Rebalancing Water?
Evidence from Day Zero in Cape Town

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Abstract

How should scarce resources be allocated between households and the firms that employ them during temporary shortages? We study Cape Town's 2016–2018 drought, when the city increased water prices sharply for households and firms. We use monthly records on all metered water use in the city and matched employer-employee tax records across the country. We find that a temporary water price increase led to large and lasting job losses through establishment closures, consistent with downward wage rigidity and credit constraints. These frictions raise the social value of water to firms above their willingness to pay. Households cut consumption sharply but remained above health and sanitation thresholds. To evaluate the efficient allocation between households and firms, we build and estimate a dynamic model of the city with imperfect labour and credit markets. Placing a larger conservation burden on households could have reduced the drought's welfare cost by 52 percent relative to the city's prices, while raising aggregate household welfare through preserved employment. A single price would have reduced the welfare cost by only 13.5 percent. When policymakers cannot address adjustment distortions directly, corrective pricing between households and firms can be used as a second-best policy to reduce the welfare cost of temporary shortages.

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1 Introduction

Shortages of essential resources such as water and energy are a recurring policy challenge. The welfare cost of such shortages depends on how easily households and firms can adjust, and on how the available supply is allocated between them. Absent externalities or distortions, a common price would reduce consumption across users at least cost (Montgomery, 1972). However, governments often shield residents and their direct consumption to ensure that shortages do not compromise basic needs or public health. This places a larger conservation burden on the firms in which those very residents work. If firms cannot borrow to cover a temporary loss or adjust wages, the social cost of conservation through firms can exceed its private cost. The efficient allocation therefore requires balancing the social costs of conservation by households and firms.

In this paper, we ask how scarce resources should be allocated between households and firms to minimise the welfare cost of a shortage. Cape Town's 2016 to 2018 drought provides an ideal setting to study this joint allocation problem. With little scope to expand supply, the city had to cut aggregate water consumption by 45 percent to avoid "Day Zero", when it would have had to shut off piped water. In response, the city raised water prices sharply, yet temporarily, for both households and firms.

We use this setting to provide three contributions to our understanding of temporary resource shortages and how best to deal with them. First, we document how a temporary rise in the price of an input that is a small share of costs can lead to large and lasting decreases in the number of firms and in employment. We use monthly records on all metered water use in the city and matched employer-employee tax records across the country to document establishment closures and follow affected workers after the drought ended. Second, we compare the full welfare costs of saving water through households and firms. To evaluate these costs under alternative allocations, we build and estimate a dynamic spatial model in which household consumption and employment adjust jointly during and after the drought. Third, we show that the allocation between households and firms is a first order margin in determining the welfare cost of a shortage. Introducing a corrective price wedge, which involves households doing a larger share of the conservation, could have reduced the welfare cost of the drought by 52 percent relative to the city's prices. Households gain in aggregate from this reallocation because the employment benefits outweigh the cost of their additional water conservation.

We begin by estimating the effects of the commercial price increase on firms and workers. The city temporarily tripled commercial water prices, applying the same increase to all firms. This represented a larger cost shock for sectors that relied more heavily on water. We measure this exposure using water cost shares in national supply-use tables. Using the matched employer-employee tax records, we implement a triple-difference strategy,

comparing water-intensive sectors to other sectors in Cape Town, against the same difference in the other large South African metropolitan areas unaffected by the drought, before and after the price increase. The identifying assumption is that, absent the price increase, the relative trend of Cape Town's water-intensive sectors would have followed that of the control cities.

We find that workers who were employed in exposed sectors at the time of the drought were 5 percentage points less likely to hold a formal job by the end of the drought. This gap had still not closed six years later. This effect was driven by an extensive margin response of firms, with a 20 percent reduction in the relative number of establishments in exposed sectors caused by higher exit and lower entry during the drought. The number of establishments had only partly recovered by 2024. Surviving firms in Cape Town did not reduce employment, and separate water meter data shows that surviving firms were only able to reduce water consumption by 12 percent in response to a threefold increase in water prices. The aggregate reduction in water consumption of firms came from establishments closing rather than substituting away. Nearby towns drawing on the same water supply faced the same drought but not Cape Town's commercial price increases, and we find no significant decline in their number of water-intensive establishments.

We then examine whether the closures and lasting employment losses reflect distortions in adjustment. Firms that exited were in fact smaller, while survivors were unable to decrease wages for either existing employees or new hires. We find that the pattern of exit among firms is most consistent with the presence of credit market failures and downward wage rigidities. We also provide evidence to show that the pattern of firm exit is not consistent with either a demand shock or a change in beliefs due to the drought itself. Firm exit can also affect other firms in the same neighbourhood through a reduction in agglomeration externalities, and we find evidence of increased exit among firms in less water-intensive sectors when located in neighbourhoods with more exposed firms. Among workers who leave a formal job in Cape Town, re-employment is rarely in a different sector or location within the city, hinting at strong spatial frictions and switching costs. This lack of reallocation of workers to other sectors or locations explains part of why the employment effects are long lasting.

We also document how households adjusted to the price increase. Water prices rose sharply for all households, leading to strong demand reductions, with households cutting their average water use by 60 percent. Household spending on water remained largely unchanged due to a near unit elasticity, limiting the effect of higher water prices on income and other consumption. Households have a basic need for water for drinking and sanitation, but also use it for gardening, taking long showers, and swimming pools. Because we observe every metered household, we can check whether households across the whole use distribution were able to consume enough water for basic needs. In our data, average consumption

in every household decile remained above 50 litres per person per day, the benchmark for basic needs recommended by the WHO and the City government. This evidence, combined with findings in Lee et al. (2023) of no increase in water related diseases during the drought, supports our baseline assumption of no household health externality above basic needs. In this baseline, households alone bear the private cost of their adjustment above basic needs, so the residential price equals the social marginal value of their water.

The data alone cannot tell us whether the same water saving could have been achieved at lower cost by allocating it differently between households and firms. To measure the welfare cost of these responses, we need to distinguish between what an efficient response would have been, and what surplus was lost due to distortions. Firms may shrink or close even under the efficient common-price benchmark.

We therefore build and estimate a dynamic spatial model of the city in which prices allocate a fixed temporary water supply between users. Firms differ in productivity and in how intensively they use water, and they face credit constraints and downward wage rigidity, while locations benefit from agglomeration externalities. Each household consists of one worker who consumes water and a composite consumption good, with a basic needs water requirement. Each year, workers choose a sector and location within the city to maximise utility, taking into account sector-location wages, their preferences and the costs of changing sector or moving location. Labour demand in other sectors and locations in the city determines how workers behave after losing a job, and together with the switching costs, how much surplus they lose and for how long. The model allows us to recover the social marginal value of water for households and firms at all allocations, including the present value of all future losses.

We estimate the model using the water meter data and the tax records. We calibrate household water demand to match average water use and expenditure on water before the drought. The elasticity of substitution away from water is estimated using the water meter data for surviving firms. Transition rates of workers across sectors and locations help identify their switching costs. The severity of credit constraints is identified from the excess exit of water-intensive establishments during the drought. We then compare the simulated paths of establishments and employment with our triple-difference results. The model captures the slow recovery after prices fall, although these full paths are not targeted in estimation.

Through the lens of the model, we find that, at the price level chosen by Cape Town, the social cost of saving an additional litre of water through firms is about eleven times the social cost of saving it through households. We then use the model to compare counterfactual water prices during the drought, using the same aggregate consumption constraint. At the lowest welfare cost allocation, higher household prices and lower

commercial prices lead households to undertake about 96 percent of the required saving, compared with 82 percent under Cape Town's actual prices. This allocation reduces the present value of the total welfare cost of the drought by 52 percent, while preserving water for basic household needs. Households gain in aggregate from this reallocation because the employment benefits outweigh the cost of their additional water conservation.

By contrast, simply charging households and firms the same price would have reduced the welfare cost by 13.5 percent, capturing only about a quarter of the welfare gain from corrective pricing. We also allow household consumption to have a social marginal value above its price, and valuing household water 20 percent higher than its price reduces the welfare gain from 52 to 49 percent. The corrective price wedge is smaller the more firms can substitute away from water, the more flexible wages are, and the better credit markets function. When policymakers cannot address these distortions directly, corrective pricing between households and firms is a second-best policy.

Our paper builds on the literature surrounding scarce environmental resources, which has often studied how households and firms individually adjust to reduced supply. We contribute by comparing the welfare costs of these responses jointly, including the lasting employment consequences of distorted firm adjustment alongside the direct cost of household conservation. There are empirical papers that seek to quantify gains from using market mechanisms to price or trade water across users (Mansur and Olmstead, 2012; Ryan and Sudarshan, 2022; Rafey, 2023), and also related work on power allocation between households and industry (Hao et al., 2025). Our finding is in line with research showing that financing constraints can make market-based water allocation inefficient (Donna and Espín-Sánchez, 2026). We complement research on the welfare consequences of household conservation and adaptation (Costa and Gerard, 2021; Abajian et al., 2026) by measuring the cost to households of increasing commercial pricing.

This paper also relates to research that tries to understand the adjustment margins of firms to resource shortages. We document that even small cost-share resources like water can lead to establishment exit and lasting employment losses following a temporary increase in prices. Papers that look at electricity and gas shortages demonstrate how substitution and alternative supply can limit production losses (Fisher-Vanden et al., 2015; Allcott et al., 2016; Moll et al., 2023). Unreliable electricity supply also affects firm scale and entry, with consequences for productivity and employment (Fried and Lagakos, 2023; Mensah, 2024). In the case of water, we find limited scope for substitution and a pattern of establishment exit consistent with wage rigidities and credit market failure constraining the ability of firms to absorb the temporary cost increase. The long run dynamics follow Walker (2013), who documents worker adjustment costs leading to long-lasting earnings losses following a change in environmental regulation. We provide evidence that these same costs result in a similar long term reduction in employment even after a temporary shortage.

Our paper further speaks to a growing body of work on the effect of temporary shocks on local economies. Work on recovery paths after large shocks (Davis and Weinstein, 2002), as well as lasting changes in industry location and city population (Redding et al., 2011; Hanlon, 2017), shows that temporary shocks can lead to different long run consequences. Our paper shows that the allocation policy during a shortage can reduce long run welfare costs by incorporating the underlying distortions that residents and firms face when adjusting.

The rest of the paper proceeds as follows: Section 2 describes the drought and the city's prices; Section 3 sets out the pricing rule; Section 4 describes the data; Sections 5 and 6 present the household, firm and worker evidence; Sections 7 and 8 develop and estimate the model; Section 9 evaluates the results; and Section 10 concludes.

2 The Day Zero drought and the policy response

The city of Cape Town, at the time with a population of about 4 million, is the largest urban cluster in the region and draws water from the Western Cape Water Supply System. The system consists of a network of six reservoirs shared with nearby municipalities and farms. Water allocations to municipalities are regulated by the national Department of Water and Sanitation (DWS), which determines restrictions on withdrawals based on water availability and expected replenishment. Under normal conditions, Cape Town accounts for approximately 60 percent of the system's allocated water supply. Each municipality then has discretion to set its own prices for households and for firms in the city, subject to the imposed resource constraint. Agricultural water allocations and restrictions are determined at the national level and fall outside the City's direct control.

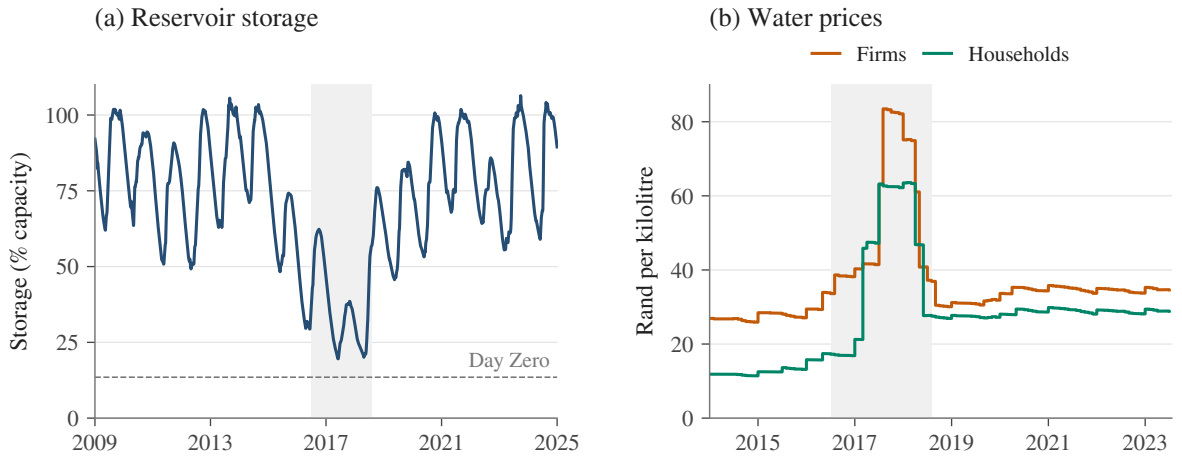
The Day Zero drought was caused by a large reduction in winter rainfall in the Western Cape region of South Africa. The city planned to shut off most taps if reservoir levels fell to 13.5 percent of capacity, a point it called "Day Zero". The drought peaked in late 2017 and early 2018 (Figure 2.1), when water levels in the reservoirs fell below 20 percent of capacity, triggering a significant reduction in the outflow allowance from the system. This reduction required that over the next 12 months, the city would have to reduce its water use by over 45 percent to avoid running out of water. By late-2018, heavy winter rainfall refilled the reservoirs, and the national outflow restrictions were largely relaxed by December 2018 (Ziervogel, 2019).

An important aspect of water and droughts specifically is that the higher prices were a response to the scarcity of water, rather than an upward sloping supply curve. The city had little scope to increase supply in the short run given that it was already entitled to a majority of all water in the system. Even an extreme reallocation of all water in the system to Cape Town would not have been able to meet Cape Town's pre-drought

water consumption. Water is costly to transport relative to its value at origin, and new sources take time to build. The desalination, groundwater and other replacement sources available during the shortage supplied only a small part of the required saving (Appendix A compares this new supply with the reduction in use). We therefore treat the resource constraint as binding.

To meet this resource constraint, the city raised prices sharply for both households and firms, along with some usage bans and a public information campaign on water conservation. Cape Town used a single commercial rate for firms, charging the same for a litre across sectors and establishment sizes. Households faced an increasing block tariff, with higher unit rates applied to higher usage households. For simplicity, we will report only the median household's average water price throughout. The city council had the freedom to set its own prices and did so regularly, eventually tripling both the commercial and average household prices at the peak of the drought (Figure 2.1).

Figure 2.1. Reservoir storage and water prices

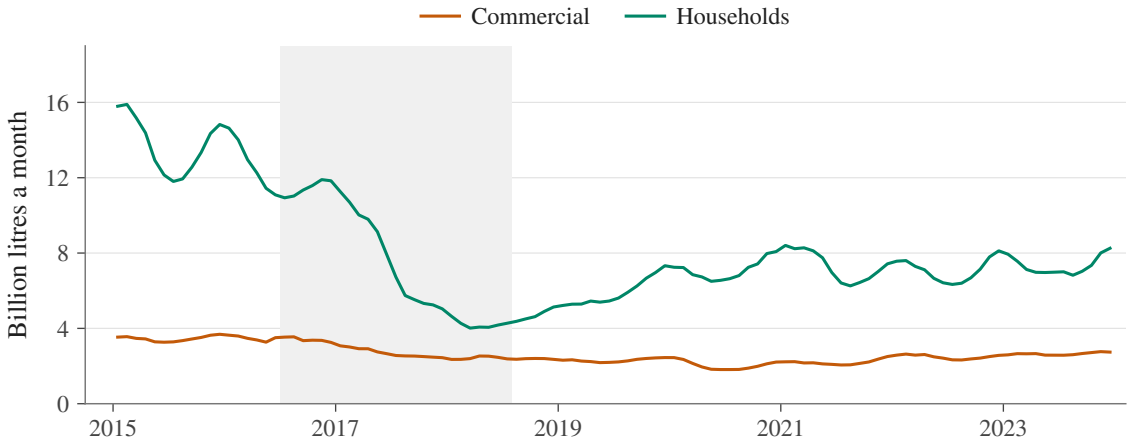


Notes: Panel (a) shows water stored in the six reservoirs of the Western Cape Water Supply System as a percentage of capacity. Panel (b) shows water prices in constant June 2026 prices (South African Rand), the single commercial rate for firms and the median household's average price. The grey band marks the period of drought pricing and restrictions. Sources: Department of Water and Sanitation; City of Cape Town tariff schedules.

In response to the large increase in prices, both households and firms reduced their water use (Figure 2.2). Water consumption of households exhibits two key characteristics in aggregate. First, it is highly seasonal, with peaks in the dry summer months and lows during the wet winter months. Second, it is highly responsive to price, with an aggregate reduction of over 60 percent by the end of the drought. The reduction in firm water consumption was less pronounced, with an aggregate reduction of 30 percent by the end of the drought. In terms of the total water reduction necessary, households supplied over 80 percent of the total saving. In the rest of this paper, we will address the question of whether this allocation was efficient, or whether a different allocation of the same water

supply could have reduced the welfare cost of the drought.

Figure 2.2. Household and commercial water use



Notes: Aggregate household and commercial water consumption in billion litres a month, from all metered accounts in Cape Town. The records exclude informal settlements that benefit from municipal taps and cover about 95 percent of all water consumption. The grey band marks the period of drought pricing and restrictions. Source: City of Cape Town billing records.

3 The social value of water

To minimise the welfare cost of the drought, the city should aim to allocate water such that the social marginal value of water is equalised between households and firms. We assume that the only policy instruments available to the city are the firm and household water prices. Determining the prices that deliver the lowest welfare cost of the drought requires distinguishing between the costs of adjusting to a shortage and the additional losses caused by distortions. The shortage will reduce welfare even under efficient adjustment, while a corrective price wedge is needed when the gap between social marginal value and willingness to pay differs across households and firms (Diamond, 1973; Richter and Schneider, 2003).

The first step in determining this corrective price wedge is to measure the social marginal value of water for households and for firms. We define welfare as total surplus in the city, or the value of what the city consumes and produces net of its real costs. Households are therefore affected both as consumers of water and as workers in the city. We aggregate the present value of total surplus lost due to the drought across all agents in the city, in money metric terms, which after dropping transfers delivers our aggregate welfare loss. The social marginal value of water for each agent is the change in welfare from a marginal change in their water consumption.

Each agent will freely choose their water consumption until their private marginal value of

water equals the price set by the city. The wedge captures the difference between the social marginal value of water and its price, reflecting an externality- or distortion-induced loss of surplus from a decrease in water consumption. The wedge can be positive or negative, depending on whether an additional unit of water preserves more surplus or less surplus than the user's willingness to pay. Denoting W as welfare, Q^H and Q^F for household and firm water consumption, p^H and p^F for the household and firm price respectively, and ω^H and ω^F for the two corresponding wedges, the water allocation with the lowest welfare cost satisfies:

$$\frac{\partial W}{\partial Q^H} = \frac{\partial W}{\partial Q^F}$$

Water must have the same social marginal value across the two users, and for each the social marginal value is the user's willingness to pay plus the wedge created at that allocation, so the condition becomes

$$p^H + \omega^H = p^F + \omega^F \tag{3.1}$$

Both sides are evaluated at the allocation the two prices produce, and the wedges change with it.

The next question is from what specific distortions a wedge may arise for either households or firms. On the household side, access to essential water for drinking, sanitation and basic hygiene is fundamental for health outcomes (Galiani et al., 2005). This is particularly important in the context of cities, where high population density increases the potential for infectious diseases to spread between residents (Bryan et al., 2020). From the WHO we take 50 litres of water per person per day as the benchmark for essential needs (Howard and Bartram, 2003), and assume that above such a level, households impose no public health externalities from reducing water consumption.

Households still bear the private cost of reducing consumption or adapting to less water above their essential needs. They may give up uses they value less than the price, invest in water-saving technology, or obtain alternative supplies (Abajian et al., 2026). Since households are free to choose these responses, and pay for their costs, their willingness to pay for piped water will reflect the alternatives available to them. These private adjustment costs therefore do not contribute to a wedge between private and social marginal value on the household side.

Private adaptation can nevertheless create externalities or face other distortions. For example, extracting groundwater can reduce availability or raise pumping costs for others that tap into the same aquifer. We abstract from these effects in the baseline and assume no household wedge as long as households remain above the requirement of 50 litres of water per person per day. Section 9.4 relaxes this assumption by introducing a wedge for

the household side, valuing household water consumption above its price. It shows how our results would be affected and how large this additional social value of household water would have to be in order to justify the city's actual policy.

On the firm side, a higher water price raises costs. Firms may absorb the higher water bill without adjusting anything else, or they may respond by substituting to other inputs, producing less, raising prices, or closing. Absent any distortions or externalities, the decision of the firm that maximises the present value of its profits also has the lowest social cost. A shortage can therefore reduce welfare even when firms adjust efficiently, and a corrective wedge arises only when an externality or a market distortion prevents the firm from adjusting in the most efficient way.

If the firm adjusts by producing less, this can mean employing fewer workers. This will decrease the demand for labour in a given sector and location of the city, and if wages can adjust freely, they will fall until labour supply equals the lower demand. This adjustment will not happen when downward wage rigidities bind, creating a deadweight loss to workers who would be willing to accept less but are instead rationed out of work (Hazell and Taska, 2025; Magruder, 2012). The worker's lost surplus is the difference between their wage and their outside option. The firm compares the worker's marginal product to the market wage, leaving the worker's surplus out of its private decision. If wages could adjust downward, some of these workers would remain employed at a lower wage. Therefore, when downward wage rigidities bind, an additional unit of water that can maintain employment is worth more to society than the firm's willingness to pay.

Firms may still end up with a temporary loss during the drought due to the higher prices. If their continuation value is larger than the temporary loss, they could cover that loss by borrowing against future profits. Credit market failures provide another source of the wedge, where a firm may be unable to finance a shortfall even when its net continuation value is positive (Holmström and Tirole, 1997, 1998). With full credit, the marginal closing firm would have a continuation value of zero, while a credit market failure can force a firm to close even when its continuation value is positive. This positive continuation value is therefore an inefficient loss in producer surplus.

