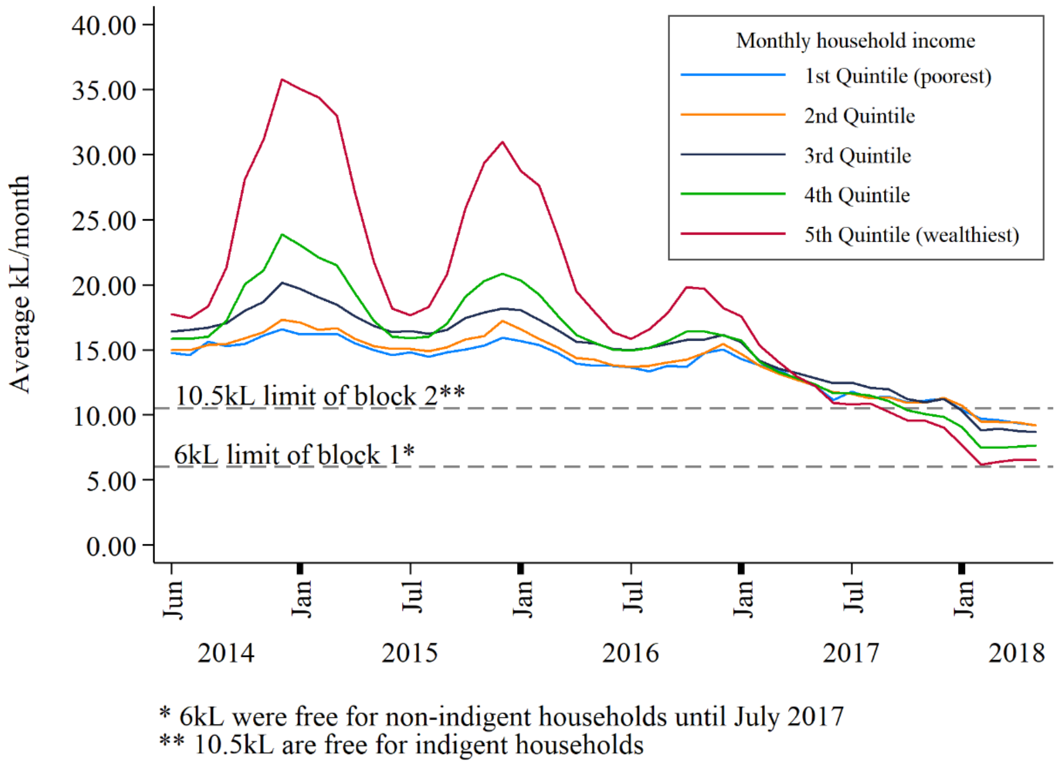
Figure 2. Correlation Coefficient between Imputed Household Income and Municipal Water use in Cape Town, Calculated Monthly, June 2014 to May 2018



Notes: Monthly household income is imputed based on the average income for the Small Area Layer (Census 2011) in which a household is located. Water use is daily average water use per account.

Figure 3 shows similar results by plotting average water use among households grouped by income quintiles. The highest-income households used much more water outdoors before the drought (e.g., two distinct seasonal peaks in water demand), but reduced their outdoor water use substantially during the drought. Near the end of the drought, the highest two income quintiles were actually using less water, on average, than the lowest three quintiles. The composition of the top 10% of *water users* was therefore changing: the average household income of the top 10% of water users in our sample was R26,004 (1,776 US$) before the drought, while the top 10% water users by March 2018 had an average income of R16,914 (1155 US$) (a 35% decline; see Appendix Table S1). We address reasons why higher-income households may have reduced their municipal water use more than lower- and middle-income households in the Discussion section.

Figure 3. Average Household Water use in Cape Town (2014-2018) by Income Quintile (6kl and 10.5kl tariff block steps are shown for reference)



4.3 Tariffs, Utility Revenue and Affordability

As discussed above, the City of Cape Town supplemented its conservation messaging and water use restrictions with steep increases in water tariffs to encourage water conservation. The tariff increases were largest in the highest tiers of water use. Prices in the highest consumption block (>50kL), for example, increased 27-fold, from ZAR 30 per kL in January 2015 to ZAR 800 in February 2018. Although this likely played a large role in driving reductions among top water users, causal identification is challenging because many other salient and well-publicized conservation programs occurred citywide at the same time as tariff increases. We instead focus on a different question: how did these tariff increases, the large water use reductions, the shuffling of the demographic composition of top water users, and the city's indigent support program affect household affordability and overall utility revenues?

Based on our simulation of utility revenues from the single-family customers that are our focus (see Methods), Table 3 illustrates that the utility is heavily dependent financially on the top 10% of water users because of the increasing block tariff structure. This was true before the drought (Apr15-Sep15), when the top 10% of water users contributed 54% of overall simulated utility revenue from single-family households. The bottom half of water users generated only R25.6 million, 5% of the total. This dependence on top users only deepened during the drought, however, with the top 10% generating 65% of revenue and the top 1% of users generating 37% (Oct17-Mar18).