The labour demand that workers face in other sectors and locations of the city determines how long the welfare losses caused by these distortions persist. Water-intensive sectors are hit harder by the price increases, so they face a larger fall in labour demand, while sectoral composition is heterogeneous across locations. Workers who lose their jobs can seek employment in other sectors or locations, but may face high switching costs to change sector (Artuç et al., 2010; Dix-Carneiro, 2014). Taking work in another part of the city may require a longer or more expensive commute (Kerr, 2017), while unfamiliarity with the area can discourage workers from considering jobs far from their current one (Dean et

al., 2026). Moving home to access these jobs can also be costly and depend on a partner's employment. These adjustment costs can prolong unemployment beyond the shortage itself and amplify the welfare losses caused by the distortions.

The adjustment of firms will also impact firms operating in the same neighbourhoods. Firms contracting or exiting free up floorspace for neighbouring firms to use. At the same time, firms benefit from positive productivity spillovers from nearby firms and workers. Therefore, losing local employment may reduce the productivity of surviving firms in the form of reduced productive agglomeration (Ahlfeldt et al., 2015; Gathmann et al., 2020) even as floorspace becomes cheaper. Individual firms do not account for these effects when making their own decisions, and can contribute to a wedge between the social and private value of water used by firms.

In the absence of the above distortions or externalities, the firm's willingness to pay equals the social marginal value of its water. If the household wedge is also zero, a single clearing price gives the lowest welfare cost, regardless of how much each of them reduces consumption (Montgomery, 1972). This is the one-price benchmark we will test against. A positive firm wedge changes the optimal policy, as the household price should exceed the firm price by the additional surplus that a unit of water preserves through firms.

Establishing whether corrective pricing is necessary is an empirical question that requires examining how households and firms adjusted to the shortage.

4 Data

Understanding how households and firms adjusted to the price shock requires observing both their water use and how they adjusted to reducing it. For households, we need to observe water consumption across users relative to basic needs, and how elastic their consumption was. On the firm side, we need to understand how the aggregate reduction in firm water consumption occurred. We do so by classifying their exposure to the price increase, and then following establishments and their workers through the drought and after. We therefore need data on cost exposure, firm water use, along with establishment and worker level outcomes.

To measure these outcomes, we obtained access to South Africa's confidential administrative tax records through the National Treasury's Secure Data Facility in Pretoria. We used individual and company tax returns to construct a matched employee-employer panel dataset from 2014 to 2024.[1]

The panel covers all formal firms, establishments, and workers across the country. Worker

[1]The South African Revenue Service (SARS) tax records are linked by the National Treasury (Pieterse et al., 2018); the confidential tax records are accessible through the National Treasury Secure Data Facility.

pay slips identify the employer, the workplace establishment, provide information on annual earnings, age, and employment status. We also observe workplace location and residential location at the postcode level. Establishments differ from the firm when a given firm has multiple establishments as they are the physical work locations. Company-level tax returns give information on firm-level sales, which can be attributed to each establishment through VAT and transfer pricing records.

Table B.1 in Appendix B reports Cape Town's population, formal employment and water accounts in 2016. It also reports the share of workers in exposed sectors at the beginning of the drought. In Cape Town, 88 percent of employment outside agriculture and private households was in the formal sector in late 2016 (Statistics South Africa, 2017b).

When assessing worker-level outcomes we focus on formal employment and annual earnings. We are able to track the worker between locations and employers across tax years, as long as they are making any single interaction with the National Treasury. Absence from the data may include informal work, self-employment and departure from the labour force with no benefits or pension.

In terms of attributing firm-level outcomes, our analysis will take place at the establishment level. This allows us to focus on the actual entity that is located within Cape Town and that will be hit by the cost shock, and whose workers will be affected. We count an establishment as entering in its first active year, and exit is recorded according to the last tax receipt coming from that establishment.

To understand the effect of the drought on establishments and workers, we need to understand their exposure to water cost shocks. An establishment's sector is a three-digit industry in the South African SIC classification (Statistics South Africa, 2012b), which is made up of 237 sectors. We use the water expenditure's share of total input costs in Statistics South Africa's 2010 Supply and Use Tables, which can be linked to the SIC classification according to Budlender and Ebrahim (2020). We assign a binary water-intensive classification to the top 20 percent of sectors by water cost share. Appendix B.3 lists their mapped shares.

To understand individual-level water use, we obtained monthly billing records from the City of Cape Town. These records cover all metered household and commercial accounts from 2014 to 2023, and record location, quantity consumed, and price paid. Each account is an individual billing contract attached to a metered property. We measure household water use per person by dividing each account's consumption by an assumed 3.5 people per account, in line with the 2011 Census mean of 3.4 people for Cape Town households with piped water (Statistics South Africa, 2015). The records are available only for Cape Town and exclude informal settlements that benefit from municipal taps. Our data therefore covers approximately 95 percent of all water consumption. Confidentiality restrictions

prevent us from linking this data to the tax records, which would have allowed us to track water use at every establishment. We therefore use these billing records to measure aggregate responses of households and firms, and use sectoral water intensity as an exposure measure in our research design.

5 Households

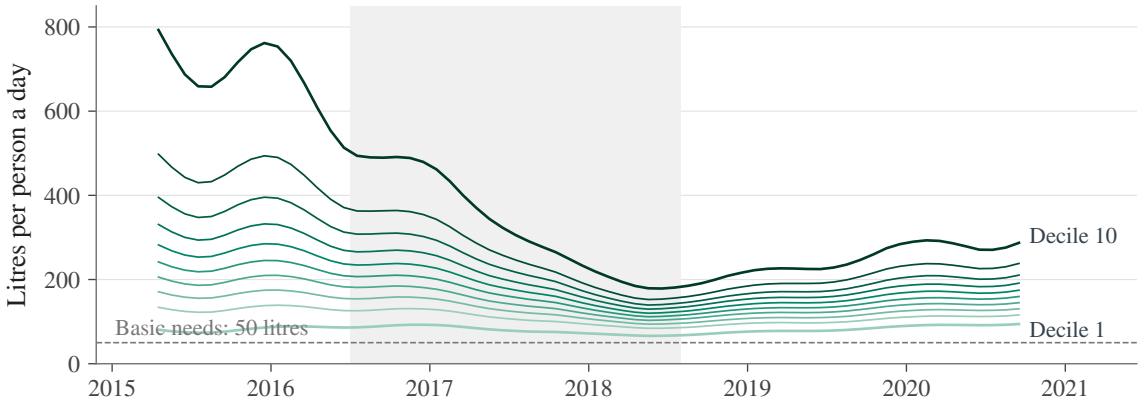
To assess the welfare cost of increasing domestic water prices we need to understand how households responded to them individually. The large aggregate reduction could reflect cuts in non-essential water use, but could also mask some households reducing water consumption below basic needs. In densely populated cities, this could lead to potential sanitation externalities. We therefore look at water consumption patterns across the distribution of water users, and the broader evidence on health during the drought. We use the meter data to estimate the price elasticity of household water demand and the effect on household income.

In 2015, water consumption in metered households averaged approximately 237 litres per resident per day across the city's population, nearly five times basic needs. To visualise the scope for saving water across users, Figure 5.1 follows deciles of household accounts over time and compares their average water use per person to the 50-litre benchmark from Section 3. Before the drought and sharp price increases, the largest users consumed several times the amount of water of low usage households. Consumption began to decrease in December 2016, reaching its lowest level in mid 2018. Between 2015 and 2018, the top three deciles supplied 62 percent of aggregate household water reduction, with the top decile reducing water consumption by 75 percent. All household deciles reduced their water consumption above basic needs by roughly 40 to 80 percent, while their average use remained above the 50-litre benchmark.

Water use recovered only partly once prices fell following the end of the drought, but remained below its pre-drought level. Part of this sustained reduction in use can be explained by the fact that household prices, unlike firm prices, never fully returned to their pre-drought real level and settled on higher median levels (Figure 2.1). This persistence is also consistent with sticky changes in resident behaviour habits, as documented for electricity use by Costa and Gerard (2021). Households also reduced their municipal water consumption through private investments, including water-saving technology such as tap aerators and low-flow showerheads, and by partially substituting to different water sources. For Cape Town, Abajian et al. (2026) document substitution toward privately financed groundwater, concentrated among the wealthy households at the very top of the water use distribution.

In terms of potential health consequences, the concern is that low-income users in high-

Figure 5.1. Household water use by pre-drought consumption decile



Notes: Average daily water use per resident in each decile of the 261,000 continuing household accounts, grouped by water use before the drought. Use per resident assumes 3.5 people per account. The grey band marks the period of drought pricing and restrictions. Source: City of Cape Town billing records.

density neighbourhoods may have been unable to access enough water to cover basic needs. This would have the potential to generate negative public health externalities. To look at health outcomes, we turn to the research that has been conducted in Cape Town following the drought. Using public health records from 2010 to 2019, Lee et al. (2023) find no increase in diarrhoeal or other infectious disease, a health risk associated with inadequate access to sufficient water and sanitation (Galiani et al., 2005).

To assess whether the higher prices also increased household water spending, we turn to the elasticity of household water demand. We use data on citywide monthly household consumption from January 2015 to December 2023, and control for calendar month to account for consumption seasonality. For the price variable, given the non-linear tariff structure, we use the household price above the first 6,000 litres a month, which are charged at a lower rate as they are seen as covering basic needs. We therefore focus only on the non-essential component of water demand as a separate consumption good. The estimated elasticity is -0.97, with a standard error of 0.08 (Appendix H.1). Alternative estimates range from -0.88 to -0.98, using individual account-level data and instrumenting each account's marginal price with the price it would face under the new prices at its 2015 consumption. The main result is that across all estimates, consumption falls approximately in proportion to the increase in marginal prices with a near unit elasticity, consistent with household spending on water remaining largely unchanged. For completeness, this average does mask differences across households. Bills rose for lower-use households during the drought, reaching around R200 (or 15 USD at the time) a month in the lowest consumption decile, while falling for the highest users who cut consumption more than proportionally to the price (Appendix Figure B.1). In terms of income effects, R200 was approximately 6 percent of the monthly national minimum wage introduced in 2018, and allowed households

to purchase over 200 litres per day. The city also provided free basic water to households qualifying for indigent support, helping maintain access to water for essential use despite the higher tariffs.

The findings on household adjustment support the baseline assumption in Section 3 that households bear the full cost of their conservation and adaptation above basic needs, with no additional household wedge. Section 9.4 allows the social marginal value of household water to exceed the price households are willing to pay and assesses how large such a difference must be to overturn our findings or justify the city's actual policy. We next look at how firms reduced their water consumption, and what distortions in their adjustment could have created losses beyond their own willingness to pay.

6 Firms and workers

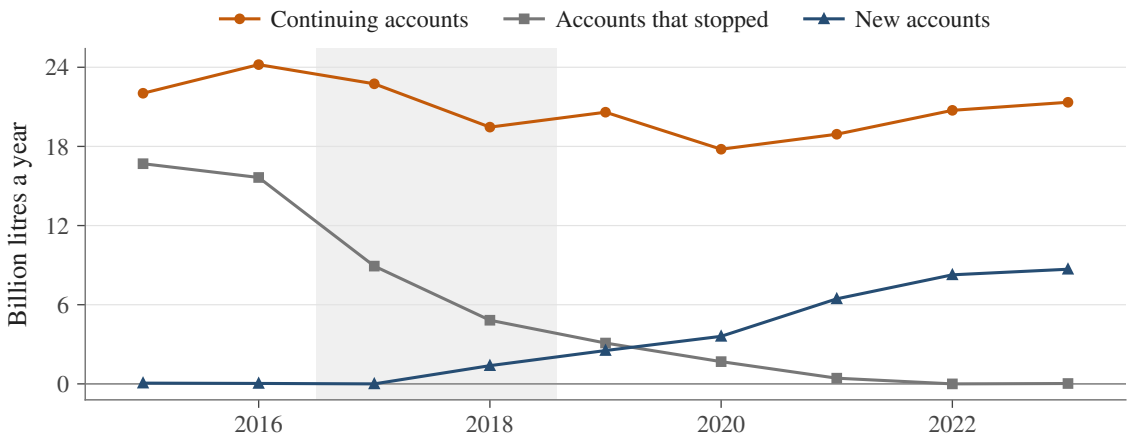
6.1 How firms saved

To assess the welfare cost of increasing prices on firms, we first need to understand how firms adjusted to higher water costs. Firms may adapt to higher costs through lower profits, higher output prices, or by reducing production or other input costs. Borrowing may allow them to remain open through a temporary operating loss, while substituting away from water can preserve production and employment. If saving water involves downsizing or closing, the consequences for households also depend on whether workers can find other jobs. As discussed in Section 3, these responses can occur even when adjustment is efficient. We therefore examine how firms saved water and what happened to employment, then consider adjustment options for workers and what may have distorted firm decisions in labour and credit markets.

Figure 6.1 decomposes firm water consumption into utility accounts that continued, exited or entered by 2023. About 80 percent of the reduction in firm water consumption came from firms that exited in 2017 and 2018. Among continuing accounts, consumption fell by only 12 percent from 2016 to 2018 despite the threefold price increase, and began to recover as prices fell after the drought, with the exception of 2020 and 2021 where Covid would have reduced economic activity and water demand.

The reduction in firm water consumption therefore came largely from establishments that closed their municipal utility account, suggesting exit, while surviving firms contributed a small amount to the total reduction. To understand what this means in terms of establishments and employment, we turn to the national tax records. These cannot be linked to the municipal data and therefore we rely on an exposure design to measure the effects of the drought and the higher water prices.

Figure 6.1. Commercial water use by account status



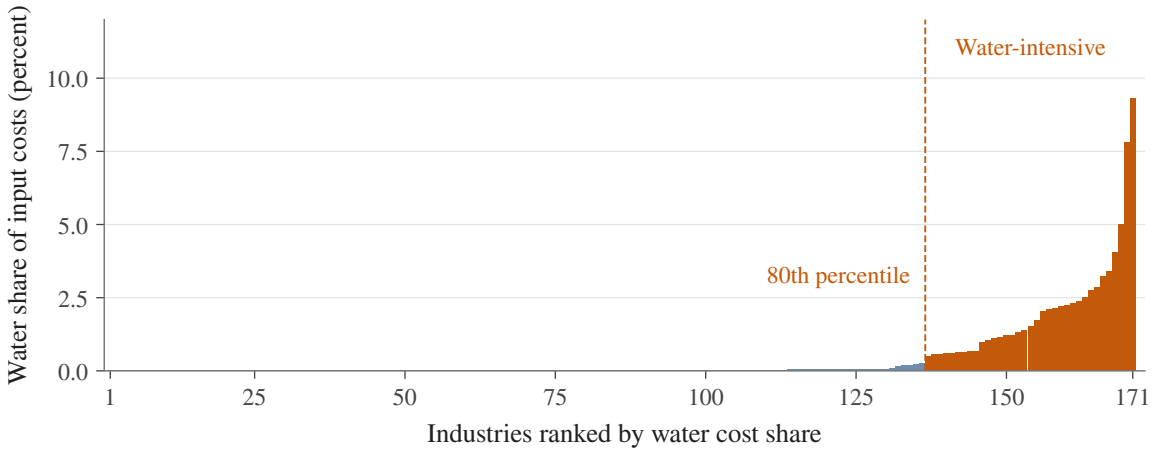
Notes: Annual water consumption of commercial and industrial accounts by account status. Accounts are classified as new if first bill occurs after the beginning of the drought. Classified as stopped by date of last utility bill, and continuing if utility account remains open. The grey band marks the period of drought pricing and restrictions. Source: City of Cape Town billing records.

6.2 Design

To estimate the effects of the commercial price increase on firms and workers, we take advantage of sectoral heterogeneity in water cost shares. We measure this exposure using the national pre-drought water cost shares described in Section 4. Water cost shares are highly skewed, with the majority of sectors spending very little on water and higher shares in the top quintile (Figure 6.2). For example, water accounted for around 3 to 6 percent of input costs in sectors such as beverage production and iron/steel processing, compared with less than 0.1 percent in telecommunications and insurance (Appendix Table B.3). At unchanged quantities, tripling the water price therefore raises total costs in exposed sectors by 6 to 12 percent. Using pre-drought shares keeps this measure of exposure fixed as firms adjust. As our exposure variable, we classify the top quintile of sectors by water cost share as water-intensive, and compare them with all remaining sectors. We also conducted the same analysis using a continuous measure of water intensity and the results are consistent (Appendix D.5).

We use a triple-difference design to compare changes in water-intensive and non water-intensive sectors in Cape Town with the same sector comparison in a group of control cities. This accounts for changes common to sectors within each city and national changes specific to each sector. The comparison cities are the other three large metropolitan areas in South Africa: Johannesburg, Pretoria, and Durban, which were unaffected by the drought given their distance and did not face Cape Town's water price increase. Their establishment-size distributions and shares of employment in water-intensive sectors are similar to Cape Town's (Appendix Figure B.2).

Figure 6.2. Water's share of input costs across national industries, percent



Notes: Each bar shows water expenditure as a percentage of total input costs for one of the 171 industries in the national 2010 Supply and Use Tables. These industries are mapped to the three-digit South African SIC classification using Budlender and Ebrahim (2020). Source: Statistics South Africa, 2010 Supply and Use Tables.

Outcome Y_{cst} is the outcome of interest in city c, sector s and year t. We estimate

$$Y_{cst} = \sum_{\kappa \neq 2016} \beta_\kappa \, \mathbf{1}\{c = \text{Cape Town}\} \, \text{WI}_s \, \mathbf{1}\{t = \kappa\} + \vartheta_{cs} + \delta_{ct} + \delta^S_{st} + u^E_{cst}, \qquad (6.1)$$

where WI_s is a dummy indicating a water-intensive sector. ϑ_{cs}, δ_{ct} and δ^S_{st} control for city-sector, city-year and sector-year fixed effects respectively. We will report our findings as an event study, with β_κ measuring the change since 2016 in the difference between water-intensive and other sectors in Cape Town, relative to the same difference in control cities. The coefficients therefore measure the relative response of more exposed versus less exposed sectors. Appendix C.1 gives the outcome construction, and Table C.1 reports the estimates behind the figures.

Our identifying assumption requires that absent any commercial price increase in Cape Town, the difference between water-intensive and other sectors in the city would have evolved as in the control group. A Cape Town-specific shock independent of the cost shock that disproportionately affected water-intensive sectors would violate this assumption. We further require that any effect in Cape Town's water-intensive sectors did not spill over to non water-intensive sectors or the control cities, for example through relocation or shifts in demand towards their firms. Appendix C.2 reports the two underlying difference-in-differences comparisons and discusses potential spillovers across sectors and cities. Negative spillovers to Cape Town's non water-intensive sectors would narrow the gap between sectors and reduce the estimated losses. We examine these local spillovers in Section 6.4 and account for them in the model in Section 7.

We cluster standard errors by city-sector for the triple-difference estimates. Because the

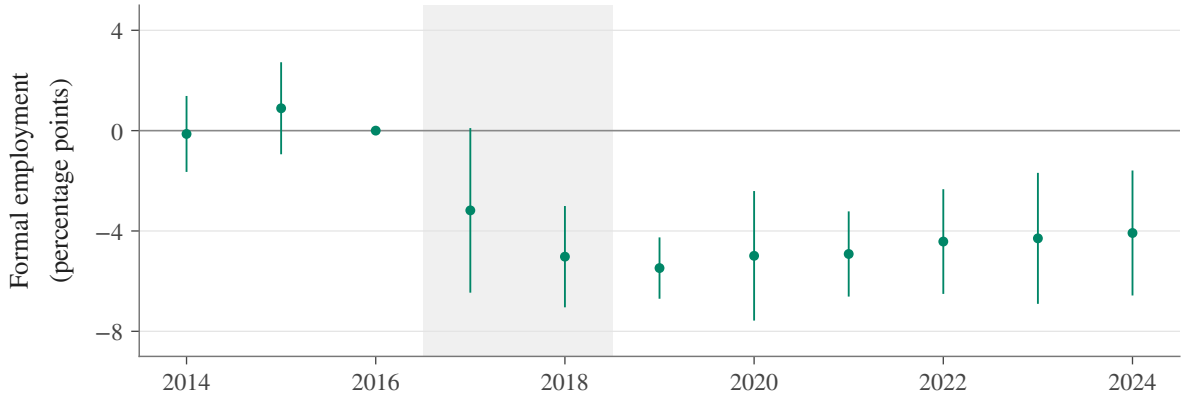
shock only occurred in one city, we also provide robustness measures on inference by reassigning treatment to other cities in the national tax panel and comparing Cape Town's estimates with the resulting distribution (MacKinnon and Webb, 2020; Conley and Taber, 2011). Appendix C.3 describes this procedure for establishments and workers.

6.3 Employment and establishments

To measure the effect of the higher commercial water prices on workers, we follow all workers formally employed in 2016. Following Walker (2013), we fix their exposure using their employment at the beginning of the drought. We do this by assigning each worker to the city and sector of their main employer in 2016, which means that exposed workers are those who in 2016 were employed in water-intensive sectors in the City of Cape Town. We estimate a linear probability model using the worker-level equation (C.1), with an indicator for formal employment anywhere in South Africa as the outcome. Appendix C.1 gives the full specification.

We find that workers initially employed in Cape Town's water-intensive sectors were 5 percentage points less likely to hold a formal job by the end of the drought in 2018, and about 4 percentage points less likely by 2024 (Figure 6.3). The reduced likelihood of employment therefore persisted long after commercial water prices fell. The estimates show no divergence in employment likelihood before the drought, with the gap opening during the price increases.