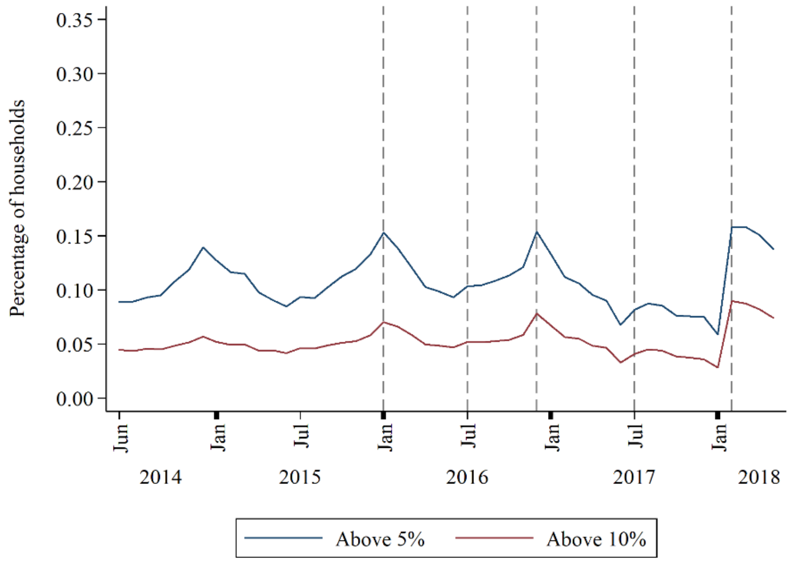
Table 3. Total Tariff Revenue by Percentile of Water Use (millions, ZAR)

	Apr15-Sep15	**Oct15-Mar16**	**Apr16-Sep16**	**Oct16-Mar17**	**Apr17-Sep17**	**Oct17-Mar18**
Top 0.1%	21.1 (24%)	35.2 (23%)	44.6 (28%)	78.4 (29%)	81.7 (35%)	87.6 (39%)
Top 1%	88.0 (18%)	151.3 (19%)	161.7 (26%)	268.2 (31%)	230.5 (38%)	225.4 (37%)
Top 10%	262.5 (54%)	452.8 (56%)	380.9 (61%)	561.6 (64%)	415.2 (69%)	400.4 (65%)
Bottom 50%	25.6 (5%)	42.3 (5%)	24.7 (4%)	30.5 (3%)	21.1 (4%)	58.2 (10%)
Total revenue	488.5	804.9	627.6	875.4	600.7	611.6

Our results suggest that, before the drought, these high users who contributed a large share of revenue were largely higher-income customers, confirming the prevailing logic that increasing-block tariffs cross-subsidize poor customers who are connected to the network. But as the correlation between income and water use declined and reversed, the demographic composition of top water users changed. These revenues then became more likely to originate from lower- and middle-income customers.

What was the impact on whether households could "afford" to pay their water and sewer bills? Figure 4 calculates the share of customers who we estimate would have spent more than 5% or 10% of their (imputed) household income during each month of our study period on combined water and sewer bills, at the prevailing tariff structure that month (see Methods). There is no universal agreement on what is an acceptable percentage of income to spend on water and sewer services; 3%, 5% and 10% are commonly-used benchmarks (Smets 2012). These calculations include the city's indigent program. Dotted vertical lines show when tariff increases went into effect.

Figure 4. Percent of Cape Town Households Estimated To Have Spent More than 5% or 10% of their Income on Water and Sewer Bills, 2014-2018 (dotted lines show tariff increases).



Using this metric, the percentage of households who would find their water bills "unaffordable" is relatively modest. Around 10-15% of households would have faced a water and sewer bill that exceeded 5% of their income. Only 5-8% of households would be paying more than 10% of their income.

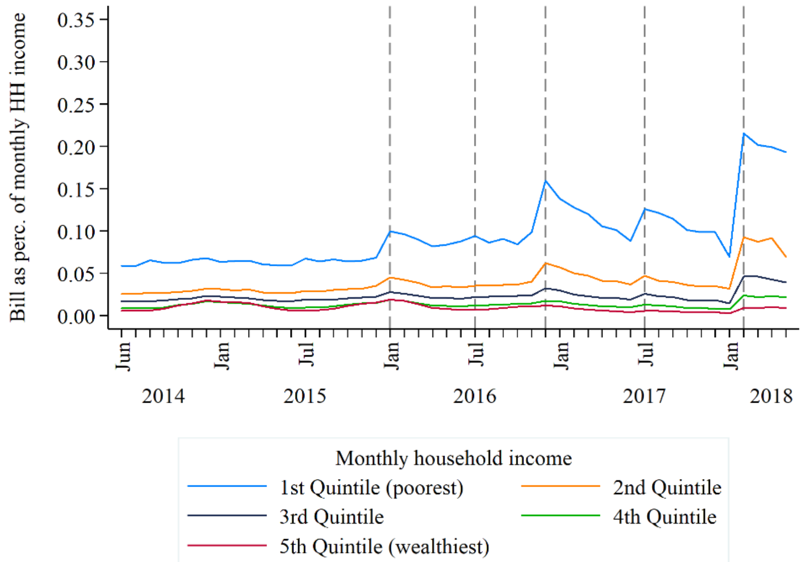
What was the effect of the indigent program in protecting customers? If we simulate bills without the indigent grant, the percentage who would find bills unaffordable rises only modestly until 2018: 10-18% of households would have paid more than 5% of their monthly income on water and sewer bills during the drought, and 5-9% of households would have paid more than 10% of their income (Appendix Figure S5). The program had a larger effect in protecting poor customers from the steep tariff increases in February 2018. Without the program, the percent of households spending more than 5% rises from 10% to 30% (Appendix Figure S5). Without the indigent support program, however, households facing higher prices would likely have reduced their consumption more and reduced their bills; our calculations do not model this price response. Poor households in some locations might also have reduced their bills by collecting more water from public standpipes free of charge.

This approach to measuring affordability, however, can mask larger concerns for subsets of customers. Figure 5 plots the average combined water and sewer bill as a percentage of household income for each of the five income quintiles. We calculate that the poorest 20% of households paid approximately 6% of their income on water and sewer before the drought and the tariff increases, on average. This calculation includes the indigent program. The result is driven by the fact that the poorest quintile used more water than the free 10.5 kL allocation, on average (see Figure 3), pushing them directly into the expensive third consumption block of the tariff for units over 10.5kL. As tariffs rose, the average household in the poorest quintile saw their water bill rise to 15% and even 20% of household income (Figure 5).

The average household in the second quintile spent 4-10% of income on water bills, and the averages in the top three quintiles were generally lower than 5%.

These statistics also mask differences in water use among households in the same income quintile. For the median household (in terms of water use) in the bottom income quintile in our sample, we observe that their combined water and sewer bill was generally zero throughout the study period. This is because median water use of the bottom income quintile was below 10.5kL (see SI Figure S6). The mean water use for households in the bottom income quintile is, however, affected by low-income customers who use larger amounts of water. This is not an artefact of a few very large water use observations: at least one-quarter of households in the indigent support program used more than 10.5kL in every month in our dataset. Note that, although we do not directly observe each household's income, we also do not believe these results for the bottom income quintile are driven by high-income households who happen to live in a low-income Small Area Layer and are incorrectly assumed to be poor. First, poverty is spatially concentrated in Cape Town. Second, when we calculate similar statistics only among those customers who are in the indigent program (which is in our billing data), we get very similar results (Appendix S2).

Figure 5. Average Water and Sewer Bill as a Percentage of Household Income, by Income Quintile



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5. Discussion

We linked demographic data to nearly 15 million monthly billing records from before and during the historic drought in Cape Town, and calculated distributional statistics of household municipal water use for the first time. These results show a strong degree of water use inequality before the drought, with the top 10% of water users receiving 31% of all water deliveries and the bottom 50% receiving only 24%. Inequality in water deliveries increased substantially during summer outdoor watering seasons. We find that the conservation programs during the drought eliminated this seasonal difference (outdoor water use was banned) and made the distribution of water use more equal.

It is very likely, however, that water use inequality among all Cape Town residents is even higher than our estimates. This is because we excluded 1) water deliveries to apartment buildings to avoid observing very large water bills that were in fact shared among many households in one building with only one master meter, and 2) deliveries to the 11% of Cape Town households who live in informal areas, do not have a piped connection, and rely on public water sources away from their home (Statistics South Africa 2017). Unconnected households must travel to collect water, so volumes collected are certainly much lower; total water use from informal areas accounted for only 4% of overall municipal water deliveries. Although we cannot observe this in our billing data, households in multifamily buildings also likely use less water per capita because of fewer opportunities for outdoor use.

In summary, we emphasize that our distributional statistics apply to the universe of free-standing homes connected to a reliable, high-quality, 24/7 service, though this is approximately two-thirds of Cape Town households. This makes our analysis less relevant for cities in low-income countries where either a higher fraction of households are unconnected to the piped network, or where the reliability of the piped system is so low that most connected households rely heavily on non-network sources that are not captured in utility billing data. Our approach is highly relevant, however, for many other cities in the U.S. and Australia with similar service levels and housing stock. Calculating these distributional statistics is computationally simple, and our approach could easily be replicated. These measures are specifically useful in so far as they allow comparisons of water use inequality cross-sectionally across cities. In addition, such measures can be used to discern whether conservation programs are achieving their goals by in fact reducing water use among the highest users or by reducing average consumption overall (leaving the Gini coefficient unchanged). Lastly, by pairing consumption with tariff data, these measures demonstrate how financially dependent utilities are on the highest water users.

It is commonly assumed that the highest water users are also the wealthiest. Although we do not observe each customer's household size or income directly in our data, we use a reasonable proxy by matching households spatially to fine-scale census data. This is a common data limitation since utilities rarely have detailed information about the demographics of their customers. Our results suggest that before the drought it was indeed true that high users were wealthier. Cape Town's use of an increasing block tariff allowed some cross-subsidy from high-income, high water users to lower-income (connected) households who qualified for the 10.5 kL indigent support program. However, this correlation is driven primarily by outdoor water use; the correlation between income and water use during the winter is much lower (0.08) than in the summer (0.32). In cities with primarily multifamily housing (and thus little outdoor use), water managers should not assume a strong correlation between water use and income when designing tariffs. We also find that the conservation measures implemented by the city to avoid Day Zero caused not only a large reduction in overall water use, but a demographic reshuffling of who are the top water users. Higher-income households reduced their water consumption much more than lower-income customers, *reversing* the correlation between income and water use near the end of the drought.

Why did higher-income households reduce water use so much more than other households? They were, on average, consuming much larger volumes of water than lower-income households before the drought, giving them lower marginal cost opportunities to reduce water usage. They may also have been more aware of the conservation campaign. A survey conducted immediately after the drought ended, among 350 households in three neighborhoods representative of low, middle, and high-income customers, found that households in the wealthier neighborhoods were far more motivated by social pressure than price increases to decrease water use than households in the less wealthy neighborhoods (Jack et al. 2019). Higher financial capacity might have allowed them to make capital investments in using their municipal supply more efficiently, such as tap-aerators, or water-efficient shower heads or toilets. However, some investments, such as buckets for re-using grey water, are relatively low cost.

Another possibility is that the wealthy were more likely to install private boreholes or other means of self-supply, such as rain water tanks and wells. This would decrease their billed consumption from the networked system but perhaps not reduce their total use of scarce water resources. This type of private self-supply among middle- and high-income customers is common in many cities in low-income countries (Pattanayak et al. 2005; Strand and Walker 2005; Orgill-Meyer et al. 2018; Gurung et al. 2017) and can lead to a downward spiral where poor service quality (including reliability) leads households to rely more on expensive self-supply options like tanker deliveries or boreholes, starving the utility of revenue needed to maintain the piped network, and driving more households to use off-network supplies. The Cape Town survey (Jack et al. 2019) found that, although middle- and high-income households in Cape Town did invest in additional infrastructure, most of their water reductions likely came through behavioral changes. Only 8 percent of households in the wealthiest neighborhood reported drilling a borehole, and, although 64% purchased rainwater catchment tanks, the amount of rainfall was negligible during the drought.