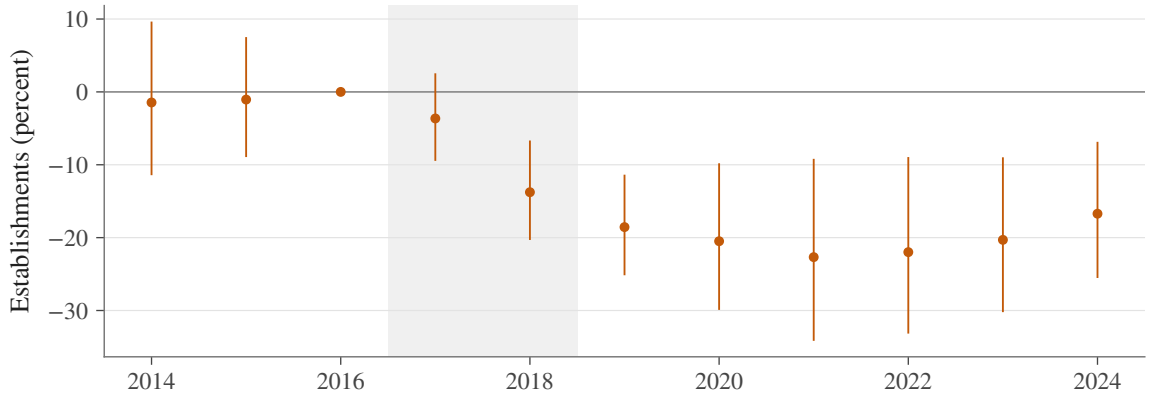
Figure 6.3. Formal employment after the price increase



Notes: Formal employment of workers employed in Cape Town's water-intensive sectors in 2016. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by the worker's 2016 city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

The employment losses were driven by a persistent decline in the number of establishments. We estimate the triple-difference specification in equation (6.1), using the log number of active establishments as the outcome. Figure 6.4 shows a clear absence of pre-trends followed by a decline in Cape Town's water-intensive sectors to approximately 20 percent below their counterfactual path. Establishment counts recovered only partly by 2024.

Figure 6.4. Establishments after the price increase



Notes: Number of active establishments in Cape Town's water-intensive sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

Higher exit and lower entry during the period of high water prices drove the decline in establishments. We estimate equation (6.1) using annual exit rates among establishments and find the exit rate rose by approximately 6–8 percentage points relative to counterfactual levels in 2017–2019 (Appendix Figure E.1). Entry also fell during this period (Appendix E.2). Both rates returned towards their counterfactual levels by 2020, but did not fully offset earlier losses.

To distinguish the response of firms to higher commercial prices from other effects of the drought, we look at the effect on placebo towns. These are cities in the same watershed that faced the same drought, but chose policies that did not place large price increases on firms, reducing consumption predominantly through households. We apply the same triple-difference specification where we assign treatment status to these towns rather than Cape Town, whilst keeping the same control cities. We find no significant decline in water-intensive establishments (Appendix Figure D.2). Appendix D.2 gives the details of the placebo.

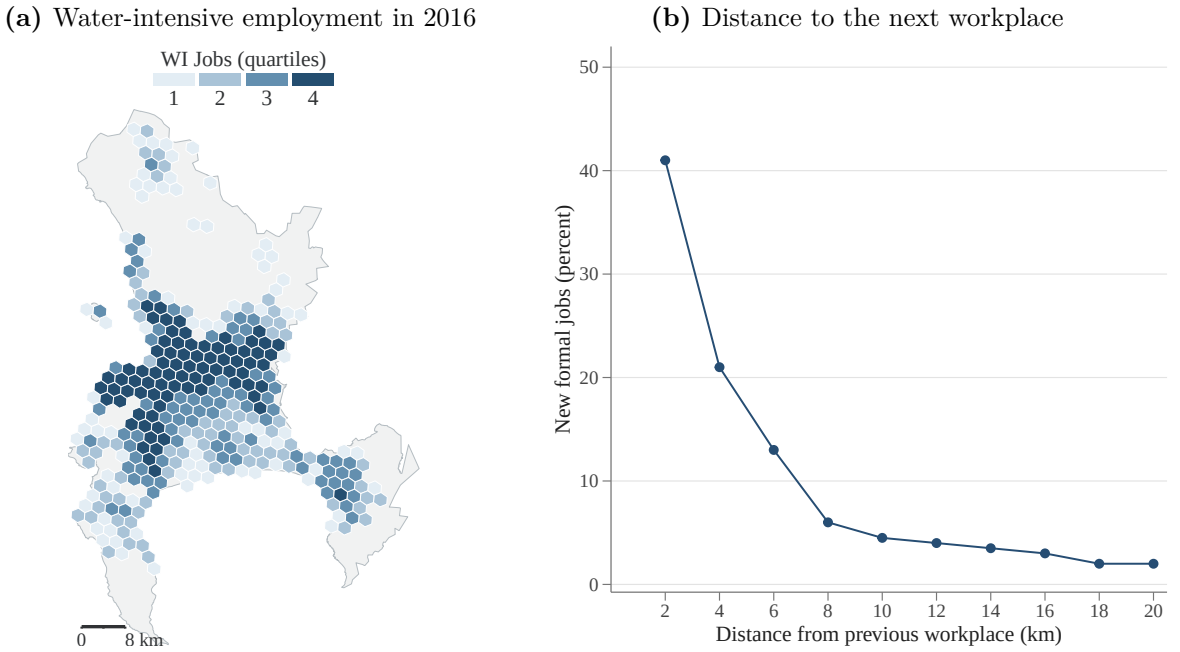
Lower local spending during the drought could also have contributed to establishment closures. We therefore compare exit in tradable and non-tradable sectors, since tradable

sectors are less dependent on local demand. We find excess exit in both groups, suggesting the decline extended beyond firms most dependent on local demand (Appendix D.3).[2]

6.4 Worker mobility and agglomeration

To understand the cost to workers associated with firm exit, we first look at where workers were located and where they found their next job. Water-intensive employment is spread across several locations within Cape Town (Figure 6.5, panel (a)). Workers however do not appear to be mobile across the city. Over half of all job switches occur within the same hexagon mapped below, and over 60 percent of new jobs are within 4 km of the old job, with a steep decline over distance (Figure 6.5, panel (b)). Switching sectors also seems to be costly. Among workers in Cape Town who changed jobs, voluntarily or involuntarily, 84 percent remain in their original sector (Appendix Figure E.5).

Figure 6.5. Employment locations and job transitions in Cape Town



Notes: Panel (a) ranks hexagons by the number of jobs in water-intensive sectors in 2016, in quartiles. Panel (b) shows the share of new formal jobs by distance from the old job, in 2-kilometre bins, for workers in Cape Town who changed jobs. Source: SARS and National Treasury tax records.

The lack of switching across sectors and locations can reflect both where jobs became available, and the costs of changing sector or workplace location. A large strand of literature in trade has established how sector changes can require workers to give up skills or experience specific to their previous job (Artuç et al., 2010; Dix-Carneiro, 2014). At the same time, accepting a job in a different location within the city can also impose large moving costs on people. This can be due to higher commuting costs (Kerr, 2017), the

[2]We find little evidence of relocation to the comparison cities (Appendix D.4). The components of the triple difference and a synthetic comparison give similar evidence of losses in water-intensive activity (Appendices C.2 and D.1).

upfront costs of moving home and associated cost of changing neighbourhood (Bergman et al., 2024), or barriers to searching for jobs in unfamiliar areas (Dean et al., 2026). At the same time, continuing establishments in water-intensive sectors did not expand employment relative to their comparison path to offset jobs lost at closing establishments (Appendix E.3).

Location specific links and spillovers between firms can also amplify the effects of higher water prices. Agglomeration externalities benefit firms through access to customers, suppliers and skilled workers, as well as learning from nearby firms (Duranton and Puga, 2004). Firm closures can weaken these benefits, although cheaper premises and greater availability of labour may favour expansion.

To examine the prevalence of these local effects, we compare annual exit rates among establishments in less water-intensive sectors across Cape Town neighbourhoods. We define neighbourhoods as the hexagons shown in the map above, and group them into quartiles by their 2016 share of water-intensive jobs. Our difference-in-differences specification compares changes in exit across these groups, controlling for neighbourhood and sector-year fixed effects (Appendix E.6).

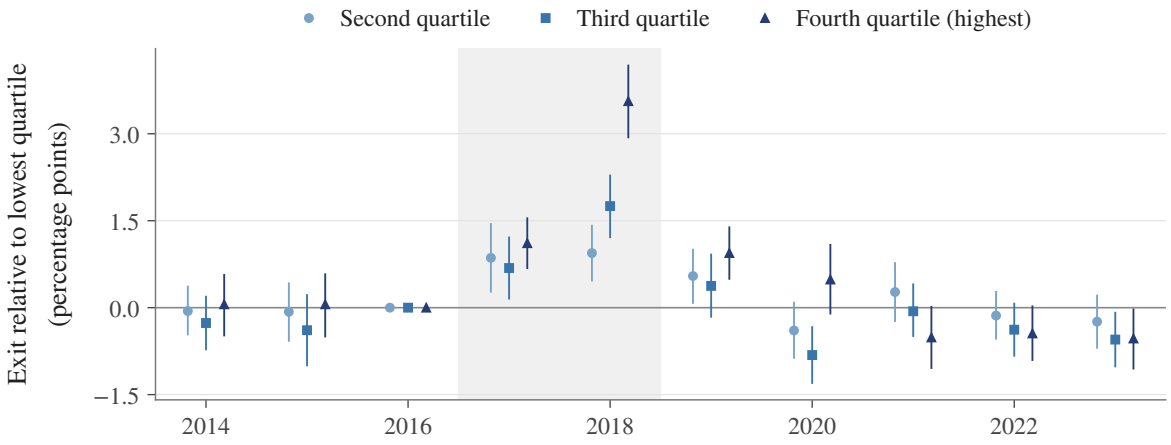
We first focus on exit in non water-intensive sectors as evidence of spillovers. We find that the exit rate rose in hexagons with a larger initial share of water-intensive employment (Figure 6.6). Pre-trends are flat yet at the peak of the drought, the exit rate of non water-intensive firms in the highest exposure quartile rose by 3.6 percentage points compared to the lowest quartile. This gap closed again by the end of the drought. We find similar effects in water-intensive sectors, suggestive of important agglomeration externalities (Appendix Figure E.7).

We examine the mechanisms behind this evidence pointing at agglomeration externalities. In neighbourhoods with a larger share of water-intensive employment, losses in other sectors were larger when they bought more from or sold more to water-intensive sectors (Appendix Table E.1). Losses were also larger in sectors employing workers in similar occupations. Appendix E.6 describes how we construct these links from national pre-drought data, following Ellison et al. (2010), and gives the full specification.

6.5 Adjustment distortions

In a competitive labour market, the decline in labour demand should put downward pressure on wages in exposed sectors and locations. This is compounded by a very steep labour supply curve given the limited movement of workers to jobs elsewhere. We should therefore observe a decrease in wages that should allow firms to reduce labour costs, and some workers to remain employed at lower pay. Given the temporary nature of the drought, firms may also borrow to smooth a temporary loss. If firms face distortions in their ability

Figure 6.6. Exit in less water-intensive sectors by neighbourhood exposure



Notes: Annual exit rate of establishments in less water-intensive sectors in Cape Town, by neighbourhood exposure. Coefficients are difference-in-differences estimates of the change since 2016 in each exposure quartile relative to the lowest quartile. Neighbourhoods are hexagons, grouped into quartiles by their 2016 share of water-intensive jobs. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

to adjust wages or borrow, they may inefficiently reduce employment or shut down. The commercial price would then understate the social value of water used by firms. We now look at evidence on whether firms did face constraints in labour and credit markets and how these may have increased the welfare cost of the drought.

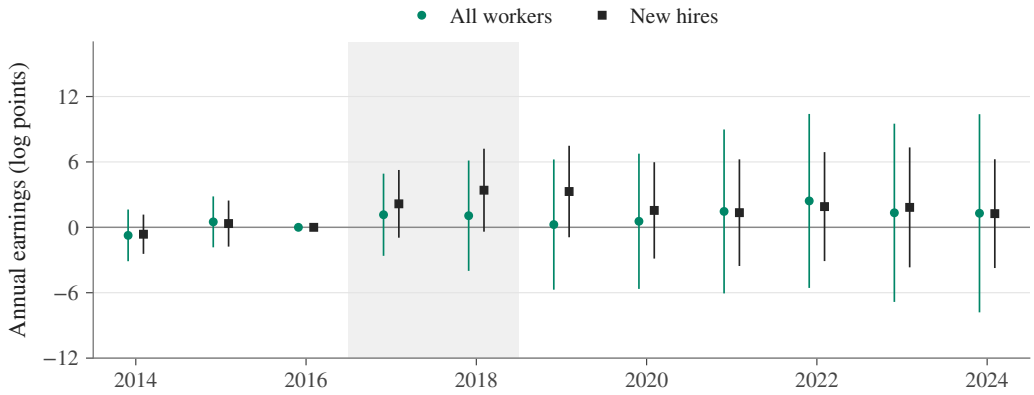
To understand whether there was any change in wages, we first look at annual earnings for all workers at surviving establishments. We run the same triple-difference comparison as the main findings, using log annual earnings as the outcome.[3] We find no decrease in earnings relative to counterfactual levels during or after the drought (Figure 6.7).

Firms may have more scope to reduce pay when recruiting rather than changing the wages of existing employees (Pissarides, 2009). Our data allows us to look at new hires specifically, defined as workers who start at an establishment where they were not employed the previous year. We estimate the triple-difference comparison at the individual level using the same earnings outcome. The regression includes establishment, city-year and sector-year fixed effects, along with controls for age, previous pay and entry from outside formal work. Appendix B.1 gives the full specification.

We find earnings for new hires did not fall relative to counterfactual levels. The estimates are close to zero before the drought and slightly positive during the drought, potentially indicative of some unobserved selection. Earnings of new hires did not fall below counterfactual levels after the drought either. We take this as evidence consistent with strong downward wage rigidities.

[3]Annual earnings depend on both pay rates and time worked during the year.

Figure 6.7. Wages at surviving establishments



Notes: Log annual earnings at surviving establishments in Cape Town's water-intensive sectors, for all workers and for new hires. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. New hires are workers who were not at the establishment the year before; their regression replaces the city-sector fixed effects with establishment fixed effects and controls for age, previous earnings and whether the worker was hired from outside formal work. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

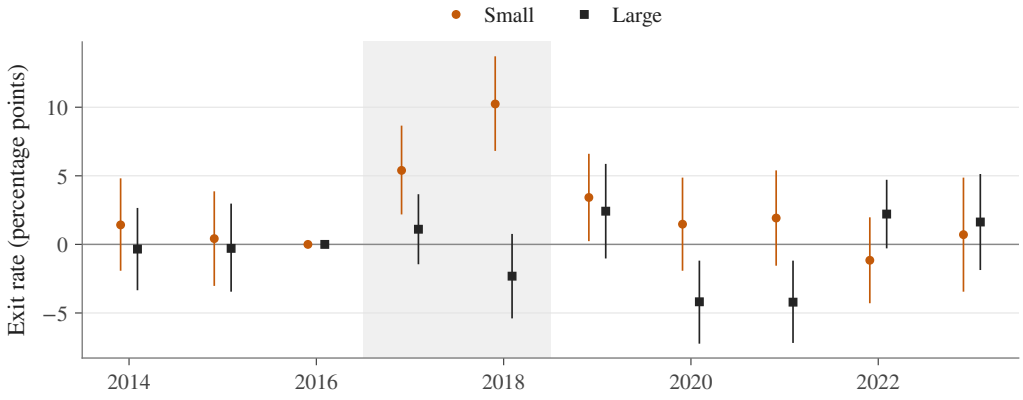
The root of this wage rigidity is embedded in how sector agreements in South Africa limit the ability of firms to adjust pay to local conditions. Bargaining councils negotiate agreements whose conditions extend to employers that did not sign them (Magruder, 2012), which can even mandate increases in hourly pay. Appendix A.4 describes the agreements covering exposed sectors. Among workers who remained employed during the drought period, wages nearly always increased (Appendix Figure E.6). The lack of any evidence pointing to wage decreases is consistent with downward wage rigidities, which will be a key adjustment distortion firms face in our model.

With limited scope to reduce wages, firms may need to borrow to cover a temporary loss. Smaller firms are more vulnerable to credit constraints (Chodorow-Reich, 2014), and in the 2020 South African Enterprise Survey, only 6 percent of small firms stated they had a bank loan or line of credit (World Bank, 2020). Credit decisions are endogenous. However, as a first step in trying to understand whether credit constraints may have distorted firm decisions, we compare exit across small and large establishments.

We use our triple-difference specification, estimating the effect on exit rates separately for small and large establishments. Establishments are classified as small if their employment is below the median, calculated within sector in 2016. We find that the excess exit of water-intensive establishments during the drought was driven entirely by small establishments (Figure 6.8). The estimates show no divergence before the drought, followed by an increase in exit among small establishments once the water price increased in 2017, reaching about 10 percentage points above counterfactual levels in 2018. This should be interpreted as 10

percentage points higher than the pattern of small firm exit would predict given what was happening in non water-intensive sectors and what was happening in the control cities. Large establishments showed no comparable increase, and exit of small firms returned to counterfactual levels after the drought. This pattern is consistent with credit constraints, though size may also reflect differences in profitability. We will use our model to disentangle the two.

Figure 6.8. Establishment exit by size



Notes: Annual exit rate of establishments in Cape Town's water-intensive sectors, separately for small and large establishments. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Small establishments have 2016 full-time-equivalent employment below the median in their sector, and exit is measured among establishments with more than one full-time-equivalent worker. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

6.6 Implications for welfare

The reduction in firm water consumption occurred largely through establishment exit, and employment losses persisted after commercial prices fell. The lack of adjustment in wages and the concentration of exit among small establishments suggest that wage rigidities and credit constraints limited the ability of firms to absorb the temporary water price increase. Workers faced frictions in changing sector and location, which could have prolonged the employment losses, while a reduction in agglomeration externalities created further losses at nearby firms.

To determine how the city should have allocated water given its binding resource constraint, we need to know how employment and firm survival would have responded to a different allocation, and how total surplus would change. This requires understanding how workers valued employment relative to their alternative options, and accounting for future firm profits after covering any temporary loss. Our empirical comparisons are only able to measure relative responses across sectors and cities at the prices Cape Town chose. We

instead need to understand how these responses would evolve across the whole city under alternative prices, and past the support of our data.

To do this, we build and estimate a dynamic spatial model of the city. Households consume water and supply labour to firms, which differ in their productivity and water cost shares. Firms face wage rigidities and credit constraints when adjusting to shocks, while workers face costs to change sector and location. Local employment also affects firm productivity through agglomeration. We measure the welfare cost of the drought through changes in total surplus, accounting for household consumption, firm entry and exit, and job transitions during and after the drought.

We use the model to quantify how these distortions and agglomeration externalities contribute to the wedge between the commercial price and the social marginal value of water described in Section 3. We compare the social marginal value of water for households and firms at different feasible allocations of water under the binding resource constraint. This allows us to determine whether a price wedge is needed and which price combination minimises the welfare cost of the drought.

7 The model

We build a dynamic spatial model of the city to measure the social marginal value of water in different uses. The model has two types of agents, households and firms, and they interact in a labour market within each sector and location. Households start every period in a sector and location, supply labour, and maximise utility by consuming water and a composite consumption good. They can pay a switching cost to change sector and/or location for the following period. Firms have heterogeneous productivity and belong to sectors which differ in their water cost shares. Labour markets are characterised by downward wage rigidities, while credit markets are imperfect. Local employment also affects firm productivity through agglomeration.

The city sets water prices for households and firms to minimise the welfare cost of the drought. The prices are the city's only instrument to clear the resource constraint, which it does in static terms every year; it does not consider how water used today may affect availability tomorrow as the resource constraint is set by the national government (Section 2 and Appendix A.1). We take the path of allowances set by the government as given: the shortage binds for the drought years and water availability returns to full capacity afterwards.

Higher water prices will therefore propagate to households through their direct consumption and through sector-location labour markets depending on firm exposure to water costs. In terms of how households adapt, the social cost of reducing water consumption is equal

to the private cost as long as basic needs are met. On the firm side, wage rigidities, credit market failures, and agglomeration externalities can create a wedge between the commercial water price and the social marginal value of water. How large this wedge is depends on how costly worker and firm adjustments are. Worker transitions follow Artuç et al. (2010), firm borrowing follows Holmström and Tirole (1998), and local productivity rises with local employment as in Ahlfeldt et al. (2015).

We take welfare as the total surplus as defined in Section 3, measured in currency units (South African Rand). Household welfare includes consumption, financed by their wage, as well as location-sector specific amenities net of switching costs. Firms and landlords enter through producer surplus net of entry costs. The city enters through its water receipts, net of the cost of supply. Total welfare is the discounted sum of these gains and losses in money-metric terms, with no distributional weights (Appendix G).

We model the city as small and open, with firms selling to outside buyers and with a fixed resident population given limited migration observed to other cities (Section 6). Residents consume water and an imported composite consumption good at a fixed price, which is the numeraire. The implication is that households reducing their water consumption affects no other market in the city. Firms belong to one of the 170 3-digit sectors s in our data, and produce in one of 24 workplace locations ℓ across the city, each with a fixed stock of commercial floorspace. We do not model residential location choice separately. Households live where they work, and the location switching cost captures all costs associated with changing workplace location including a more expensive commute, higher search costs, and household decisions or investments tied to the current location. This cost increases with distance (Section 6.4). The drought arrives as a surprise, but after that all agents have perfect foresight about the aggregate adjustment path, including water allowances and prices (Appendix F.6).

7.1 Households and workers

Households value water and a composite consumption good bought on the national market. A household in sector s and location ℓ with income Y chooses water q_t and consumption c_t^I in year t to solve

$$\max_{q_t,\, c_t^I} (1-\theta)\ln c_t^I + \theta \ln(q_t - \bar{q}) + a_{s\ell} \qquad \text{subject to} \qquad c_t^I + p_t^H q_t = Y, \tag{7.1}$$

where p_t^H is the household water price, $\bar{q}$ represents non-homothetic demand for basic needs water, θ the Cobb-Douglas share on water above basic needs and $a_{s\ell}$ the amenity value of the household's sector and location. Conditional on income being able to cover

basic water needs, water demand is

$$q_t(Y) = \bar{q} + \theta \frac{Y - p_t^H \bar{q}}{p_t^H} \tag{7.2}$$

The implication is that basic water needs must be satisfied before any other consumption, and water demand above that has a spend share of θ, giving a unit elasticity. As water consumption approaches $\bar{q}$, water becomes extremely privately valuable and the price must increase more. Households choose water until their private marginal value of water equals the price. This price also reflects the household's social marginal value of a litre, since we assume no household externality once basic needs are satisfied (Section 3).