The demographic reshuffling of the top water users has important implications for affordability and tariff design. Large reductions in household water usage, especially during summers, led to an initial shortfall in revenues during the drought period (Reddick and Kruger 2019). At the same time, water supply costs increased due to the development of new water supply sources (Taing et al. 2019). As a result, the City of Cape Town increased water tariffs and introduced a fixed charge after the height of the drought, with the aim of covering 25% of the utility's fixed costs (City of Cape Town 2018b). Because of increasing block tariff structures, the financial health of the utility depends heavily on the top 10% of water users, who generated two-thirds of rate revenue for the utility by the end of the drought (note again that this excludes rate revenue from multifamily or commercial users from the total). Because of the dramatic collapse in water use among high-income households, these top 10% were increasingly likely to be poorer or middle class. Cape Town's free "basic" water program was successful in protecting many of those poor customers from high bills, but a significant fraction of the poorest income quintile found it difficult to reduce their water use below the 10.5 kL allocation. Large tariff increases drove the average bill for the poorest quintile to nearly 20% of monthly income, driven by the approximately one-quarter of indigent households who used more than the allocation (median water use was still below 10.5 kL with a corresponding zero bill). It is important to better understand why these low-income, high-use households had difficulty reducing water consumption, though our data cannot speak to this. These households may have very large families, or there may be multiple households living on one property and sharing a meter (Whittington 1992). They may also have been unable or unwilling to make investments because they rent their homes. The City could consider targeting these households, or their landlords, with conservation assistance programs like rebates for low-flow toilets or assistance in fixing leaky fixtures.

Data Availability

Data was provided by the City of Cape Town to researchers under a cooperative agreement. Because this billing data contains sensitive private information, the agreement states that researchers may not share the dataset with anyone not party to the agreement. The City of Cape Town, however, has created a formal procedure whereby any researchers wanting to use the data for research purposes can approach them independently.

Code Availability

Analysis was performed in Stata, v.15. Our Stata code is available on request.

References

Andres, L., M. Thibert, C. L. Cordoba, A. Danilenko, G. Joseph, and C. Borja-Vega. (2019). Doing More with Less: Smarter Subsidies for Water Supply and Sanitation. Available at: http://documents.worldbank.org/curated/en/330841560517317845/Doing-More-with-Less-Smarter-Subsidies-for-Water-Supply-and-Sanitation.

Beck, T., Rodina, L., Luker, E., and Harris, L. (2016). Institutional and policy mapping of the water sector in South Africa. Program on Water Governance, University of British Columbia, Canada.

Berthe, A. (2018). L'accès à l'eau et à l'assainissement au brésil, un enjeu de développement soutenable à évaluer. *Problemes d'Amerique Latine*, *4*(111), 59–83.

Booysen, M. J., Visser, M., and Burger, R. (2019). Temporal case study of household behavioural response to Cape Town's 'Day Zero' using smart meter data. *Water Research*, *149*, 414–420.

Brick, K., De Martino, S., and Visser, V. (2018). Behavioural nudges for water conservation: Experimental evidence from Cape Town. Working Paper, University of Cape Town. doi: 10.13140/RG.2.2.25430.75848.

Brühl, J., Serman, K., and Visser, M. (2020). Motivating high users to conserve water during times of crisis: Evidence from drought-stricken Cape Town. Working Paper, University of Cape Town.

Brühl, J., and Visser, M. (2020). The Cape Town drought: What measures worked to prevent 'Day Zero'? Working Paper, University of Cape Town.

Burger, C., and Jansen, A. (2014). Increasing Block Tariff structures as a water subsidy mechanism in South Africa: An exploratory analysis. *Development Southern Africa*, *31*(4), 553–562.

Cheesman, J., Bennett, J., and Son, T. V. H. (2008). Estimating household water demand using revealed and contingent behaviors: evidence from Vietnam. *Water Resources Research 44(*W11428*).* Available at: https://doi.org/10.1029/2007WR006265.

City of Cape Town. (2018a). Annexure 4: Revised Consumptive Tariffs, Rates and Basic Charges for Electricity Services, Water Services and Waste. (May). Waste'. Available at: http://resource.capetown.gov.za/documentcentre/Documents/Financial documents/Budget 2018-2019 Annexure 4 Consumptive Tariffs_Final.pdf.

City of Cape Town. (2018b.) Water Outlook 2018. Available at:

https://resource.capetown.gov.za/documentcentre/Documents/City research reports and review/Water Outlook 2018 - Summary.pdf.

Cook, J., Whittington, D., Fuente, D., and Matichich, M. (2020). A global assessment of non-tariff customer assistance programs in water supply and sanitation. In Z. Chen, W. M. Bowen, and D. Whittington, eds. *Development Studies in Regional Science: Essays in Honor of Kingsley E. Haynes*. Springer Nature, forthcoming.

Cullis, J., and Van Koppen, B. (2007). Applying the Gini coefficient to measure inequality of water use in the Olifants River Water Management Area, South Africa. Available at: https://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB113/RR113.pdf

Department of Water Affairs and Forestry (DWAF). (2001). *Free Basic Water Implementation Strategy Document (Version 1)*. Department of Water Affairs and Forestry South Africa. Available at: https://www.ircwash.org/sites/default/files/Palmer-Development-Group-2002-Free.pdf.

Department of Water and Sanitation. (2018). Water and sanitation tariffs - Level 6. :1–2.

Enqvist, J.P.J.P., and Ziervogel, G. (2019). Water governance and justice in Cape Town: An overview." *Wiley Interdisciplinary Reviews Water*, 1–15, doi: 10.1002/wat2.1354.

Foster, V. 2(004). *Toward a Social Policy for Argentina's Infrastructure Sectors: Evaluating the Past and Exploring the Future*. The World Bank. Available at: http://elibrary.worldbank.org/doi/book/10.1596/1813-9450-3422.

Fuente, D., Gakii Gatua, J., Ikiara, M., Kabubo-Mariara, J., Whittington, D., Mwaura, M., and Whittington, D. (2016). Water and Sanitation Service Delivery, Pricing, and the Poor: An Empirical Estimate of Subsidy Incidence in Nairobi, Kenya. *Water Resources Research*, *52,* 4845–4862. Available at: http://doi.wiley.com/10.1002/2015WR018375.

Guragai, B., Takizawa, S., Hashimoto, T., and Oguma,, K. (2017). Effects of inequality of supply hours on consumers ' coping strategies and perceptions of intermittent water supply in Kathmandu Valley , Nepal. *Science of the Total Environment, 600,* 431–441.

Gurung, Y., Zhao, J., Kumar KC, B., Wu, X., Suwal, B., and Whittington, D. (2017). The costs of delay in infrastructure investments: A comparison of 2001 and 2014 household water supply coping costs in the Kathmandu Valley, Nepal. *Water Resources Research, 53*(8), 7078–7102.

Hu, Z., Chen, Y., Yao, L., Wei, C., and Li, C. (2016). Optimal allocation of regional water resources: From a perspective of equity-efficiency tradeoff. *Resources, Conservation and Recycling*, *109*, 102–113. Available at: http://dx.doi.org/10.1016/j.resconrec.2016.02.001.

Jack, K., Visser, M., Robertson, E. and Berger, K. (2019). Day Zero – Understanding responses to the Cape Town water crisis. Report to the City of Cape Town.

Joubert, L., and Ziervogel, G. (2019). Day Zero: One city's response to a record-breaking drought. Available at: https://www.africancentreforcities.net/wp-content/uploads/2019/07/Day_Zero_Joubert_Ziervogel_2019.pdf.

Kuznets, S., and Jenks, E. (1953). Shares of upper income groups in income and savings. National Bureau of Economic Research.

Mahlanza, L., Ziervogel, G., and Scott, D. (2016). Water, rights and poverty: An environmental justice approach to analysing water management devices in Cape Town. *Urban Forum, 27*(4), 363–382.

McDonald, R .I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G., and Montgomery, M. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change, 27*(1), 96–105.

Millington, N., and Scheba, S. (2020). Day zero and the infrastructures of climate change: Water governance, inequality, and infrastructural politics in Cape Town's Water Crisis. *International Journal of Urban and Regional Research*. doi: 10.1111/1468-2427.12899.

Morales-Novelo, J. A., Rodríguez-Tapia, L., and Revollo-Fernández, D. A. (2018). Inequality in access to drinkingwater and subsidies between low and high income households in Mexico City. *Water, 10*(8). doi: 10.3390/w10081023.

Muller, M. (2019). Some systems perspectives on demand management during Cape Town's 2015–2018 water crisis. *International Journal of Water Resources Development, 1–19 doi: 10.1080/07900627.2019.1667754.*

Nobre, C. A., Marengo, J. A., Seluchi, M. E., Cuartas, L. A., and Alves, L. M. (2016). Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. *Journal of Water Resource and Protection, 8*(2), 252–262.

Orgill-Meyer, J., Jeuland, M., Albert, J., and Cutler, N. (2018). Comparing contingent valuation and averting expenditure estimates of the costs of irregular water supply. *Ecological Economics, 146* (September 2017), 250–264.

Otto, F. E. L., Wolski, P., Lehner, F., Tebaldi, C., van Oldenborgh, G. J., Hogesteeger, S., Singh, R., Holden, P., Fučkar, N. S., Odoulami, R. C., and New, M. (2018). Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters, 13*(12), 124010.

Parks, R., Mclaren, M., Toumi, R., and Rivett, U. (2019). Experiences and lessons in managing water from Cape Town. London, England. Available at: https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Experiences-and-lessons-in-managing-water.pdf.

Pattanayak, S. K., Yang, J., Whittington, D., and Kumar, K. C. B. (2005). Coping with unreliable public water supplies : Averting expenditures by households in Kathmandu , Nepal." *Water Resources Research, 41*(1), 1–11.

Piketty, T., Saez, E., and Zucman, G. (2018). Distributional national accounts: Methods and estimates for the United States. *Quarterly Journal of Economics, 133*(2), 553–609.

Reddick, J., and Kruger, R. (2019). "2019 Market Intelligence Report." Cape Town. Available at: https://www.green-cape.co.za/assets/Uploads/WATER-MIR-2019-

Roeland, M. (2018). Water curbs: a tale of rich and poor. *The Daily Maverick*. Available at: https://www.groundup.org.za/article/water-curbs-tale-rich-and-poor/.

Saez, E. (2017). Income and Wealth Inequality: Evidence and policy implications. *Contemporary Economic Policy, 35*(1), 7–25.

Saez, E., and Zucman, G. (2016). Wealth inequality in the United States since 1913: Evidence from capitalized income tax data. *Quarterly Journal of Economics, 131*(May), 519–578.

Sinclair-Smith, K., Mosdell, S., Kaiser, G., Lalla, Z., September, L., Mubadiro, C., Rushmere, S., Roderick, K., Brühl, J., McLaren, M., and Visser, M. (2018). City of Cape Town's water map. *Journal of American Water Works Association, 110*(9), 62–66.

Sinclair-Smith, K., and Winter, ,K. 2(019). Water demand management in Cape Town: Managing water security in a changing climate. In *Scott D, Davies H, New M (eds). 2019. Mainstreaming Climate Change in Urban Development: Lessons from Cape Town.* Cape Town: UCT Press.

Smets, H. (2012). Quantifying the affordability standard. In M. Langford and A. F. S. Russell, eds. *The Human Right to Water: Theory, Practice and Prospects.*

Smith, J. (2012). Free water for all the world's poor? A review of the strategy of South Africa's free basic water policy. *Water Policy, 14*(6), 937–956.

Statista. (2020). South Africa: Inflation rate from 1984 to 2021. Available at: https://www.statista.com/statistics/370515/inflation-rate-in-south-africa/ (Accessed: 3 June 2020).

Statistics South Africa. (2011). Census 2011. Available at: https://www.datafirst.uct.ac.za/dataportal/index.php/catalog/485.