Households are also workers. Each year a worker in sector s and location ℓ is hired with probability $e_{s\ell,t}$ at wage $w_{s\ell,t}$. The probability is below one only when downward wage rigidities bite and there is excess labour supply at the wage floor, in which case the jobs are allocated by lottery. If they are not hired, they receive home production income b. A worker not hired remains in the same sector and location, differing only by realised income. A worker's income determines their consumption, and workers then choose next year's sector and workplace location, paying τ_S to change sector and τ_L per unit of distance. The location switching cost is a reduced form cost that covers all potential moving and search frictions which increase with distance. Workers draw an idiosyncratic taste shock every period from a Gumbel distribution with precision ν over sector-location pairs.

With $u^c(Y, p_t^H)$ the utility a household gets from water and consumption at income Y and price p_t^H, and β the discount factor, the value function for a worker in sector s and location ℓ is

$$\begin{aligned} V_{s\ell,t} &= \bar{u}_{s\ell,t} + \frac{1}{\nu} \ln \sum_{s',\ell'} \exp\Big\{\nu\Big[\beta V_{s'\ell',t+1} - \tau_S \mathbf{1}\{s' \neq s\} - \tau_L \text{dist}_{\ell\ell'}\Big]\Big\}, \\ \text{where} \quad \bar{u}_{s\ell,t} &= e_{s\ell,t} u^c(w_{s\ell,t}, p_t^H) + (1 - e_{s\ell,t}) u^c(b, p_t^H) + a_{s\ell} \end{aligned} \tag{7.3}$$

The worker receives this year's expected utility and amenity value, $\bar{u}_{s\ell,t}$. The second term is the expected value of the best destination the worker can choose given their Gumbel draws. This term is larger the higher the values of other sector-locations and the lower the switching costs of reaching them. Intuitively, a worker has a high continuation value if there are many good jobs in the same sector in nearby locations. If the other jobs are all in distant locations or in other sectors, the continuation value is lower. The parameter ν controls how sensitive workers are to wage differences. If ν is high, workers go where the wage is highest, which implies a very elastic labour supply to each market. If ν is low, tastes are more important in deciding if and where workers move. The distribution of workers across markets then responds sluggishly to changes in labour demand.

Since the taste draws are independent Gumbel, the expected value of the best destination takes the log-sum form in equation (7.3), and the share of workers choosing each destination is a logit in its discounted value net of switching costs. This is what we estimate from gross flows in Section 8.

Being hired increases the worker's surplus by the difference between the market wage in their sector-location, and their outside value. This means the potential welfare loss given by the wage rigidity is $w_{s\ell,t} - b$.

7.2 Production and water

Firm j in sector s and location ℓ sells output $y_{j,t}$ nationally. It combines water $Q_{j,t}$, labour $L_{j,t}$ and floorspace $H_{j,t}$ with production function

$$y_{j,t} = A_{\ell,t}\varphi_j \left[(\gamma_s^W)^{1/\varepsilon} Q_{j,t}^{(\varepsilon-1)/\varepsilon} + (1-\gamma_s^W)^{1/\varepsilon} \left(L_{j,t}^{1-\gamma_f} H_{j,t}^{\gamma_f} \right)^{(\varepsilon-1)/\varepsilon} \right]^{\varepsilon/(\varepsilon-1)} \tag{7.4}$$

Water is combined with a bundle of labour and floorspace with elasticity ε, which determines how much water a firm can save without cutting output. Within the bundle, labour and floorspace enter in fixed cost proportions, with a floorspace cost share of γ_f, so when output falls the firm uses less of both. The parameter γ_s^W is the cost share of water in sector s at pre-drought water prices. The parameter φ_j is the firm's own productivity, drawn at entry and constant over time, and $A_{\ell,t}$ is the productivity of its location, which is increasing in local employment as explained in Section 7.5.

Each firm faces demand from outside the city with constant elasticity $\sigma > 1$. Price is therefore a constant markup of $\sigma/(\sigma-1)$ over unit cost. When a firm exits, its demand is not reallocated to remaining firms, consistent with our evidence on surviving firms (Section 6). Since we leave out the surplus of outside buyers, the markup does not create a wedge on the social value of water embedded in the produced goods, and a continuing firm values an additional litre at exactly the price it pays for it. The firm water price p_t^F is therefore the firm's private marginal value of water.

Holding wages, rents and productivity fixed, and denoting by $s_{s\ell,t}^W$ the current cost share of water for sector s in location ℓ in year t, the response of water use to the commercial water price is

$$\frac{\partial \ln Q_{j,t}}{\partial \ln p_t^F} = -\underbrace{\varepsilon(1 - s_{s\ell,t}^W)}_{\text{substitution}} - \underbrace{\sigma s_{s\ell,t}^W}_{\text{lower output}} \tag{7.5}$$

Firms can save water through three margins. First, they can reduce the amount of water that they use per unit of output, as water becomes more scarce. Second, they can reduce output; the increase in the water price raises their unit cost and their price, so that they

sell less, and so use less of each input. Third, some firms may exit, in which case their demand for water, labour and floorspace goes to zero.

The second and third margins connect water to employment outcomes. Since water is typically only a small fraction of total cost, if output decreases it can have a larger than proportional effect on wages. If input prices are fixed, then a fall in output cuts all inputs in proportion. In this case

$$\left.\frac{\partial(w_{s\ell,t}L_{j,t})}{\partial(p_t^F Q_{j,t})}\right|_{\text{output}} = \frac{w_{s\ell,t}L_{j,t}}{p_t^F Q_{j,t}} = \frac{(1-\gamma_f)(1-s_{s\ell,t}^W)}{s_{s\ell,t}^W} \tag{7.6}$$

In words, a proportional fall in output lowers the wage bill and the water bill by the same proportion. This means the reduction in the wage bill, per unit reduction in water expenditure, is the ratio of the two costs. Given water is a small percentage of costs and the labour share of income is over 50 percent, the wage bill falls by multiple times the fall in water expenditure. In other words, because labour is a larger share of input costs than water, saving water by cutting output reduces labour costs by an order of magnitude more than it reduces water costs. By contrast, substitution reduces water use per unit of output without reducing labour demand. The labour cost associated with a litre of water therefore depends on how much of the saving comes through lower output and exit rather than substitution, which depends on ε. Whether lower labour costs translate into lower wages or lower employment, and hence whether they represent a transfer or a welfare loss, is the subject of the next subsection. We will encounter this ratio again in the wedge.

Which firms will experience losses first depends on their operating profits $\pi_{j,t}$, which are equal to revenue less the bill for water, wages, rent and the fixed operating cost f. A firm with higher productivity φ_j will have lower unit cost, and so with a common markup will charge a lower price. It will thus sell more, and so make more in variable profits, to offset the fixed cost f (as in Hopenhayn, 1992; Melitz, 2003). We will assume that φ_j is Pareto distributed, with shape parameter k, which determines how many firms sit near the level of productivity where variable profits just offset the fixed cost of operation f. When the price of water rises, it is these least productive and smallest firms which will see profits fall below this threshold first (Section 6.5). Whether a lower wage bill means lower pay or fewer jobs depends on whether wages can adjust, and whether firms which make losses for a year close depends on whether they can finance these losses. We turn to these questions in turn in the next two subsections.

7.3 Wages and hiring

We model labour markets with downward wage rigidity. This means that the wage in each labour market is bounded below by its realised level in the previous period (Schmitt-Grohé

and Uribe, 2016). This is the adjustment distortion documented in Section 6.5, where the wages of new hires did not fall with labour demand, and Appendix A.4 describes the collective bargaining agreements behind it. All workers in a given labour market supply labour inelastically within the period (Appendix F.2) and, if hired, earn the same market wage $w_{s\ell,t}$. Wages, labour demand and employment are thus given by the complementary slackness conditions

$$\begin{aligned} w_{s\ell,t} \geq w_{s\ell,t-1}, \qquad & L^d_{s\ell,t} \leq \widetilde{L}_{s\ell,t}, \\ (w_{s\ell,t} - w_{s\ell,t-1})(\widetilde{L}_{s\ell,t} - L^d_{s\ell,t}) = 0, \qquad & e_{s\ell,t} = \frac{L^d_{s\ell,t}}{\widetilde{L}_{s\ell,t}} \leq 1 \end{aligned} \tag{7.7}$$

The realised wage, $w_{s\ell,t}$, cannot fall below last period's realised wage, $w_{s\ell,t-1}$. If labour demand at that wage exceeds labour supply, the wage rises until the market clears. If labour demand falls short of labour supply, the wage floor binds, there is excess labour supply, and jobs are rationed by lottery. Every worker in the market is hired with the same probability, the employment rate $e_{s\ell,t}$, which equals the ratio of labour demand to labour supply. Since all workers are willing to work at the prevailing wage, rationing constitutes what we call involuntary unemployment. Realised wages are thus state variables of each labour market, since a wage increase in one period raises the floor in the next. In the benchmark economy of Section 9, wages are flexible and bounded below by the worker's outside option, home production income b (Appendix F.5), so the labour market clears and all workers are employed whenever the market-clearing wage exceeds b.

With downward rigid wages, a worker who is rationed out of employment loses the surplus from the match, the gap between the wage and the outside option, $w_{s\ell,t} - b$. With flexible wages that can decrease down to b, the marginal worker is indifferent between employment and home production and no surplus is lost. On the firm side, the marginal worker hired earns a wage equal to the marginal revenue product of labour, so the firm forgoes no profit on the marginal job it does not fill. The deadweight loss from involuntary unemployment therefore accrues entirely to workers, and the firm does not internalise it in its water demand.

Downward wage rigidity also slows the recovery of employment. With flexible wages, a labour market in which labour demand has fallen would absorb its workers at a lower wage. With the floor, it employs only as many workers as firms demand at the prevailing wage. This means that when the water price returns to its initial level, the workers rationed out of employment remain unemployed until labour demand returns. Labour demand recovers at continuing firms as their costs fall, but the labour demand of the firms that exited returns only through entry, which is costly and does not immediately refill the lost stock of firms (Sections 7.4 and 7.5). Alternatively, workers can pay the switching costs τ_S or τ_L to reallocate to a different labour market. The switching costs and the dispersion of

idiosyncratic tastes introduced in Section 7.1 thus govern the speed of labour reallocation out of rationed markets, and hence the duration of involuntary unemployment.

7.4 Exit, entry, and credit

The second adjustment distortion we motivated was in the credit market. A temporary increase in the water price may turn the operating profit of lower productivity firms negative, even though many of them would be profitable again once the water price returns to normal. Whether such a firm survives depends on whether its discounted value of profits is still positive, and whether it can borrow against them to cover the loss. If it cannot, firms that are worth keeping open close, their workers lose their jobs, and the city loses the value these firms would have created. This is the component of the model that generates the excess exit of small establishments documented in Section 6.5.

A firm that makes a loss must borrow to stay open. Lenders are competitive and located outside the city, meaning they lend at an actuarially fair rate. Firms can borrow $\beta(1-d)$ units this year in exchange for one unit next year, where d is the probability that a firm dies exogenously in a given year. However, firms can only borrow up to a pledgeable fraction of their value λ (Holmström and Tirole, 1997, 1998). How much a firm can borrow therefore depends on how much it is worth and on what share of that value it can pledge. Denoting this year's operating profit by $\pi_{j,t}$ and next year's value before debt by $\Pi_{j,t+1}$, the value of the firm along any feasible plan is

$$\Pi_{j,t} = \pi_{j,t} + \beta(1-d)\Pi_{j,t+1}$$

A firm with no inherited debt exits if

$$\begin{aligned} \text{Full credit:} \quad & \pi_{j,t} + \beta(1-d)\Pi_{j,t+1} < 0, \\ \text{Limited credit:} \quad & \pi_{j,t} + \lambda\beta(1-d)\Pi_{j,t+1} < 0 \end{aligned} \tag{7.8}$$

Under full credit ($\lambda = 1$), the firm exits only if its loss exceeds the value of staying open. This is the voluntary exit boundary, at which a firm is indifferent between continuing and exiting. Under limited credit ($\lambda < 1$), the firm exits if its loss exceeds its pledgeable value, $\lambda\beta(1-d)\Pi_{j,t+1}$, the most it can borrow.

A firm between the two boundaries would prefer to continue, since its value from doing so is positive, but it cannot borrow enough to cover its loss. Since lenders are repaid at the fair rate, the loss falls out of producer surplus: at the limited-credit boundary the firm loses its non-pledgeable value, $V^{\text{cl}} = (1-\lambda)\beta(1-d)\Pi_{j,t+1}$. The least productive firms, whose variable profit is lowest against the same fixed cost, reach this boundary first.

Downward wage rigidity can interact with exit. A firm whose loss at the prevailing wage

exceeds the whole value of continuing exits at the voluntary boundary even under full credit. Producer surplus is unaffected at the margin, but its workers lose their jobs and earn home production income instead. A wage floor can therefore account for many exits even when the value lost at the limited-credit boundary is small.

If firms carry debt from a previous period, it reduces their continuation value and therefore their ability to borrow in the current period. A lower water price in one shortage year thus affects not only that year's operating profit but also the debt the firm carries into later years. Appendix F.4 gives the exit condition with inherited debt.

There is an unbounded pool of prospective entrants in each sector and location. Free entry drives the expected value of entering down to the sunk entry cost f^E. If a firm decides to pay the entry cost, it then draws its productivity from the same Pareto distribution as existing firms and, if the draw covers its costs, enters from the following period. Appendix F.4 characterises where entry takes place and shows that the marginal entrant adds no net value, so the resources spent on entry do not affect the wedge. Entry only slowly replaces firms that exited. This is due to the fact that even once water prices decrease again, the steady state entry rate was enough to only replenish the exogenous death rate. Lower floorspace rents and worker switches will gradually allow entry to rise, but the stock of firms will refill slowly.

7.5 Rents, local productivity and equilibrium

In each location ℓ the supply of commercial floorspace is fixed at $\bar{H}_\ell$, and the commercial rent $\rho_{\ell,t}$ clears the floorspace market. When firms exit, they free up floorspace, which lowers rents and benefits the remaining firms and new entrants. Rents rise with local employment, which is one of the dispersion forces that spreads firms across locations in the model. Section 6.4 shows, however, that exit rose not only among water-intensive firms but also among nearby firms in other sectors, even though cheaper floorspace would have favoured their expansion. We therefore let local productivity increase with local employment, $A_{\ell,t} = \bar{A}_\ell L_{\ell,t}^{\alpha}$, where $L_{\ell,t}$ is total paid employment in location ℓ in year t, $\bar{A}_\ell$ is the location's fundamental productivity and α is the elasticity of local productivity with respect to local employment. Firms take $A_{\ell,t}$ as given when they hire or enter, so this spillover is not internalised. It differs in kind from the two adjustment distortions. The wage floor and the borrowing constraint prevent a trade between a firm and a worker or a lender and leave the loss on one of the two parties, whereas agglomeration is a pure externality that affects aggregate output and welfare.

Each year has three stages. First, production takes place and the labour and floorspace markets clear. Given the workers in each market and the firms in each location, wages, employment, commercial rents and local productivity are determined jointly, and firms

that cannot finance a loss exit. Second, households consume from their realised income. Third, the forward-looking decisions are made. Households choose their sector and location for the following year, and entrants pay the entry cost. The next period will then begin with the workers in their chosen sector-location and entrants producing. A fraction d of firms dies at the start of each year. Appendix F.6 gives the full timing.

The resource constraint is announced at the beginning of the period, once households have already committed to a sector-location and entrants have paid the entry cost. From then on, the path of the resource constraint and prices is known to everyone. In each shortage year the city sets the two water prices so that household use Q_t^H and firm use Q_t^F exhaust the resource constraint $\bar{Q}_t$. In other years water prices are at their normal levels, where the resource constraint is slack. Conditional on the inherited state and continuation values, and provided that firm water demand slopes down and household water use stays above basic needs, there is a unique pair of water prices that delivers any feasible split of the resource constraint between households and firms (Lemma F.1 in Appendix F.6). Intuitively, firm water demand pins down the firm price, and household demand, given the incomes that hiring then generates, pins down the household price. Water prices and water quantities are therefore equivalent instruments (Weitzman, 1974), and we characterise a policy during the shortage by the share of the water saving, the reduction from normal use, that falls on households.

The state at the beginning of year t consists of the labour supply $\widetilde{L}_{s\ell,t}$ in each sector and location, the incumbent firms with their productivity draws and debt, last year's entrants, and last year's wages $w_{s\ell,t-1}$.

Given the state, the resource constraint and continuation values, a within-year equilibrium is a set of wages and employment rates, rents, local productivity, operating firms and water prices such that

1. households demand water according to equation (7.2);
2. operating firms maximise profit given the production technology (7.4), and a firm operates if and only if it can finance its loss, equation (7.8);
3. wages and employment rates in each labour market satisfy the complementary slackness conditions (7.7);
4. in each location, rents equate floorspace demand to the fixed supply $\bar{H}_\ell$, and local productivity is $\bar{A}_\ell L_{\ell,t}^{\alpha}$;
5. in shortage years, household and firm use exhausts the resource constraint, $Q_t^H + Q_t^F = \bar{Q}_t$, and in other years water prices are at their normal levels.

Given the initial state and the path of the resource constraint, an equilibrium is a sequence of within-year equilibria, worker values and destination choices, financing plans and entry, such that

1. worker values are given by equation (7.3), and next year's labour supply in each market is the number of workers who choose it;
2. firms choose financing plans to maximise value subject to the pledgeability constraint, and lenders break even;
3. entry is positive only in sectors and locations where the expected value of entering equals the sunk entry cost f^E;
4. the set of firms and their debt evolve through exit, death, entry and financing;
5. after the shortage is announced, all agents have perfect foresight of the resource constraint and prices.

The initial state is stationary, with entry replacing firm deaths and no firm holding debt. Appendix F.6 gives the formal statement. For any given policy, we trace out the equilibrium path from this pre-shortage city. In Section 7.6 we use this path to value a small reallocation of water from households to firms.

7.6 The social marginal value of firm water

In this section we compute the social value of an additional unit of water used by firms. As shown above, it can exceed the price firms pay for three reasons. First, with binding downward wage rigidity, an additional unit of water reduces the rationing of labour. Second, it may allow firms with a positive continuation value to survive in the presence of credit market failures. Third, it supports positive productivity spillovers, an agglomeration externality. To quantify these effects, we reallocate one unit of water from households to firms in a drought year m, holding the resource constraint in that year fixed, and follow the equilibrium effects from m onwards.

Three objects summarise these effects. We denote by $J_{s\ell,t|m}$ the equilibrium change in the number of workers hired in year t among those in the labour market of sector s and location ℓ, per unit of water reallocated in year m. It is non-zero only in markets where the wage floor binds, equation (7.7). We denote by $N^{\mathrm{cl}\prime}_{s\ell,t|m}$ the number of credit-constrained firms, those at the limited-credit margin of equation (7.8), that the additional unit of water keeps in business, and by $V^{\mathrm{cl}}_{s\ell,t}$ the value such a firm would have lost by closing, equal to $(1-\lambda)\beta(1-d)\Pi_{j,t+1}$ for a firm without debt at the limit set by the pledgeable share, and to its continuation value net of debt for a firm with debt (Appendix G). Finally, we denote by $\pi_{s\ell,t}$ the aggregate operating profit of the firms in sector s and location ℓ in

year t. All objects with a subscript $t \mid m$ are changes along the equilibrium path after the reallocation in year m.

In order to aggregate welfare gains and losses across households and years, we need to measure them in a common unit. The natural choice is Rand, but a Rand is not equally valuable in all years. During the water shortage, a Rand of income buys households less consumption than usual, because of the higher price of water. We therefore measure welfare in Rand at the pre-shortage household water price $\bar{p}^H$, and convert incomes received in shortage years into this unit. To derive the conversion, note that, up to an additive constant, the consumption utility of a household with income Y is $\ln(Y - p_t^H \bar{q}) - \theta \ln p_t^H$. The value, in Rand at normal prices, of one Rand received by a household in year t is therefore

$$\xi_t \equiv \left(\frac{p_t^H}{\bar{p}^H} \right)^{-\theta} \tag{7.9}$$

In shortage years $\xi_t < 1$, so a Rand received by a household during the shortage is worth less than a Rand at normal prices, and after the shortage $\xi_t = 1$. The conversion is exact for any level of income above the cost of basic water.

The conversion also gives rise to a remainder term r_m. Firm owners live outside the city, so a Rand they gain or lose is worth the same in every year, while a Rand gained or lost by a household is worth ξ_t. Changes in wages, which are transfers between the two sides, therefore do not cancel exactly, and the part that remains is the first component of r_m. Given the small share of water in household spending, ξ_t stays close to one and this component is small. The other three components are changes in water use after the shortage valued at normal prices, workers moving between sectors and locations, and the continuation value at the end of the horizon. We report r_m alongside the three main terms in Section 9.

We can therefore express the social marginal value of water used by firms net of its price, the wedge between its social and private value, as

$$\begin{aligned} \omega_m^F = \sum_{t=m}^{\infty} \beta^{t-m} \sum_{s,\ell} \Bigg[& \underbrace{J_{s\ell,t|m}\, \xi_t (w_{s\ell,t} - b)}_{\text{involuntary unemployment}} \\ & + \underbrace{N^{\text{cl}\prime}_{s\ell,t|m} V^{\text{cl}}_{s\ell,t}}_{\text{inefficient exit}} \\ & + \underbrace{\alpha \frac{\partial \ln L_{\ell,t}}{\partial Q_m^F} \frac{\partial \pi_{s\ell,t}}{\partial \ln A_{\ell,t}}}_{\text{agglomeration externality}} \Bigg] + r_m \end{aligned} \tag{7.10}$$

The first term is the value to households of the employment that downward wage rigidity rations. Each job is worth the difference between the market wage and home production

income, converted at ξ_t, multiplied by the employment effect of the wage rigidity, $J_{s\ell,t|m}$, in every market and year in which the wage floor binds. At the floor the firm earns no profit on the marginal job, so the whole difference $w - b$ is surplus lost by the worker, the welfare loss from involuntary unemployment in the literature on downward wage rigidity (Schmitt-Grohé and Uribe, 2016; Rodríguez-Clare et al., 2026). The employment effect $J_{s\ell,t|m}$ counts only workers already in the market in that year; workers who move there because hiring has improved enter the remainder term. With flexible wages the involuntary unemployment term is zero, since either the labour market clears, so $J = 0$, or the wage falls to home production income, so $w - b = 0$. Appendix G breaks the term down per Rand of firm water as the product of three objects: i) the fall in the wage bill per Rand of water saved through lower output, equation (7.6); ii) the fraction of the wage that a rationed worker loses; and iii) the reduction in excess labour supply that a Rand of water produces, equation (G.9). In the estimated model, the involuntary unemployment term is smaller the more easily firms can substitute away from water, the higher is home production income, and the lower are workers' switching costs.

The second term is the producer surplus that the additional unit of water preserves. It counts the credit-constrained firms of equation (7.8), firms whose continuation value is positive but which cannot borrow enough to cover their current loss. Each such firm is worth its continuation value net of what it can pledge, $V^{\text{cl}}_{s\ell,t}$. Firms with a negative continuation value do not enter, since they would exit even under full credit, and the cost of their exit to workers is already in the first term. Under full credit, $\lambda = 1$, no firm is credit constrained and the term is zero. The surplus a unit of water preserves depends on i) how many firms are close to the credit constraint, which rises with the shape parameter k as more firms sit near the productivity threshold for staying in business, and ii) how much a unit of water to firms reduces their operating loss, equation (7.5). Holding prices and the allocation fixed, in the estimated model the term falls as λ rises and rises with k.

The third term is the agglomeration externality, the productivity spillover from higher employment within a location (Section 7.5). It is the spillover elasticity α times the response of employment in the location to the additional water, times the response of operating profit in each sector and location to local productivity. With no spillover, $\alpha = 0$, the term disappears. Of the three terms it is the only one that remains in the benchmark economy, since firms there still take local productivity as given.

Let W_m denote welfare from shortage year m onwards, discounted to the date of the announcement.

Proposition 7.1. *Suppose that water consumption above basic needs has only private benefits. Conditional on the state inherited at m, the welfare effect of reallocating one unit*

of water from households to firms when the resource constraint binds is

$$\frac{\partial W_m}{\partial Q_m^F} = \beta^m [p_m^F - p_m^H + \omega_m^F] \tag{7.11}$$

Intuitively, the cost of taking a unit of water away from households when it has only private benefits is their willingness to pay, p_m^H. In terms of welfare, when reallocated to firms, it provides firms with their private value p_m^F, plus the wedge ω_m^F from the distortions in adjustments discussed above. Changes in rents and water prices do not matter for our money-metric welfare term as they simply redistribute resources among households, firms, landlords and the city, except for small differences that enter the remainder. By the envelope theorem, changes in firm input choices have no first-order effect on profits, and with free entry the expected profit of an entrant is zero (Appendix G). The efficient allocation therefore satisfies

$$p_m^H = p_m^F + \omega_m^F, \tag{7.12}$$

which is equation (3.1) with the household wedge set to zero. If the firm wedge is positive, efficiency calls for the household price to exceed the firm price.

Corollary 7.2. *If firm water demand is downward sloping and household consumption remains above basic needs, then with flexible wages, full credit, $\alpha = 0$ and a zero remainder term, $\omega_m^F = 0$ and a single water price is efficient (Montgomery, 1972).*

The remainder term collects small residual effects of the conversion and of later adjustment, and it is close to zero in our estimates (Section 9). With no wedge, the marginal effect of reallocation is $p_m^F - p_m^H$. It falls as firms get more water, since p_m^F falls along the firm demand curve while p_m^H rises as households approach basic needs and as changes in employment change their incomes. This means there is a single cross between the two prices that optimally allocates water. Section 9 compares the realised outcomes with this benchmark at the same prices through the lens of the model, allowing us to back out the welfare cost of the adjustment distortions.

The wedge itself is not constant. Each of its terms is a response measured at the given water allocation determined by the prices chosen. If prices adjust to allow firms to consume a larger share of the resource constraint, involuntary unemployment decreases in markets, which allows J to fall. Credit constraints will bind less tightly for firms, preventing inefficient exit with every additional unit of water. In the estimated model, the wedge therefore shrinks as the household share of water conservation increases.

Section 9 will evaluate alternative water allocation policies. These can be summarised by x, that is, the share of the total water saving that is undertaken by households. The welfare effect of a marginal change in x, that is, shifting a marginal litre of water between households and firms, has the same form as equation (7.11), with every response taken

along the whole announced path and each year weighted by how much water is reallocated in that year. This gives a household price, a firm price and a firm wedge for each allocation rule, which we denote $\widetilde{p}^H(x)$, $\widetilde{p}^F(x)$ and $\widetilde{\omega}^F(x)$ (Appendix G). Section 8 estimates the parameters that determine the size of each term of the wedge.

8 Estimation and fit

We now turn to the parameters of the model. We estimate six parameters using the tax records and water billing data described in Section 4: the elasticity of substitution between water and the other inputs in production, ε; the switching costs τ_S and τ_L and the taste precision ν; the pledgeable share of a firm's value, λ; and the agglomeration elasticity α. The remaining parameters are calibrated to match moments from pre-drought data or taken from the literature. Table 8.1 presents all the parameters of the model, along with their sources and interpretation, and Appendix H gives the details of the estimation and calibration, including the moments and equations used. Appendix H.8 discusses uncertainty in the parameter estimates and the model.

Each parameter provides a direct contribution to the wedge of equation (7.10). The substitution elasticity ε and the cost shares determine the employment effects. Home production income b and the switching costs τ_S and τ_L determine the value of the employment losses and how long they persist. The shape of the productivity distribution k and the pledgeable share λ determine which firms exit and whether they could have survived with perfect credit markets. Finally, α determines the size of the agglomeration externality. We estimate these parameters in Sections 8.1 to 8.5, and assess how well the model matches the employment and establishment series in Section 8.6.

8.1 Household demand

Household water demand determines the social marginal value of water used by households. This depends on two parameters. The first is the share of household spending on water above basic needs θ. We use average billing on non essential water consumption and income data to measure this share as 3 percent of income in 2016. We then set the basic needs quantity $\bar{q}$ as the city's (and the WHO's) definition of a basic water allocation, 50 litres a person a day. Given these two parameters, the household demand curve is calibrated to match average water use, average expenditure on water, and population in 2016. Given θ and $\bar{q}$, the model implies that demand for water above basic needs is unit elastic. This is consistent with our findings in Section 5 which provided an estimated price elasticity of -0.97. Appendix H.1 provides more detail on the calibration of household water demand, and Appendix H.9 discusses the sensitivity of our results to different values of $\bar{q}$ and θ.

Table 8.1. Model parameters

Symbol	Parameter	Moment or source	Value
Estimated			
ε	Water substitution	Water use of continuing accounts	0.095 (0.09)
τ_S	Sector switching cost	Gross flows between sectors	3.6
τ_L	Location cost per kilometre	Within-sector moves over distance	0.18
ν	Taste precision	Response of flows to next-year earnings	1.3
α	Productivity elasticity	IV initial exposure	0.03 (0.01)
λ	Pledgeable share	Excess exit during drought	0.048 [0, 0.34]
Measured or matched to the pre-drought city			
γ_s^W	Water weight	Sector water cost shares, Supply and Use Tables	By sector
$b/\bar{w}_0$	Home income share	Quarterly Labour Force Survey, 2016	0.40
d	Exogenous death	Exit above the sector median, pre-drought	0.05
k	Productivity-tail shape	Employment tail slope 1.48, pre-drought	3
θ	Household water weight	Non essential water spending share pre-drought	0.03
$\bar{q}$	Basic water	City's basic amount, litres a person a day	50
f, f^E	Operating and entry costs	Mean establishment size; stationary free entry	
$a_{s\ell}$	Amenities	Pre-drought distribution of residents	
Set externally			
β	Discount factor	Annual discounting	0.95
σ	Outside demand elasticity	Hsieh and Klenow (2009)	3
γ_f	Floorspace share	Ahlfeldt et al. (2015)	0.20

Notes: Standard errors in parentheses. For λ the bracket is the range of values obtained by moving the matched 2017 to 2019 excess exit one standard error either way, truncated at zero. Wages in each market cannot fall below last year's level (equation (7.7)), imposed on the evidence of Section 6.5. Appendix H gives the moments and equations behind each row.

8.2 Firms and substitution

The elasticity ε determines how much a firm can move away from water without cutting output. We estimate this elasticity of substitution between water and the composite input using data on the water consumption of commercial establishments. From equation (7.5), holding output fixed, the elasticity of water use with respect to the price of water faced by a firm is $-\varepsilon(1 - s^W)$, where s^W is the cost share of water. We cannot observe sector information in the water usage data, and since water costs are only a few percent of total costs for firms, we assume $s^W = 0$ and later test for variations around potential values of s^W. Aggregate water consumption in surviving commercial accounts declined by around 12 percent between the start of 2016 and 2018, the peak of the drought. Over this time the price of water increased from R17 to R65 per kilolitre in the units used for estimation. This implies $\varepsilon = 0.095$, assuming that the output of these establishments did not change over this period. Appendix E.3 supports this assumption, showing that the sales of establishments present throughout the period in the tax data stayed close to those predicted by counterfactual establishments. We obtain a standard error of 0.09 for ε from a regression of log annual use on the log real price for the same accounts (Appendix H.3).

The elasticity of substitution is therefore relatively low, and of a similar magnitude to the short-run elasticity of substitution between gas and other inputs that Bachmann et al.

(2024) use for Germany's gas shortage. This is consistent with the large employment and establishment effects we find. With little scope to substitute, most of the reduction in commercial water use occurred through lower output and firm exit. Other estimates of ε from these accounts range from 0.07 to 0.15, including one using the recovery in water use when prices fell after 2018 (Appendix H.3).

For the elasticity of substitution between varieties in outside demand we set $\sigma = 3$, the value in Hsieh and Klenow (2009). We set the floorspace share in the composite input to $\gamma_f = 0.20$, the cost share of commercial floorspace in Ahlfeldt et al. (2015). For each sector s we calibrate the weight on water in production, γ_s^W, to match the cost share of water in that sector in South Africa's Supply and Use Tables at normal water prices. We re-solve the model with σ of 2.5 and 3.5 in Appendix H.9.

8.3 Worker decisions

We now turn to the parameters that govern how workers behave, and their implications for the welfare cost of involuntary unemployment. Home production income, b, is the income a worker can obtain without a formal job. We calibrate it to 0.4 of average earnings before the drought, $\bar{w}_0$, using the 2016 Quarterly Labour Force Survey (Statistics South Africa, 2017a). This corresponds to the average ratio of earnings outside formal work to earnings in the formal labour market. Thus, for a worker on the average wage, each year of involuntary unemployment implies approximately a 60 percent loss of income. In Appendix J we also present results with b between 0.5 and 1.0 of the average wage.

Switching costs and the taste precision determine how workers move to jobs in other sectors and locations. This is particularly important in the case of labour rationing as they determine the duration of involuntary unemployment. To estimate these parameters we use transitions in sector and location of employment for workers in Cape Town before the drought. Following Artuç et al. (2010), we estimate the switching costs using gross flows between sectors and locations.

Let $\mu_{s\ell \to s'\ell',t}$ be the share of workers in sector s and location ℓ who choose sector s' and location ℓ' next year. We define $\tau_{s\ell \to s'\ell'} = \tau_S \, \mathbf{1}\{s' \neq s\} + \tau_L \, \text{dist}_{\ell\ell'}$ as the moving costs; sector moving costs are modelled as a single fixed cost to change sectors while location moving costs increase linearly with distance. The estimating equation follows in three steps. First, the logit destination shares implied by equation (7.3) give the log odds-ratio of moving over staying as

$$\ln \frac{\mu_{s\ell \to s'\ell',t}}{\mu_{s\ell \to s\ell,t}} = \nu\beta\Big(V_{s'\ell',t+1} - V_{s\ell,t+1}\Big) - \nu\, \tau_{s\ell \to s'\ell'}$$

The continuation values for each sector-location are not observed but can be inferred from

future transitions. The value of a state is this year's expected utility plus the discounted value of staying, plus the option value of leaving

$$V_{s\ell,t} = \bar{u}_{s\ell,t} + \beta V_{s\ell,t+1} - \frac{1}{\nu} \ln \mu_{s\ell \to s\ell,t}$$

We can therefore write the value difference in the first equation using this expression for the value function. In our estimation, the difference in expected utility $\bar{u}$ between locations corresponds to the difference in mean log earnings, $\overline{\ln w}$. At the same time, we can capture the continuation value of locations by their future switching probabilities. This gives the estimating equation

$$\ln \frac{\mu_{s\ell \to s'\ell',t}}{\mu_{s\ell \to s\ell,t}} = \beta \ln \frac{\mu_{s\ell \to s'\ell',t+1}}{\mu_{s'\ell' \to s'\ell',t+1}} + \nu\beta\left(\overline{\ln w}_{s'\ell',t+1} - \overline{\ln w}_{s\ell,t+1}\right) - (1-\beta)\,\nu\,\tau_{s\ell \to s'\ell'} + X'_{s\ell \to s'\ell',t}\eta$$

where $X_{s\ell \to s'\ell',t}$ is a matrix of origin, destination and year fixed effects (Appendix H.4).

The three parameters can be identified separately. The precision parameter ν comes from how strongly transitions respond to next year's earnings gap, whose coefficient is $\nu\beta$. We impose $\beta = 0.95$ rather than estimate it, as it is poorly identified from flows (Artuç et al., 2010), which allows us to back out an estimate of $\nu = 1.3$. The two-way log odds of moving between sectors give $\nu\tau_S = 4.68$ (standard error 0.08), giving $\tau_S = 3.6$. The location switching cost comes from workers moving between hexagons within a sector, taking the distance between centroids, for which we estimate $\tau_L = 0.18$ per kilometre.

Given the estimated costs of switching sector or location, we can invert the model to back out sector-location amenities $a_{s\ell}$ that rationalise the pre-drought distribution of workers.

8.4 Firm-level parameters

The amount of exit depends on how many establishments are close to the productivity at which they stop covering their operating cost, and on how large a loss they can finance. We estimate the first from pre-drought data and the second from excess exit during the drought.

We cannot observe productivity directly, so we use the distribution of employment. At given prices, an establishment's employment is proportional to its productivity to the power of $\sigma - 1$. This means that with Pareto-distributed productivity with shape parameter k, employment is Pareto with shape $k/(\sigma - 1)$. Following Helpman et al. (2004), we estimate this shape from a regression of log rank on log employment in the upper tail before the drought, which gives an absolute slope of 1.48 and, with $\sigma = 3$, $k = 2.96$, which we round to 3. Since $k > \sigma - 1$, average establishment size is finite.

We set the exogenous death probability d to 0.05, equal to the pre-drought exit rate

among establishments with above-median employment in their sector. The operating cost f determines the size cutoff for firms. We therefore set f such that the average size of incumbent firms in the model matches the pre-drought data. Free entry sets the entry cost f^E equal to the expected discounted value of a new productivity draw at pre-drought prices, with entry in the stationary economy equal to establishment deaths.

The credit constraint parameter λ sets the largest loss that an establishment with positive continuation value can finance (equation (7.8)). With full access to credit, $\lambda = 1$, an establishment exits only if its loss from the drought exceeds its continuation value. This means that given k, d, f and downward wage rigidity, the model can determine the level of exit under perfect credit markets. We use the additional exit in the data to identify $\lambda < 1$.

Specifically, we match the excess exit of water-intensive establishments found in the triple-difference coefficients (Appendix Figure E.1). Setting $\widehat{\varsigma}_\kappa$ for the data coefficient in year κ and $\varsigma_\kappa^M(\lambda)$ as its model analogue, we measure the difference in exit between water-intensive and other establishments. We set λ to match

$$\sum_{\kappa=2017}^{2019} \varsigma_\kappa^M(\lambda) = \sum_{\kappa=2017}^{2019} \widehat{\varsigma}_\kappa$$

which finds $\lambda = 0.048$. Shifting the right-hand side up and down by one standard error gives a range for λ between zero, where the bound binds, and 0.34. Given our other coefficients, at $\lambda = 0.048$ an establishment without debt can borrow about five months of pre-drought profits (Appendix H.6).

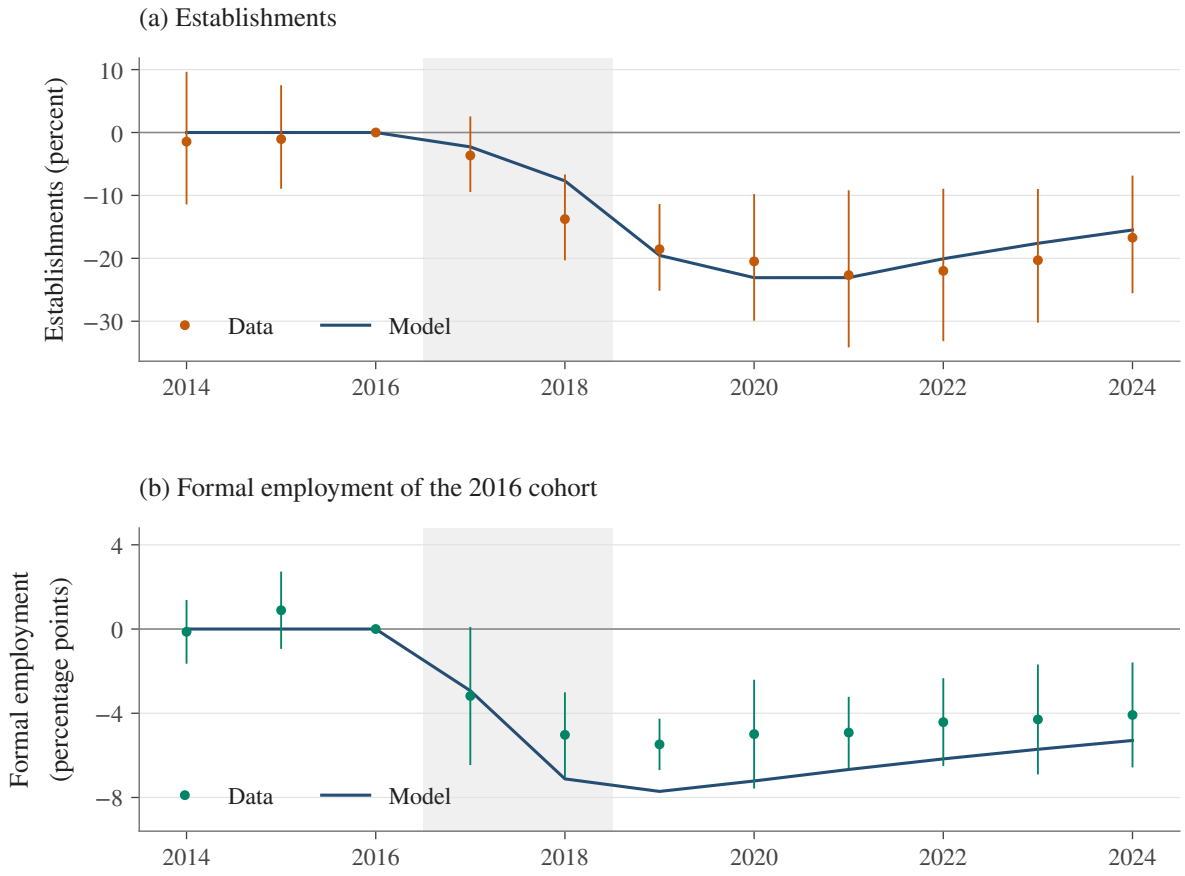
8.5 Local productivity

The elasticity α governs the relationship between local employment density and productivity, $A_{\ell,t} = \bar{A}_\ell L_{\ell,t}^\alpha$. We recover productivity at the location level by inverting the model at observed employment, wages, water prices and rent. Since employment is endogenous to productivity, we instrument the change in local employment with the location's initial share of water-intensive employment. The exclusion restriction we rely on is that initial exposure must be unrelated to changes in fundamental productivity other than through its effect on employment. The estimate of α is the value at which the change since 2016 in $\ln A_{\ell,t} - \alpha \ln L_{\ell,t}$ is uncorrelated with the instrument in every year from 2017 to 2021, estimated jointly (Appendix H.7 gives the details). Our estimate is $\alpha = 0.03$ (standard error 0.01), which implies that local productivity falls by 0.3 percent in locations where paid employment falls by 10 percent.

8.6 Fit

Figure 8.1 compares the model path with the main results from our triple-difference specification. By construction, the model matches employment, wages and the number of establishments in 2016, which amenities, operating costs, entry costs and the levels of productivity are chosen to reproduce. The estimation uses excess exit over 2017–2019 for λ and the response of local employment to initial exposure for α. It does not target the path of establishments or the employment status of these workers. The model's path for establishments lies within the 95 percent confidence intervals of the empirical estimates in all years. For employment, the model's gap is deeper than the data's during the shortage and narrows at the same pace afterwards.

Figure 8.1. Establishments and employment: model and data



Notes: Number of establishments in Cape Town's water-intensive sectors (panel a) and formal employment of workers employed in those sectors in 2016 (panel b). Dots are the triple-difference estimates with 95 percent confidence intervals. Lines show the model path at the city's prices, which the estimation does not target. The grey band marks the period of drought pricing and restrictions. Sources: SARS and National Treasury tax records; model solutions.

In both the model and the data, recovery for establishments and employment remains slow after water prices have fallen. This is due to the relatively small effect that floorspace price declines have in attracting firms, and therefore entry rates settling only marginally

above steady-state levels due to the downward wage rigidity. To better understand what this entails for welfare, Section 9 reports the wedge, its three terms, and the estimated welfare cost of alternative allocations.

9 Results

We now use the estimated model to study how the city could have allocated water to minimise the welfare cost of the drought. We refer to the outcome that was realised by Cape Town's actual drought policy and pricing as the city's allocation. Each alternative allocation we consider applies a household-to-firm price ratio that clears the resource constraint, and we compare the path of each with the path of the same pre-drought city without a shortage.