Statistics South Africa. (2012). Census 2011 Municipal Report Western Cape. Available at: http://www.statssa.gov.za/census/census_2011/census_products/WC_Municipal_Report.pdf

Statistics South Africa. (2017). General Household Survey 2017. Available at: https://www.datafirst.uct.ac.za/dataportal/index.php/catalog/723.

Strand, J., and I. Walker. (2005). Water markets and demand in Central American cities. *Environment and Development Economics, 10*(3), 313–335.

Taing, L., Chang, C. C., Pan, S., and Armitage, N. P. (2019). Towards a water secure future: Reflections on Cape Town's Day Zero crisis. *Urban Water Journal, 16*(7), 530–536.

Tortajada, C. (2008). Challenges and realities of water management of megacities: the case of Mexico City metropolitan area. *Journal of International Affairs, 61*(2), 147–166.

Visser, M., and Brühl, J. (2018). OpEd: A drought-stricken Cape Town did come together to save water. *The Daily Maverick*. March. Available at: https://www.dailymaverick.co.za/article/2018-03-01-op-ed-a-drought-stricken-cape-town-did-come-together-to-save-water/.

Whittington, D. (1992). Possible adverse effects of increasing block water tariffs in developing countries. *Economic Development and Cultural Change*, *41*(1), 75–87.

Wolski, P. (2018). How severe is Cape Town's 'Day Zero' drought? *Significance*, 15(2), 24–27.

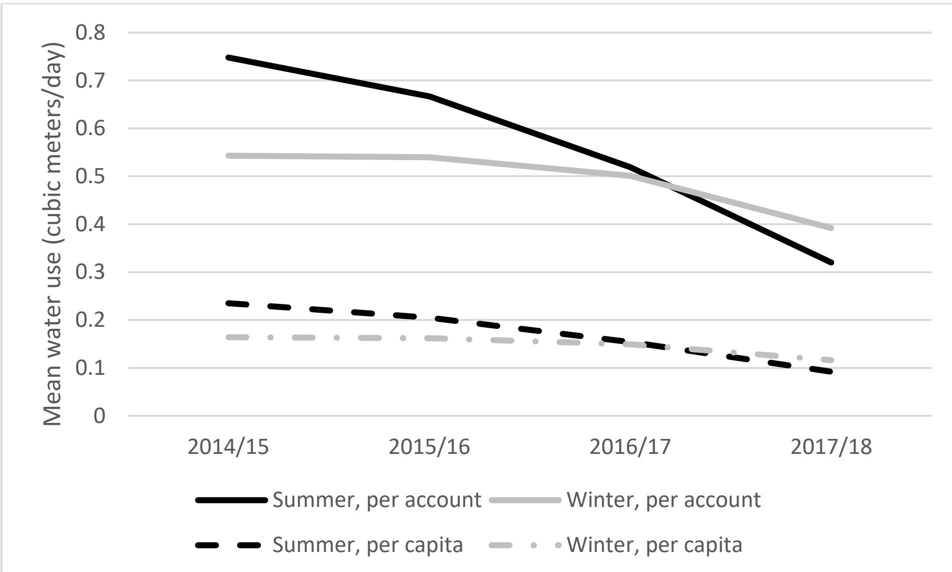
Wolski, P., Hewitson, B., and Jack, C. (2017). Why Cape Town's drought was so hard to forecast. *The Conversation, 1–4.* Available at: https://theconversation.com/why-cape-towns-drought-was-so-hard-to-forecast-84735.

Yang, H., Bain, R., Bartram, J., Gundry, S., Pedley, S., and Wright, J. (2013). Water safety and inequality in access to drinking-water between rich and poor households. *Environmental Science and Technology*, 47(3), 1222–1230.

Ziervogel, G. (2018). What the Cape Town Drought Taught Us: 4 Focus Areas for Local Governments. Cities Support Programme. Available at: https://www.africancentreforcities.net/wp-content/uploads/2019/02/Ziervogel-2019-Lessons-from-Cape-Town-Drought_A.pdf.

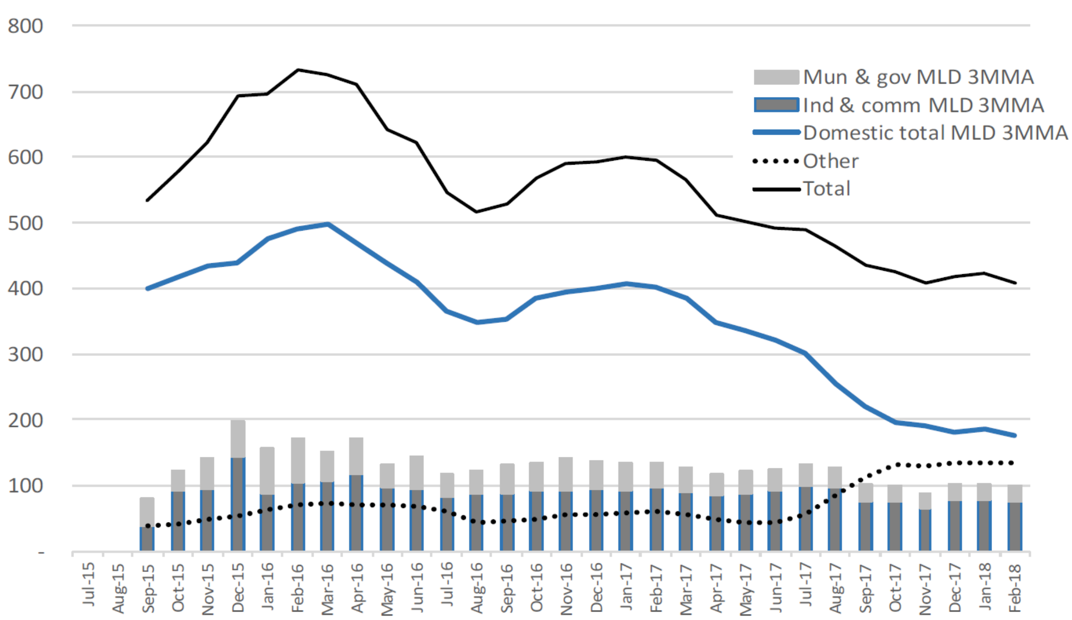
Supplementary Information (SI)

Figure S1. Change in mean residential water use 2014-2018



Notes: Source is municipal billing data. Household size is not observed directly: per capita calculations made using household size at the Small Area Layer level using 2011 Census data. "Summer" average across the billing months of December, January and February. "Winter" average across June, July and August.