The rest of this section proceeds as follows. Section 9.1 asks how much of the observed establishment closures the two distortions explain, compared with how much exit would have been efficient. Section 9.2 computes the social marginal value of firm water at the city's allocation, explains its components, and follows the two social marginal values as water moves from firms to households. We will report the allocation rule as the percentage reduction of water consumption that is borne by households; in other words, given the resource constraint, how much of the reduction in aggregate water use is provided by households cutting their own use. Since there is no uncertainty, water prices and the allocation rule are equivalent. Section 9.3 measures the welfare cost of the shortage under each allocation, Section 9.4 asks how much our assumptions must change to affect these conclusions, and Section 9.5 discusses what water prices can and cannot do.

9.1 Closures with and without the distortions

A key question the paper seeks to understand is how much exit would have occurred without the two adjustment distortions. Figure 9.1 shows the fall in the number of establishments through the model with and without the different distortions. With both distortions present, we see a much larger decline in the number of establishments (in line with the data, as seen above) compared to an otherwise identical benchmark economy without the two distortions. The distortions therefore create an inefficient decline in the number of establishments of about 18 percentage points, which would not have occurred with flexible wages and perfect credit markets.

Credit constraints create inefficient exit by closing establishments whose continuation value is positive. With only the credit constraint, establishments close because they cannot finance the losses they make during the shortage (Caballero and Hammour, 2005; Barlevy, 2003). Through the lens of our model, removing credit constraints while maintaining

downward wage rigidity preserves approximately 6 percentage points more establishments at the trough. However, once downward wage rigidities are removed, the marginal impact of credit market failures is very small, contributing less than 1 percentage point of the establishment decrease. In fact, removing the downward wage rigidity on its own allows our modelled economy to move very close to the baseline efficient level of exit. The reason that flexible wages move us close to the efficient level of exit even at Cape Town's prices is that workers accept a lower wage rather than lose the job, since their alternative within the year is home production and moving to another sector or location is costly and takes time. Firms' losses then fall with the wage bill, so fewer viable establishments close, something that downward wage rigidity does not allow for.

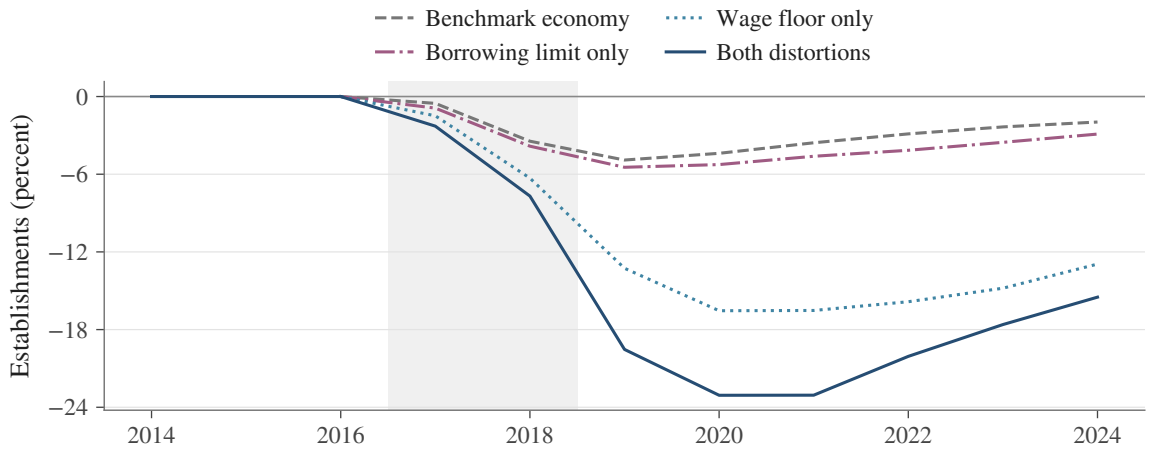
The credit market failure amplifies the effect of the wage floor. If wages are flexible, firms make smaller losses and therefore fewer firms need credit or need less of it. If wages are downward rigid, the pledgeable share provides a cutoff for which loss-making establishments survive. Relative to the no-failure benchmark, the wage floor alone contributes to an increase in establishment exit of about 12 percentage points, and the credit constraint a further six points, even though on its own it adds only 0.6. In terms of how this translates to welfare losses, the distortionary closures do not move workers to more productive establishments. For most workers the alternatives are in their own sector and location (Section 6.4), so a closure does not seem to have cleansing effects, at least not in the support of our data.

Figure 9.1 also shows what happens after the shortage ends, the end of the grey band. The recovery rate is slow in all scenarios due to the real costs that firms and workers face to enter or switch. This amplifies the effect of the depth of the drought, as even with slow recovery the benchmark economy returns close to counterfactual levels 6 years later. After local labour market shocks, workers leaving is the main adjustment margin (Blanchard and Katz, 1992), and this margin is weak in our setting because workers rarely change location or sector in search of a job (Section 6.4). Other local shocks have been followed by recovery (Davis and Weinstein, 2002; Kocornik-Mina et al., 2020) or by lasting losses (Hanlon, 2017).

9.2 The social marginal value of firm water and alternative allocations

We next compute the social marginal value of firm water at the city's allocation. We report it per unit of water moved from households to firms along the allocation rule, that is, how much of the total reduction in water consumption is provided by households. At Cape Town's actual prices, we find that the wedge is large enough that the social value of firm water consumption is approximately 11 times the marginal value of that unit of

Figure 9.1. Establishment losses with and without the distortions



Notes: Model paths of the number of establishments at the city's prices, with and without the different distortions. Under the wage floor, wages cannot fall below last year's level. Under the borrowing limit, firms can only borrow up to a pledgeable fraction of their value. The benchmark economy has flexible wages and perfect credit markets. All paths keep the same shortage and agglomeration externality. The grey band marks the period of drought pricing and restrictions. Source: model solutions.

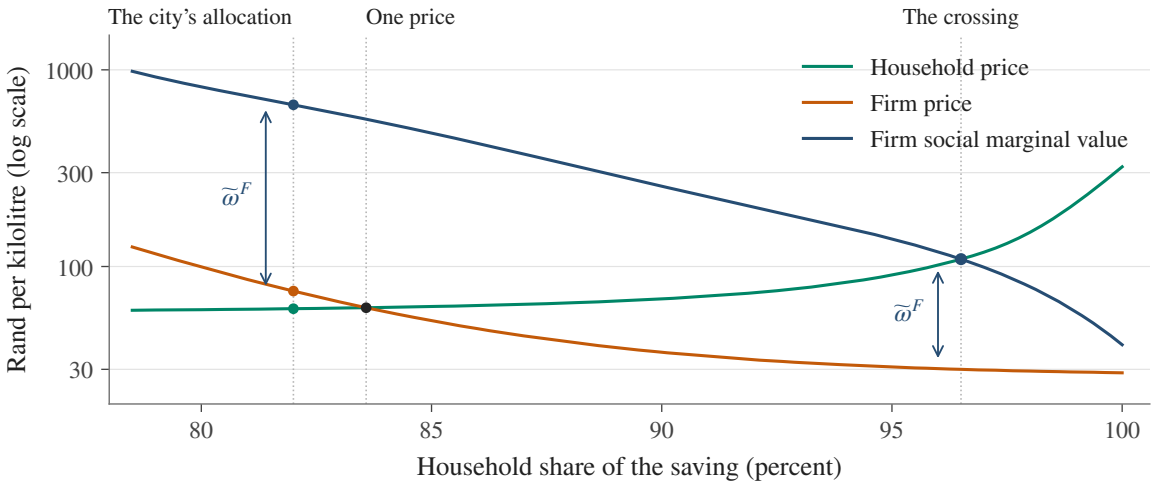
water to households.

The wedge is this large because labour supply exceeds hiring at the prevailing wage in many labour markets at the city's allocation, and involuntary unemployment generated by downward rigid wages is socially very costly. A firm that uses an extra litre of water can employ workers who are already looking for work in its sector and location. In fact, involuntary unemployment accounts for 78 percent of the wedge due to the surplus lost by workers, the loss in producer surplus from inefficient exit accounts for 15 percent and the agglomeration externality for 5 percent.

Figure 9.2 plots the prices required by the model, on households and firms, at each allocation rule to meet the resource constraint. From left to right the graph requires households to contribute a larger share of total water savings, which entails higher household prices and lower firm prices. The household price rises steeply as they save more, since they begin approaching their basic needs quantity (Section 7.1) where their willingness to pay for water is very high. From right to left, firms start shouldering a greater share of water use reduction and their private willingness to pay rises as well. The third curve is the social marginal value of water for firms predicted by the model. This is the firm's willingness to pay plus the wedge, which is the vertical distance between this curve and the firm price. It falls faster than the price due to fewer distortions binding when firms reduce water consumption little, but remains above the firm price even with no reduction due to the positive agglomeration externality.

Three features of Figure 9.2 are important. The first is observing how misallocated water

Figure 9.2. Prices and social marginal values



Notes: Each point on the horizontal axis is an allocation of the same total water saving between households and firms. The arrows show the wedge, the vertical distance between the social marginal value of water for firms and the firm price. Dotted lines mark the city's allocation, one price, and the crossing, where the price faced by households equals the social marginal value of water to firms. Source: model solutions.

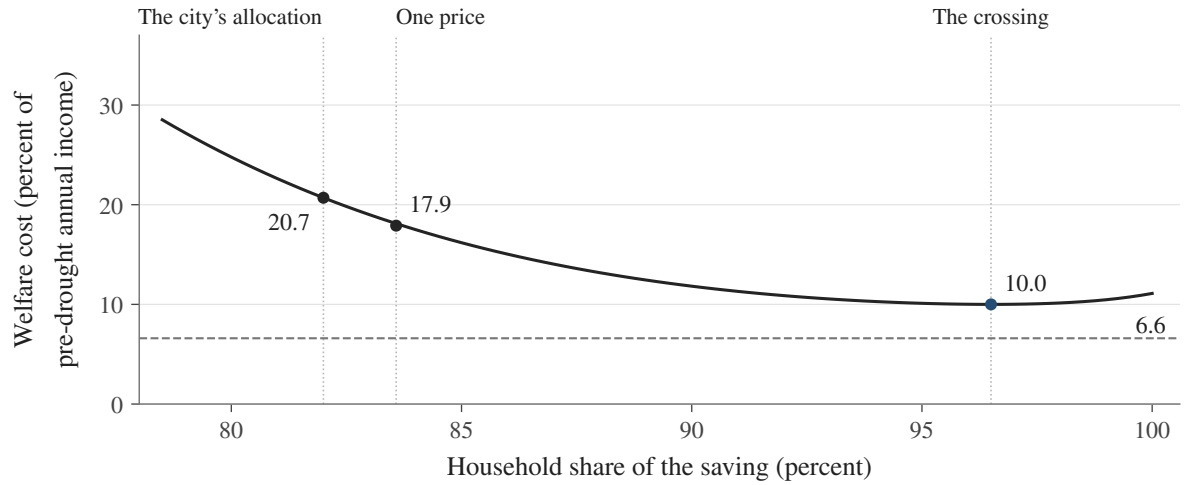
was at Cape Town's pricing, on the left of the graph. The actual drought policy allocated approximately 82 percent of total water saving to households, yet left the social value of firm water about 11 times the household price. The second point of interest is the single price allocation, which would be efficient only if the wedge were zero (Corollary 7.2; Montgomery, 1972). This reallocates some water from households to firms, arriving at 84 percent conserved by households. Third, if we look at the actual efficient crossing, where the price faced by households equals the social marginal value of water to firms, households provide about 96 percent of total water conservation. The gain from departing from a single price comes from household uses having low marginal value when consumption is much greater than basic needs. However, given firms face strong distortions in their ability to adjust to lower water, reducing their water is always relatively costly.

Both curves become steeper around the efficient crossing. The household price rises by about 15 percent for every additional percentage point of water they save at those levels. The social marginal value of water to firms falls by about 18 percent for every additional percentage point of water they keep, because the distortions bite less on smaller water cuts. A wedge remains, but because both curves are steeper at the efficient crossing, small changes to individual components of the wedge affect the optimal level only slightly. An important clarification is that even at the efficient crossing, where households provide nearly the entire saving, households still consume the majority of the city's water.

9.3 The welfare cost

We measure the discounted present value of the welfare cost of an allocation relative to the economy without a shortage. We express this welfare loss as a percentage of the city's annual income in the model at steady state. Figure 9.3 plots the resulting welfare cost for each of the allocations of interest and along the full path of feasible water saving allocations between households and firms.

Figure 9.3. The welfare cost at alternative allocations



Notes: Discounted present value of the welfare cost of the drought, relative to no shortage, at each allocation of the same total water saving between households and firms, expressed as a share of one year of pre-drought annual income in the city. The dashed line is the benchmark economy, with flexible wages and perfect credit markets. Source: model solutions.

At the city's actual policy allocation, the welfare cost of the shortage is 20.7 percent of annual income. At one price this decreases to 17.9 percent, 2.8 points lower, and at the socially efficient crossing it is 10.0 percent, a further 7.9 points lower and 52 percent below the city's allocation. In the benchmark economy that has no adjustment distortion, the welfare cost would be 6.6 percent of annual income. The wage floor and the borrowing limit are thus tripling the welfare cost of the shortage. Table 9.1 shows the prices and welfare cost at a given set of allocations of interest. Even in the extreme case of households providing the entire reduction in water use, the welfare cost would be 46.4 percent lower than at the city's allocation.

To give a sense of scale, at our discount factor a present value of 20.7 percent of annual income is equivalent to a permanent decrease in income of about 1 percent every year. The gain of moving to the socially efficient allocation is therefore about half a percent of income a year. The welfare cost is especially sensitive to the specific allocation chosen near the policy of the city, since the welfare curve is steeper there, and much less so near the efficient level. Asking households to provide 88 instead of 82 percent of aggregate

Table 9.1. Allocations and welfare costs

Allocation	Household share of saving	Household price	Firm price	Firm social marginal value	Welfare cost	Reduction, percent: Main measure	Reduction, percent: Equivalent variation
The city's allocation	82	61	75	664	20.7		
One price	84	62	62	558	17.9	13.5	
The crossing	96	109	30	109	10.0	52	57
All saving from households	100				11.1	46.4	
The benchmark economy	82				6.6	68.1	

Notes: Each row is an allocation of the same total water saving between households and firms, and the last row is the benchmark economy, with flexible wages and perfect credit markets, at the city's allocation. One price is a single common price for households and firms. Prices and the firm social marginal value are in Rand per kilolitre. Welfare costs are discounted present values relative to no shortage, as a percentage of pre-drought annual income. Reductions are relative to the city's allocation. Source: model solutions.

water saving lowers the welfare cost to 13.2 percent of annual income. Close to the efficient level predicted by the model the exact split hardly matters. At 92 percent the cost is 10.9 percent of annual income, at the efficient level 10.0, and if households provided all the saving 11.1. This wide margin is discussed in the following robustness section.

Table 9.2. Sources of welfare cost and gain

Source	Cost at the city's allocation: Share, percent	Cost at the city's allocation: Points of annual income	Gain at the crossing: Share, percent	Gain at the crossing: Points of annual income
Water prices	31	6.4	−10	−1.1
Involuntary unemployment	52	10.8	95	10.2
Inefficient exit	3	0.6	9	1.0
Agglomeration externality	5	1.0	6	0.6
Other	9	1.9	0	0.0

Notes: Cost compares the city's allocation with no shortage, and gain compares it with the crossing, in shares and in points of pre-drought annual income. Water prices combines the effect of the prices households face on their consumption, firms' operating profits, and the city's receipts from water. Source: model solutions.

We decompose the welfare cost by source in Table 9.2. At the city's chosen allocation, involuntary unemployment accounts for approximately half of the discounted welfare cost. The water-prices component combines the effects on household consumption, firm operating profits and the city's water receipts. Avoided closures and higher local productivity account for 9 and 6 percent of the welfare gain when reallocating water to firms. The gains from preserved employment more than offset the cost of additional household conservation, raising aggregate household welfare.

9.4 Robustness

We conduct several robustness checks to validate the results of the model. First, we solve the model at alternative values of the parameters that we had set outside the estimation, those borrowed or calibrated. Alternative values of the outside demand elasticity σ, the Pareto shape k, the amount of water households need for basic needs, and the share of income households spend on water do not meaningfully change our results (Table H.2 in Appendix H). Allocating a large share of water conservation to households continues to minimise the welfare cost of the shortage.

In a second step, we vary the parameters that were estimated in the model by using their sampling error. The welfare gain from moving to the efficient level, which the model estimates to be 52 percent, has a standard error of 9 points and the ratio of the firm to the household social marginal value, 11, a standard error of 2.2 (Appendix H.8).

Third, we consider just how far the assumptions that pin the social marginal values of each user must change to alter our conclusions. On the household side, we introduce a wedge between the social and private value of water corresponding to 10 or 20 percent above the price they pay. The efficient share of saving moves by less than 1 percentage point towards firms, and the potential welfare gain from moving to it falls from 52 to 49 percent (Appendix J). The efficient share is insensitive to small changes because both curves are steep around it, as shown above.

On the firm side, we increase home production income and remove other components of the wedge one at a time (Table J.1 in Appendix J). In every exercise, up to a home production income of 0.8 of the market wage, at least 94 percent of the water saving should come from households. None of these alternatives puts the efficient share near the 82 percent of the city's allocation, and even assuming away the whole wedge means that the single common price is efficient and that would deliver a saving share of 84 percent.

Lastly, we examine the sensitivity of our results to using a different welfare metric common in the literature. We compute the change in constant annual income that would leave each household group just as well off, at prices and employment opportunities of the no-drought economy, as under the alternative allocation (Caliendo et al., 2019). Using this equivalent variation measure, the efficient share lowers the welfare cost of the drought by 57 instead of 52 percent estimated with our welfare metric (Appendix I).

9.5 The limits of water prices

Water prices cannot address the distortions themselves. Even with the household and firm price set at the efficient level, labour, water, exit and entry remain misallocated and the welfare cost of the drought remains higher than our efficient economy benchmark. The

optimal water price policy does close approximately three quarters of the gap between the welfare cost at the city's allocation and the cost in the benchmark economy. A single firm water price also cannot discriminate in a way that would allow us to allocate water efficiently across firms whose wedges differ by sector and location (Diamond, 1973).

Expectations on when the drought ends matter mainly through inefficient exit, which accounts for 15 percent of the wedge. A longer, anticipated shortage narrows the difference between the two pricing rules through that term, but as long as wages cannot fall, firms should not face a higher water price than households. If the shortage were permanent, the inefficient-exit component would disappear. This is because an establishment making losses at the new price has no valuable continuation (Appendix K).

Finally, other policies can address some of these distortions directly. The city sets water prices but has no say in wage setting or in lending decisions. Following Bhagwati and Ramaswami (1963), policies that target hiring and credit directly are more effective against these distortions than water prices alone. Allowing firms to defer water bills or supporting temporarily unprofitable but solvent firms (Philippon, 2021) would ease credit constraints during a shortage, although, as Section 9.1 shows, most of the inefficient closures would still occur given the wage floor alone. Policies that support employment during temporary shocks (Giupponi and Landais, 2023) target the largest component of the wedge.

10 Conclusion

How should a city divide a resource during a supply shock between households and firms? We address this question in the context of Cape Town's Day Zero drought, combining empirical evidence from water consumption and tax records with a structural urban model. We find that firms face important distortions in their ability to adjust to temporary high prices, through downward wage rigidities and credit market failures. This leads to inefficient firm exit and labour rationing. Households, by contrast, were able to cut their water consumption by 60 percent without consumption decreasing to socially risky levels. We build and estimate a model that incorporates these facts, which finds that at the margin, given Cape Town's actual prices, a litre of water allocated to firms is worth about 11 times more than for households. The drought policy with the lowest welfare cost therefore asks households to provide a larger share of the total water consumption reduction. We find that raising the household share of the water consumption reduction from 82 to 96 percent could have halved the welfare cost of the drought.

How the shortage is allocated between households and firms matters greatly for welfare. A common price across households and firms for a shared input is efficient only if it equates the social marginal value of water across them. In Cape Town this would not have been efficient due to the distortions firms faced in adjusting to lower water consumption, which

generated strong inefficiencies and thus social costs. We find that a common price would have reduced the drought's welfare cost by 13.5 percent, compared to 52 percent under efficient corrective pricing. Households were instead able to adjust through a private margin - this was still costly for the households, yet there were no inefficiencies in how they chose their reduction as the social cost of their water reduction was equal to their willingness to pay. This difference in social and private values on firm adjustment creates a corrective pricing wedge, which is smaller the more firms can substitute away from water, the more flexible wages are, and the better credit markets function. Ultimately, prices cannot remove the distortions, but as a second-best policy instrument can do a lot to minimise the welfare cost of the drought. At the optimal pricing suggested by the model, prices alone can close three quarters of the gap in welfare loss between the actual policy and the efficient benchmark economy.

These findings generalise beyond droughts and beyond Cape Town. Cities, and governments more generally, make allocation decisions across many inputs that are shared by residents and the firms that employ them. During shortages governments often protect households and their consumption. Our results suggest that this priority can be counterproductive where firms face distortions in their ability to adjust. In fact, when firm adjustment is distorted and household basic needs are protected, the optimal policy places the burden of conservation on the households. Our findings suggest that during shortages, if governments want to protect residents, they should keep prices low for firms.

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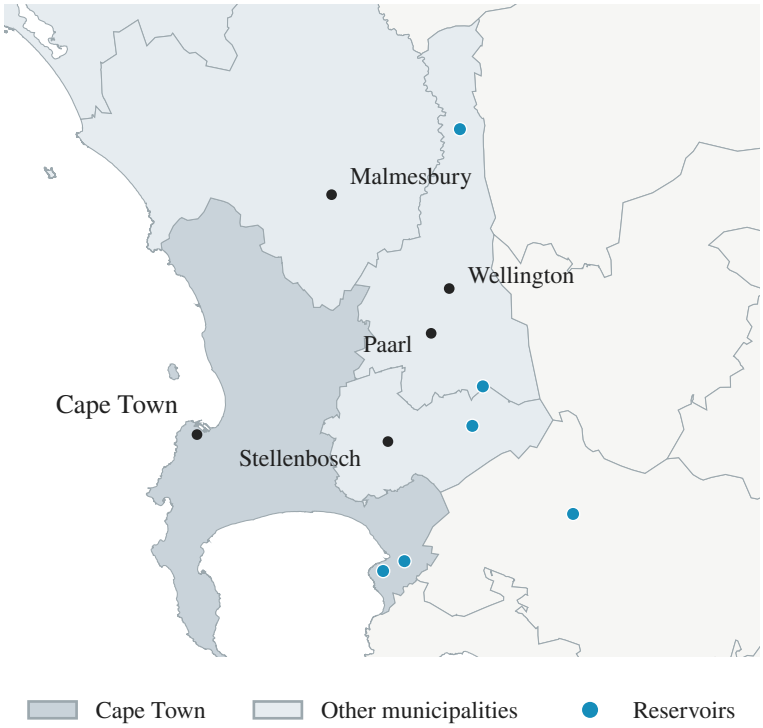
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A Institutions

A.1 Supply and the national allowance

The city of Cape Town is part of the Western Cape Water Supply System, together with other municipal and agricultural users. Agriculture used around 30 percent of the supply (Department of Water and Sanitation, 2014). The system consists of six reservoirs, shown in Figure A.1 together with the municipalities the system supplies.