Figure S2. Water sales (Megaliters/day), 3 month moving average 2015-2018



Source: Cape Town Water Outlook 2018

Figure S3. Gini coefficient in municipal water deliveries (household usage (green line) and per capita usage (red line), Cape Town (June 2014 to May 2018), **without dropping observations we believe are leaks**

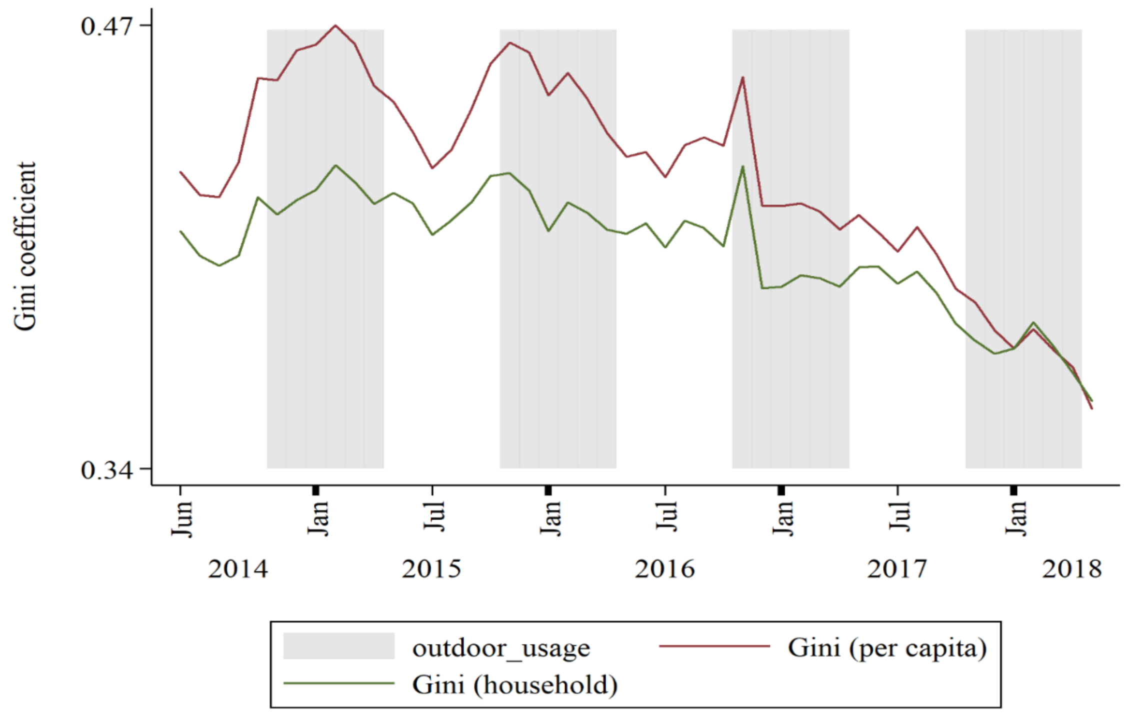


Figure S4. Lorenz Curves for water for the month of February (left) and household income (right)

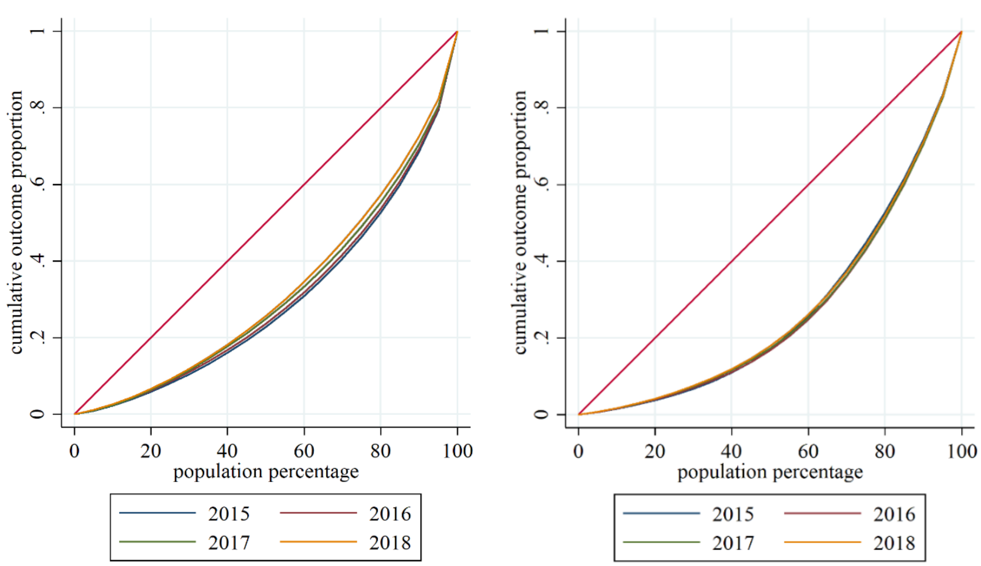


Figure S5. Percent of Cape Town households predicted to be spending more than 5% or 10% of their income on water and sanitation, **excluding indigent grants**.