Figure A.1. The Western Cape Water Supply System



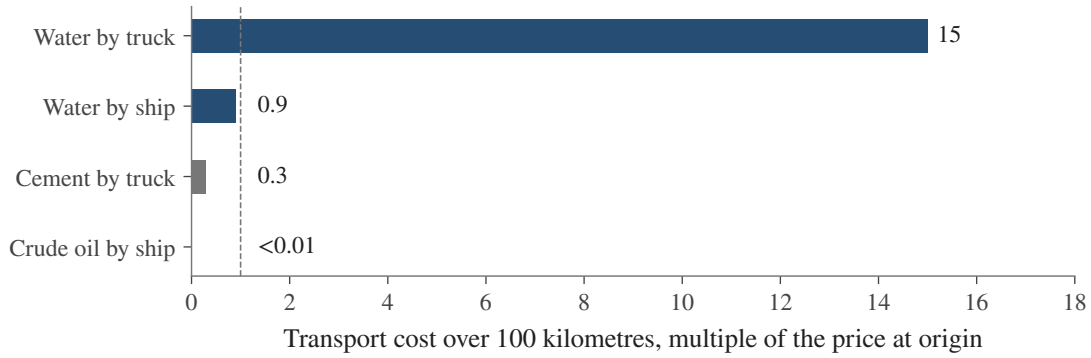
Notes: The six reservoirs of the Western Cape Water Supply System and the municipalities that share them. Source: Department of Water and Sanitation.

A.2 New supply

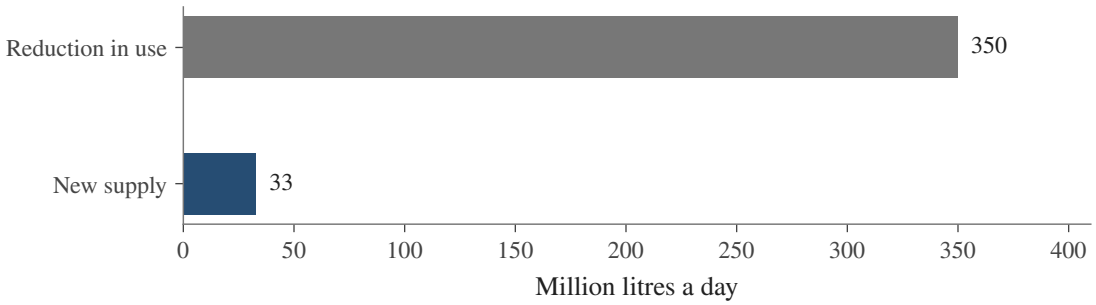
Figure A.2 compares the 350 million litres a day reduction in the city's water use with new sources of supply. New sources, including water from a neighbouring farm, groundwater and springs, and desalination, amounted to only 33 million litres a day. Transporting water 100 kilometres by truck costs around 15 times its price at origin. For other bulk goods such as cement and crude oil, the same transport cost is a small fraction of their price.

Figure A.2. Transport costs and Cape Town's water supply in 2018

(a) Transport cost relative to the good's price



(b) Reduction in use and new supply



Notes: Panel (a) shows the cost of moving each good 100 kilometres by truck or ship, relative to its price at origin. The dashed line marks a cost equal to that price. Panel (b) compares the reduction in the city's water use in 2018 with new supply from a neighbouring farm, groundwater and springs, and desalination. Sources: Oki et al. (2017); American Transportation Research Institute (2026); Water Development Department (2009); Miller and Osborne (2014); United States Geological Survey (2026); S&P Global Commodity Insights (2025); City of Cape Town (2018).

A.3 Prices

All prices in Figure 2.1 are real, in June 2026 Rand, deflated with Statistics South Africa's headline consumer price index (Statistics South Africa, 2026).

A.4 Wage agreements

Many workers in exposed industries, such as hospitality and metals and engineering, earn wages set through centralised agreements. These agreements are negotiated in bargaining councils between employer organisations and trade unions, and the Minister of Labour can extend them to all firms and employees in the industry, including those not involved in the negotiations (Republic of South Africa, 1995; Magruder, 2012). Hence, a cost shock specific to Cape Town cannot lower the wages that covered employers must pay.

The agreement in the metals and engineering industry required increases in actual wages, including for workers earning above the minimum, of 7, 6.75 and 6.5 percent in 2017, 2018 and 2019 (Steel and Engineering Industries Federation of Southern Africa, 2019). The sectoral determination for hospitality, which includes catering and restaurants, raised the minimum wage by inflation plus 1.5 percentage points every year (Department of Labour, 2017). These minimum wages also applied to new hires. Before the drought, around 30 percent of workers earning below the threshold in the Basic Conditions of Employment Act (Republic of South Africa, 1997) had wages set through representative bargaining, and around 45 percent were covered by sectoral determinations (Bhorat and Stanwix, 2018). Under section 64(4), workers can demand that existing terms and conditions be kept while a dispute over an employer's unilateral change is in conciliation (Republic of South Africa, 1995). Union wages in South Africa do not respond to local unemployment (Kingdon and Knight, 2006).

B Data

We use the employer-employee matched tax records of the South African Revenue Service, linked by the National Treasury (Pieterse et al., 2018), together with Cape Town's municipal water billing records. Descriptions of the cities come from the publicly available Version 6 of the Spatial Tax Panel (Nell and Visagie, 2025).

Table B.1. Cape Town in the 2016 baseline

Measure	Value
Population and formal employment	
Residents	4,004,793
Full-time employed	1,465,425
Establishments	50,287
Water accounts	
Household accounts billed, monthly average	901,735
Commercial accounts billed, monthly average	41,988
Water-intensive sector shares	
Share of formal employment	29.3%
Share of establishments	30.6%

Notes: Population is the 2016 Community Survey estimate. Full-time employed is full-time-equivalent employment. Employment and establishments refer to the 2016 fiscal year. Water accounts average the twelve months of 2016. Water-intensive sectors are the top quintile of sectors by water cost share. Sources: Statistics South Africa, Community Survey 2016; SARS and National Treasury tax records; City of Cape Town billing records.

B.1 Tax records

An establishment is a workplace reporting unit, and we take the postcode of its business address to measure its location. We measure employment in full-time equivalents by adding up the fraction of the tax year worked in each job. We group Cape Town's postcodes into 24 broader locations, or main places (Statistics South Africa, 2012a). Sales come from the company income tax return.

A worker's main job is the job with the most full-time-equivalent employment, and the sector and city of that job in 2016 determine the worker's exposure. The entry rate is the number of entrants in a city-sector cell divided by the number of establishments in that cell in 2016. The exit rate is the number of exits divided by the number of establishments in the cell that year. For exit we keep establishments with more than one full-time-equivalent worker. An establishment is small if its 2016 full-time-equivalent employment is below the median in its sector.

A continuing establishment is present in both 2016 and 2020 with at least one full-time-equivalent worker. A new hire is a worker observed at a continuing establishment who was not there in the year before. Our estimating equation for the earnings of new hires is

$$\begin{aligned}\log \text{Pay}_{hjt}^{\text{hire}} = &\sum_{\kappa \neq 2016} \beta_{\kappa}^{\text{hire}} \mathbf{1}\{c(j) = \text{Cape Town}\} \text{WI}_{s(j)} \mathbf{1}\{t = \kappa\} \\ &+ \vartheta_j + \delta_{c(j)t} + \delta_{s(j)t}^{S} + X_{hjt}' \boldsymbol{\beta}^{X} + u_{hjt}^{\text{hire}},\end{aligned}$$

where $\text{Pay}_{hjt}^{\text{hire}}$ is the annual earnings of hire h at establishment j in year t. Establishment fixed effects ϑ_j replace the city-sector fixed effects of equation (6.1). X_{hjt} controls for age, previous earnings and whether the worker was hired from outside formal work. Standard errors are clustered by city-sector.

B.2 Water accounts

We classify commercial and industrial accounts as new if they are billed only after the drought, stopped if they are billed only before it, and continuing otherwise (Figure 6.1).

For households we use 261,000 continuing accounts. We group them into deciles by water use before the drought, and measure use per person as account use divided by 3.5 people per account, as described in Section 4. Figure 5.1 shows use for these deciles, and Table B.2 reports the price elasticities of Section 5.

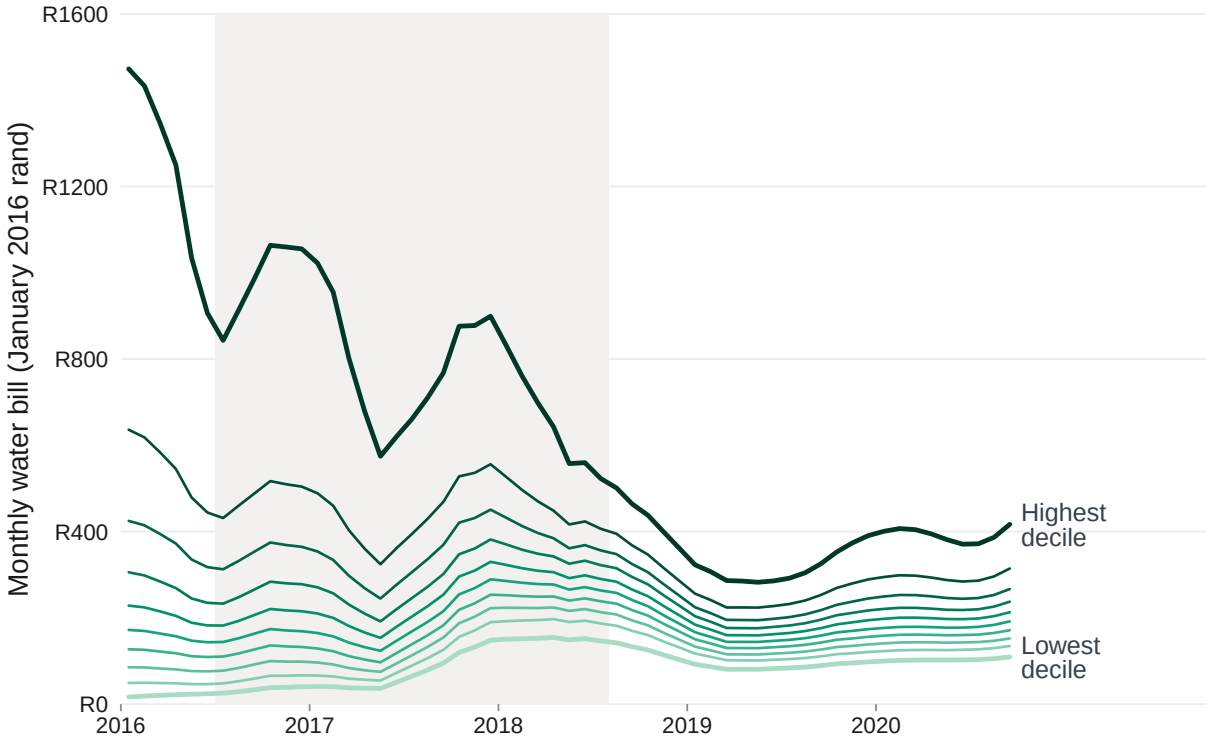
Figure B.1 reports average monthly water bills for these accounts by decile. The bills apply the residential tariff in effect each month to consumption, include VAT, and exclude fixed charges and sanitation fees.

Table B.2. Household price response

Sample	Fixed effects	Period	Elasticity	Standard error
Citywide monthly use above the first 6,000 litres	Calendar month	2015–2023	−0.97	0.08
Accounts	Account, calendar month	2015–2023	−0.88	0.002
Accounts	Account, calendar month	2015–2019	−0.98	0.002
Accounts above 6,000 litres a month	Account, calendar month	2015–2023	−0.90	0.002
Accounts	Account, year-month	2015–2019	−0.88	0.02

Notes: Price elasticity of household water demand. The first row uses citywide monthly use above the first 6,000 litres. The other rows instrument each account's price with the price it would face at its 2015 consumption under each month's tariff schedule, and cluster standard errors by account. Sources: City of Cape Town billing records and tariff schedules.

Figure B.1. Computed water charges by pre-drought consumption decile



Notes: Average monthly water bill of the household accounts in each decile. Deciles are fixed by 2015 consumption. Bills apply the standard residential tariff to each month's consumption, include VAT and exclude fixed charges and sanitation fees, in January 2016 Rand. The grey band marks the period of drought pricing and restrictions. Sources: City of Cape Town billing records and tariff schedules.

B.3 Sector exposure

The concordance in Budlender and Ebrahim (2020) maps the industries of the 2010 Supply and Use Table to three-digit tax sectors. With it we measure water's share of input costs in each sector, reported for selected water-intensive and comparison sectors in Table B.3 and across all industries in Figure 6.2. Figure B.2 compares Cape Town with the three control cities.

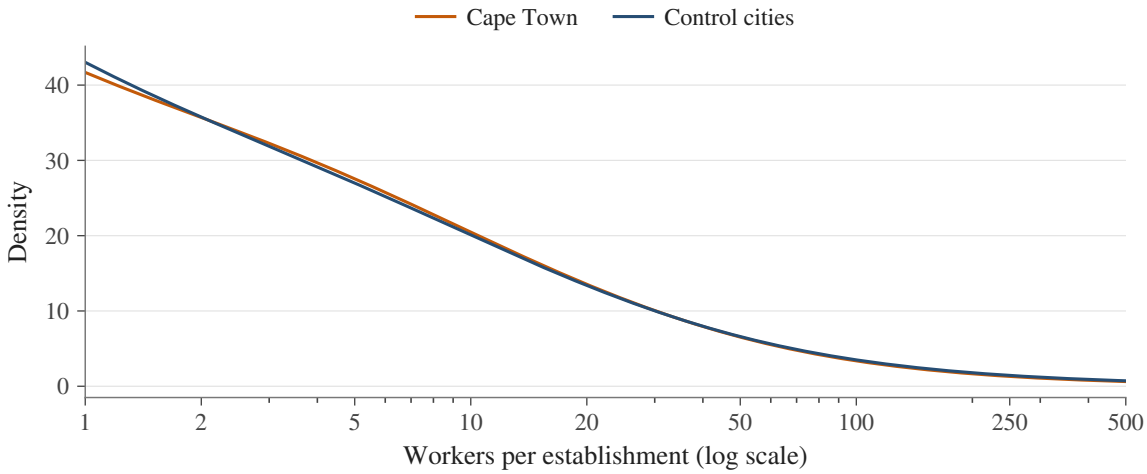
Table B.3. Water-intensive and comparison sectors

Sector	Water share of input costs, percent
Water-intensive	
Basic iron and steel	5.60
Beverages	5.30
Fruit and vegetable processing	4.60
Restaurants and catering	4.40
Food and beverage retail	3.30
Comparison sectors	
Legal and accounting	0.20
Banking	0.10
Telecommunications	0.07
Insurance	0.01

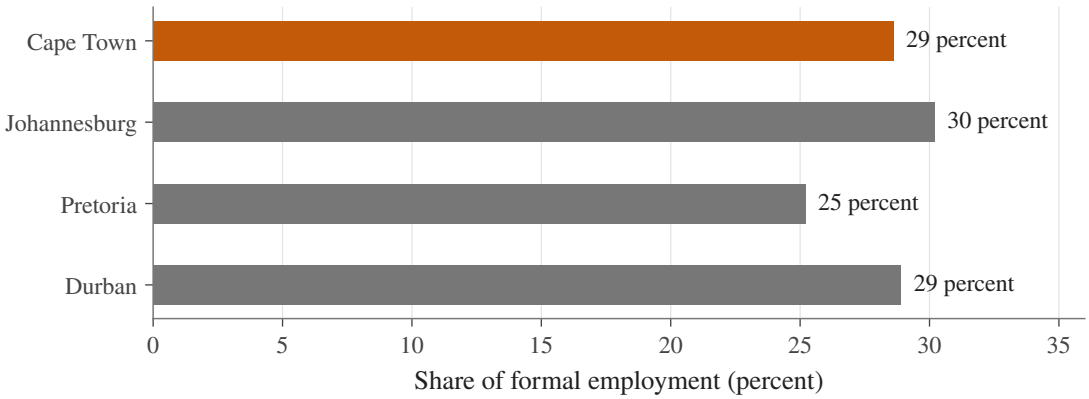
Notes: Water share of input costs in the 2010 Supply and Use Tables, for selected sectors. Water-intensive sectors are the top quintile of sectors by water cost share. Source: Statistics South Africa, 2010 Supply and Use Tables.

Figure B.2. Establishment sizes and water-intensive employment, 2016

(a) Establishment sizes, all sectors



(b) Water-intensive share of formal jobs



Notes: Panel (a) shows the distribution of establishments by number of workers, all sectors, in Cape Town and in the three control cities pooled (Johannesburg, Pretoria and Durban). Panel (b) shows the share of formal employment in water-intensive sectors. Water-intensive sectors are the top quintile of sectors by water cost share. Source: public Spatial Tax Panel, Version 6.

C Design and inference

C.1 Establishment and worker comparisons

We estimate equation (6.1) for establishments in four cities, Cape Town, Johannesburg, Pretoria and Durban, over 2014–2024. The outcome is the log number of active establishments, those reporting employment, in a three-digit sector and city. Coefficients and confidence bounds are converted to percentage effects using $100[\exp(\beta_\kappa) - 1]$.

We also estimate equation (6.1) with the exit rate and the entry rate as outcomes, defined in Appendix B.1, and multiply these coefficients by 100 to report percentage points. We split the sample into small and large and into tradable and non-tradable establishments to estimate the response within each group. Outcomes for continuing establishments use establishment-year observations (Appendix E.3).

For workers we estimate

$$\begin{aligned} \text{Formal}_{ht} = &\sum_{\kappa \neq 2016} \beta_\kappa^W \mathbf{1}\{c(h) = \text{Cape Town}\}\text{WI}_{s(h)}\mathbf{1}\{t = \kappa\} \\ &+ \vartheta_{c(h)s(h)} + \delta_{c(h)t} + \delta^S_{s(h)t} + u^W_{ht}, \end{aligned} \tag{C.1}$$

where Formal_{ht} indicates whether worker h is formally employed anywhere in South Africa in year t, and $c(h)$ and $s(h)$ are the city and sector of the worker's main job in 2016. This specification follows Walker (2013), and the sample is the cohort of workers employed in 2016. Coefficients are multiplied by 100 to give percentage points.

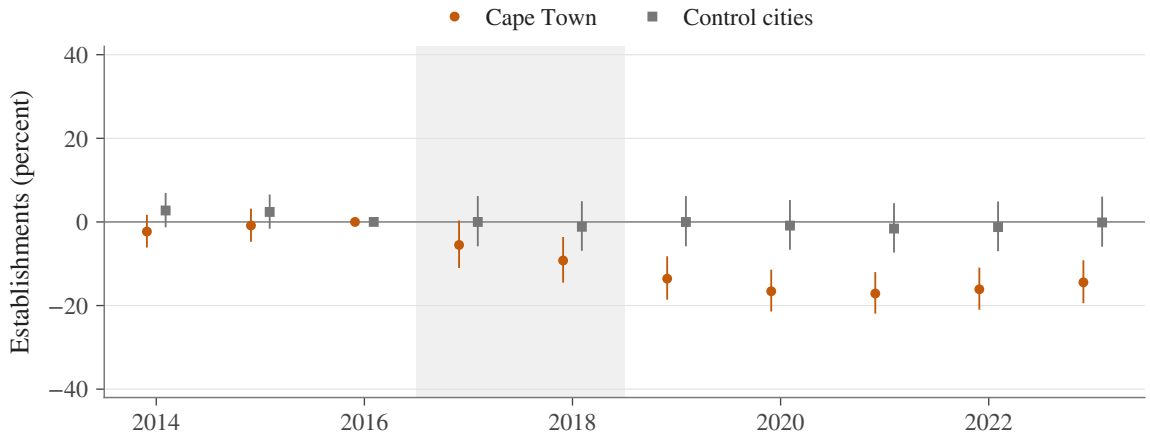
All event studies omit 2016 and report 95 percent confidence intervals. Standard errors are clustered by city-sector for establishments and by the worker's initial city-sector for workers.

C.2 The components of the comparison

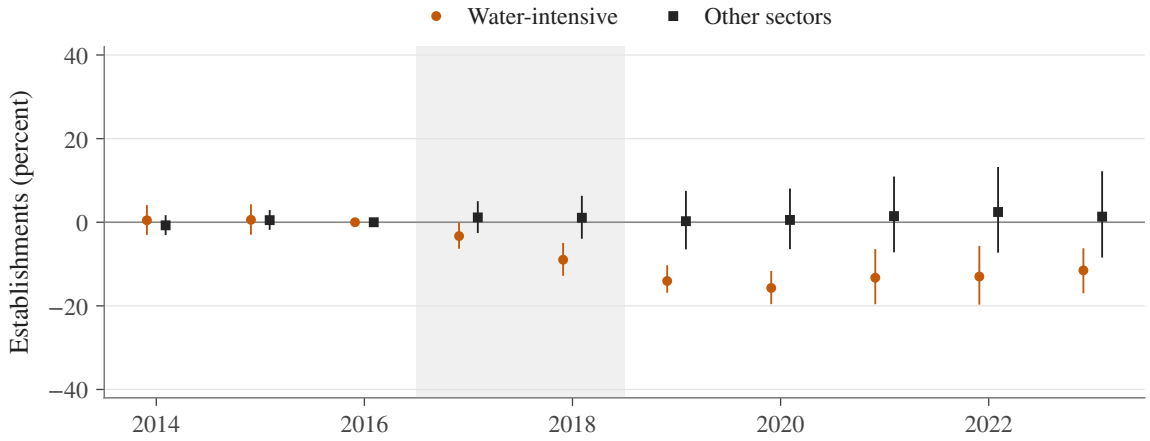
Figure C.1 splits the comparison in equation (6.1) into its two difference-in-differences components. Panel (a) compares water-intensive with other establishments, within Cape Town and within the control cities. Panel (b) compares Cape Town with the control cities, for water-intensive and for other establishments. From 2017, water-intensive establishments in Cape Town fall behind both other establishments in Cape Town and water-intensive establishments in the control cities, while all series are close to zero before the drought. The rise in exit of other establishments near water-intensive employment (Section 6.4) is concentrated in the most exposed neighbourhoods, so it does not move the aggregate number of other establishments in Cape Town and does not drive the estimates.