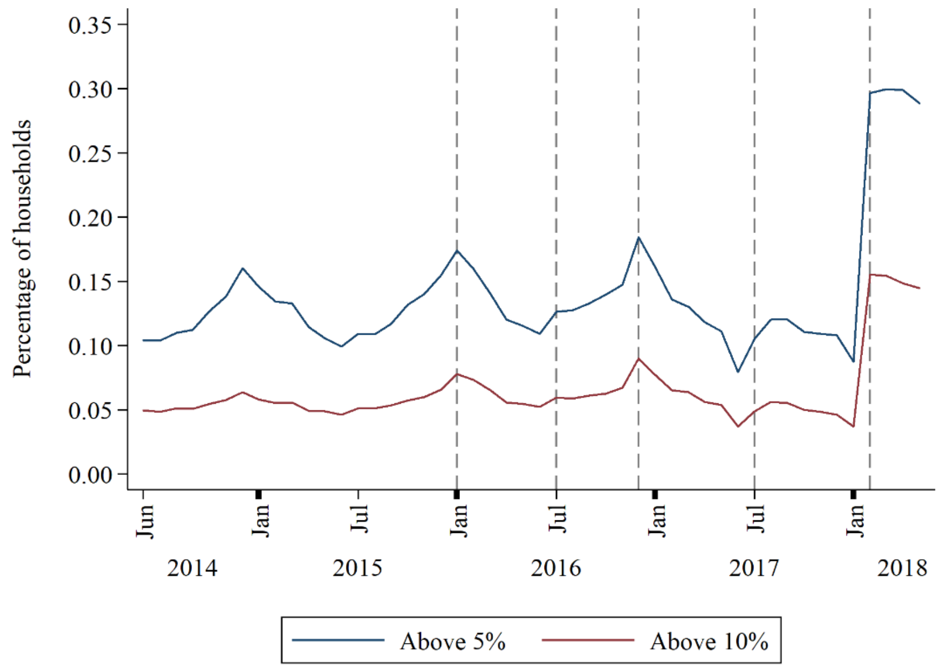
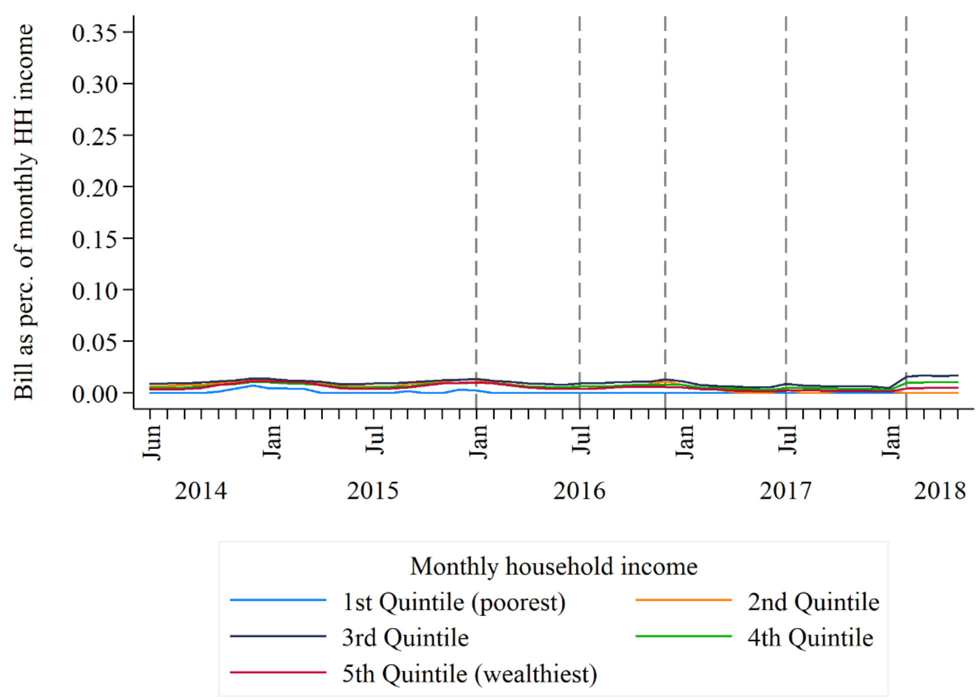


Figure S6. **Median** Water and sewer bill as a percentage of household income, by income quintiles.



Note: Includes indigent grant program.

Table S1. Average monthly household income (in South African Rand) in the top 10% of Water Users over Time (April 2015 to May 2018), Cape Town

Monthly household income (ZAR)	Apr15-Sep15	Oct15-Mar16	Apr16-Sep16	Oct16-Mar17	Apr17-Sep17	Oct17-Mar18	after Mar18
Average (standard deviation)	26,004 (21,665)	32,794 (23,829)	25,252 (21,658)	25,922 (22,208)	22,095 (19,443)	18,305 (17,405)	16,914 (16,460)
Median	19,726	30,164	18,564	18,895	16,324	11,930	10,515

Table S2. Median and mean ratio of combined water and sewer bill to household income, including the indigent support program, among only households who are listed as receiving the indigent support program in the billing data.

Seasons	Median	Mean
Jun14-Sep14	0	.045
Oct14-Mar15	.0045	.047
Apr15-Sep15	0	.043
Oct15-Mar16	.0029	.056
Apr16-Sep16	0	.055
Oct16-Mar17	0	.074
Apr17-Sep17	0	.065
Oct17-Mar18	0	.078
After Mar18	0	.126

Municipal water utilities around the globe face a daunting set of challenges. In high-income countries, they must maintain piped networks that deliver high-quality, reliable water supply to homes and remove household waste via piped sewerage networks. In most cities in low- and middle-income countries, they must improve the quality and reliability of services, connect households to the network, and plan for large population influxes. Utilities need financial resources to attack these problems, but tariffs in many places are too low: only 35% of utilities in the World Bank's International Benchmarking Network for Water and Sanitation Utilities (IBNET) database collect enough revenue to cover operations and maintenance costs, and only 14% collect enough to cover the full economic cost of service provision