Figure C.1. Establishment effects by city and sector exposure

(a) Water-intensive relative to other sectors



(b) Cape Town relative to control cities



Notes: Number of active establishments, split into the two difference-in-differences comparisons behind the triple difference. Panel (a) compares water-intensive with other sectors, within Cape Town and within the control cities. Panel (b) compares Cape Town with the control cities, for water-intensive and for other sectors. Coefficients are the change since 2016, with each comparison estimated separately. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

Table C.1. Event-study estimates behind the main figures

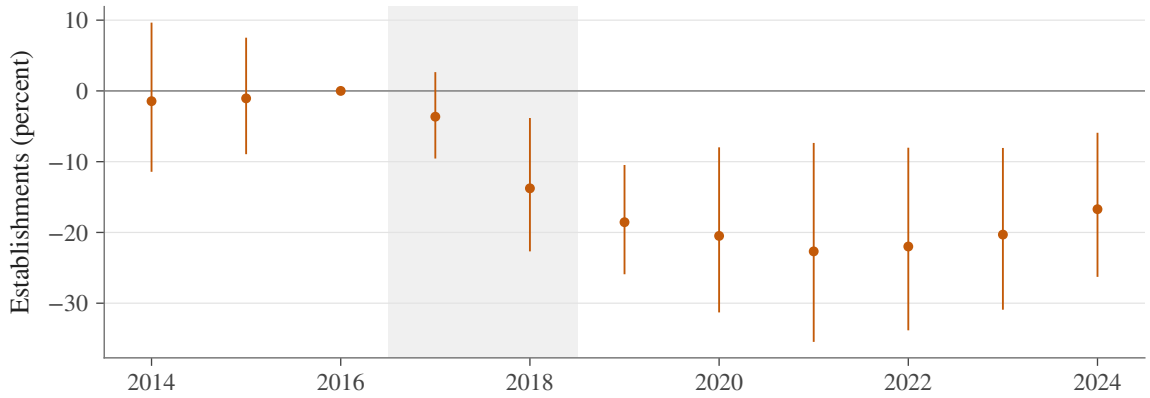
	2017	2018	2019	2021	2024[a]
Panel A. Establishments in water-intensive sectors, percent					
Number of establishments	−3.6	−13.8***	−18.6***	−22.7***	−16.7***
	(3.2)	(4.0)	(4.3)	(8.2)	(5.7)
Panel B. Annual exit rate of water-intensive establishments, percentage points					
All establishments	6.5**	7.9***	5.8**	−2.3	2.3
	(2.6)	(2.3)	(2.8)	(3.1)	(3.4)
Small establishments	5.4***	10.2***	3.4**	1.9	0.7
	(1.7)	(1.8)	(1.6)	(1.8)	(2.1)
Large establishments	1.1	−2.3	2.4	−4.2***	1.6
	(1.3)	(1.6)	(1.8)	(1.5)	(1.8)
Panel C. Workers employed in water-intensive sectors in 2016					
Formal employment, percentage points	−3.2*	−5.0***	−5.5***	−4.9***	−4.1***
	(1.7)	(1.0)	(0.6)	(0.9)	(1.3)
Earnings of new hires, log points	2.2	3.4*	3.3	1.3	1.3
	(1.6)	(1.9)	(2.1)	(2.5)	(2.5)
Panel D. Annual exit rate in less water-intensive sectors, percentage points					
Second exposure quartile	0.9***	0.9***	0.5**	0.3	−0.2
	(0.3)	(0.2)	(0.2)	(0.3)	(0.2)
Third exposure quartile	0.7**	1.8***	0.4	−0.1	−0.6***
	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)
Fourth exposure quartile (highest)	1.1***	3.6***	0.9***	−0.5*	−0.5*
	(0.2)	(0.3)	(0.2)	(0.3)	(0.3)

Notes: Coefficients are triple-difference estimates of the change since 2016; Panel D reports difference-in-differences estimates relative to the lowest-exposure quartile. Water-intensive sectors are the top quintile of sectors by water cost share. Standard errors in parentheses, in log points for establishments. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. [a]Exit estimates in Panels B and D refer to 2023. Source: SARS and National Treasury tax records.

C.3 Randomisation inference

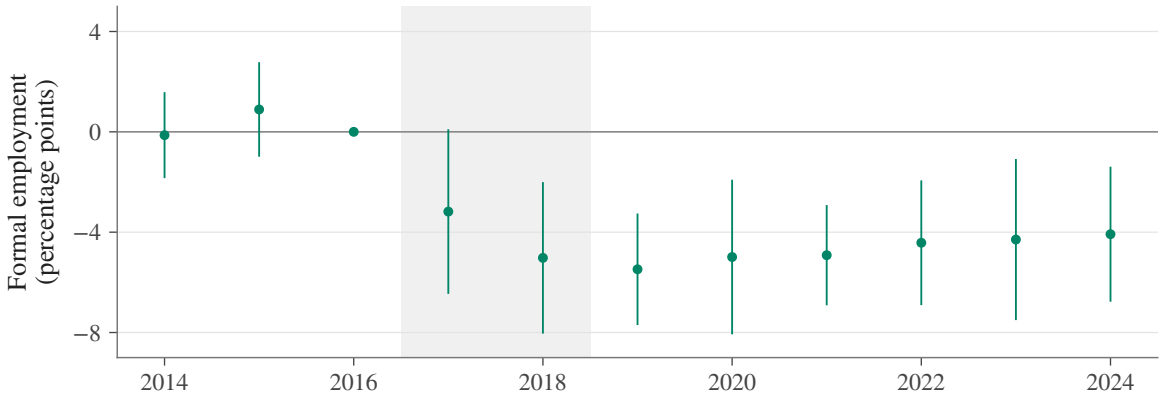
To compute randomisation p-values and confidence intervals we follow MacKinnon and Webb (2020) (see also Conley and Taber, 2011). We draw 50 cities at random from the municipalities in the tax panel, treat each in turn as the exposed city, and estimate equation (6.1) for establishments and equation (C.1) for workers. The resulting estimates form the reference distribution. The point estimates are identical, the randomisation intervals are marginally wider than the clustered intervals, and the conclusions are unchanged (Figures C.2 and C.3).

Figure C.2. Water-intensive establishments in Cape Town: randomisation inference



Notes: Number of active establishments in Cape Town's water-intensive sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Bars are 95 percent randomisation-inference intervals, from 50 cities drawn at random from the municipalities in the tax panel, each treated in turn as the exposed city. Water-intensive sectors are the top quintile of sectors by water cost share. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

Figure C.3. Formal employment of the 2016 worker cohort: randomisation inference



Notes: Formal employment of workers employed in Cape Town's water-intensive sectors in 2016. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Bars are 95 percent randomisation-inference intervals, from 50 cities drawn at random from the municipalities in the tax panel, each treated in turn as the exposed city. Water-intensive sectors are the top quintile of sectors by water cost share. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

D Robustness checks

This appendix turns to alternative explanations for the decline in the number of water-intensive establishments in Cape Town and shows that each is inconsistent with the data. Each subsection rules out one explanation.

D.1 Differences between Cape Town and the control cities

Before the drought, the share of jobs in water-intensive establishments and the size distribution of establishments were similar in Cape Town and the control cities (Figure B.2).

Figure D.1 presents a synthetic difference-in-differences exercise (Arkhangelsky et al., 2021), which builds a counterfactual Cape Town from the other municipalities in our sample. Employment in water-intensive establishments falls by around a tenth relative to its synthetic counterfactual, while employment in other establishments tracks its counterfactual.

D.2 The drought rather than the commercial price

Paarl and Worcester draw on the same water supply as Cape Town and so faced the same drought, but not Cape Town's commercial price increases. Figure D.2 re-estimates equation (6.1) with Paarl and Worcester in place of Cape Town, and we find no significant decline in their number of water-intensive establishments.

D.3 Lower local spending

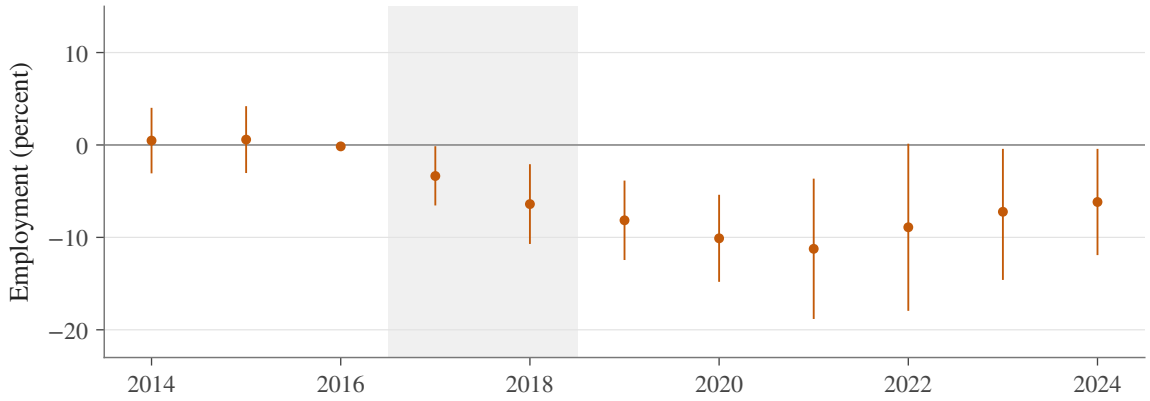
If the decline reflected lower local demand, households would have cut their other spending, sales at continuing establishments would have fallen, and the effect would be concentrated in non-tradable industries. Household spending on water changed little (Section 5), sales at continuing establishments did not fall (Figure E.4), and both tradable and non-tradable industries show excess exit (Figure D.3; Moretti, 2010).

D.4 Activity moved to the control cities

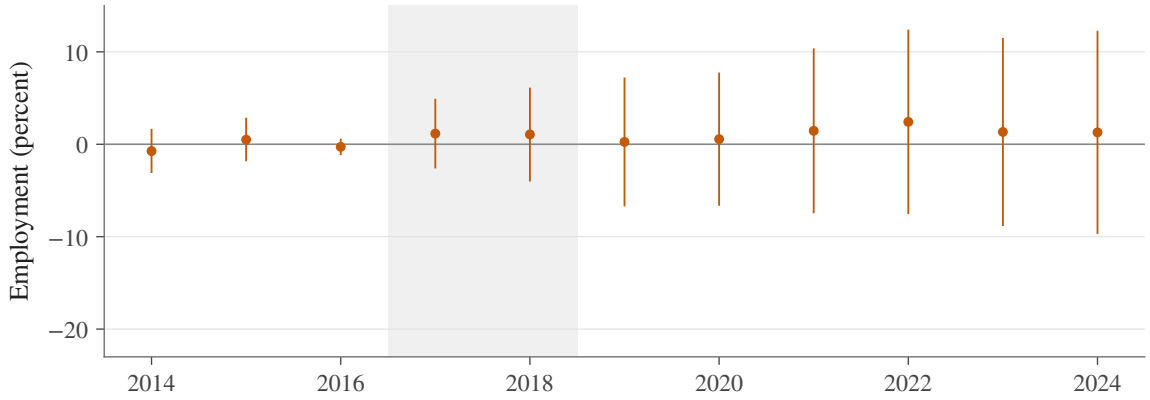
If establishments had relocated to the control cities, water-intensive establishments there would have grown relative to other establishments. Figure C.1, panel (a), shows that they did not. Figure D.4 follows firms with establishments in both Cape Town and a control city. Among those with water-intensive establishments in Cape Town, employment in the control cities did not rise relative to other multi-plant firms. We estimate these comparisons by Poisson pseudo-maximum likelihood (Santos Silva and Tenreyro, 2006).

Figure D.1. Employment relative to a synthetic comparison

(a) Water-intensive sectors

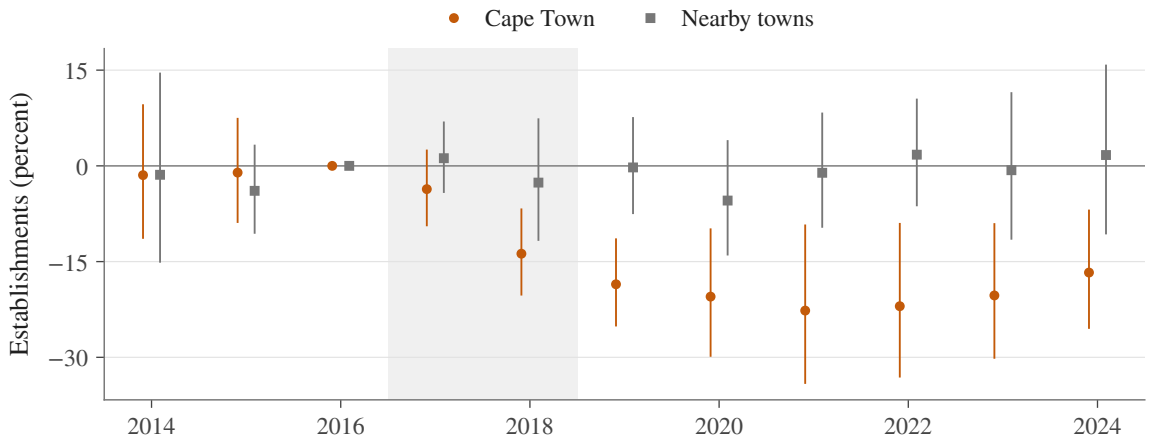


(b) Other sectors



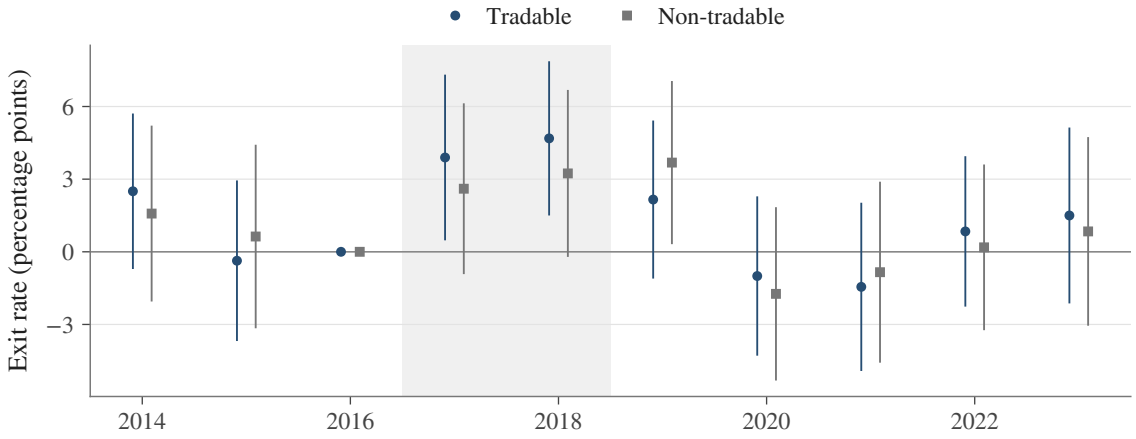
Notes: Employment in Cape Town's water-intensive sectors (panel a) and other sectors (panel b). Coefficients are synthetic difference-in-differences estimates of the change since 2016, relative to a counterfactual Cape Town built from the other municipalities in our sample. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

Figure D.2. Establishments in Cape Town and nearby towns



Notes: Number of active establishments in water-intensive sectors in Cape Town and in Paarl and Worcester, nearby towns that draw on the same water supply but did not face Cape Town's commercial price increases. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in each place, against the same difference in the control cities. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

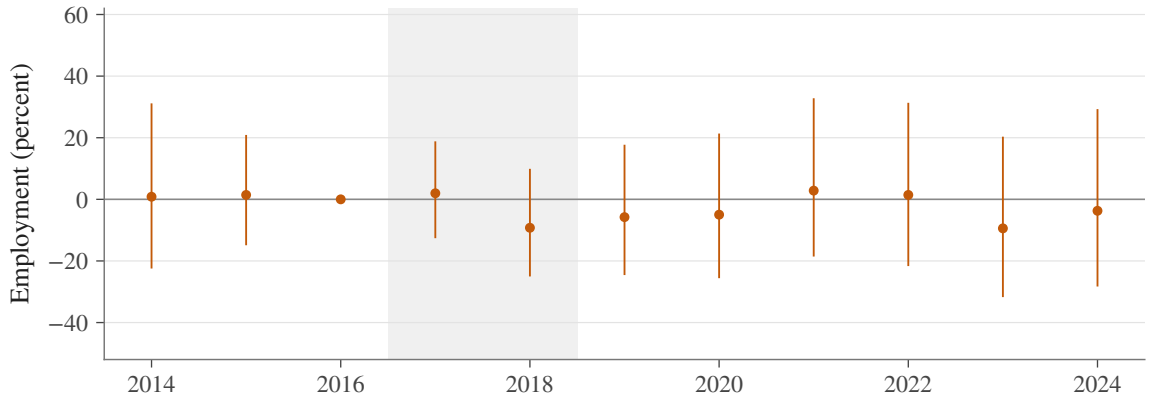
Figure D.3. Exit by sector tradability



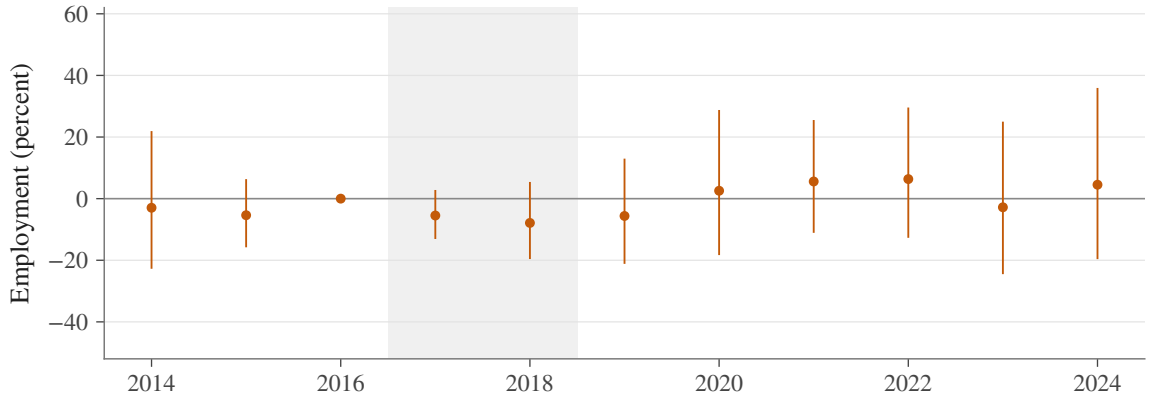
Notes: Annual exit rate of establishments in Cape Town's water-intensive sectors, separately for tradable sectors (agriculture, mining and manufacturing) and non-tradable sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

Figure D.4. Employment at multi-plant firms

(a) Cape Town workplaces



(b) Workplaces in the control cities

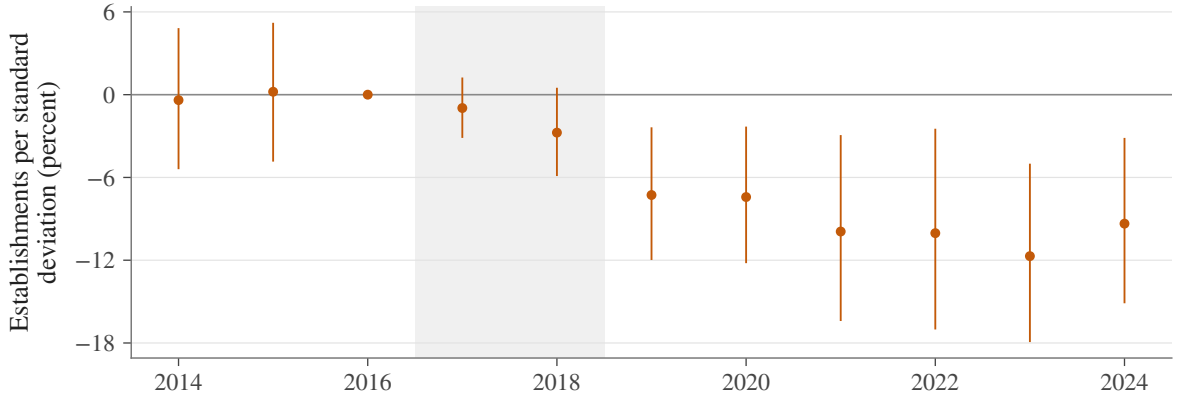


Notes: Employment of multi-plant firms with establishments in both Cape Town and a control city, at their Cape Town workplaces (panel a) and their workplaces in the control cities (panel b). Coefficients are Poisson pseudo-maximum likelihood estimates of the change since 2016 for firms with water-intensive establishments in Cape Town, relative to the other multi-plant firms. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

D.5 How exposure is measured

Exposure is built from national industry cost shares before the drought, so it cannot reflect Cape Town's price increase. Figure D.5 re-estimates equation (6.1) using as treatment the standardised log of the industry's national water cost share. Coefficients before the drought are again close to zero, and more water-intensive industries see a larger decline in the number of establishments.

Figure D.5. Establishments and continuous water exposure



Notes: Number of active establishments in Cape Town. Coefficients are triple-difference estimates of the change since 2016 per standard deviation of the log of the industry's national water cost share, in Cape Town relative to the control cities. 95 percent confidence intervals. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

D.6 Expectations, takeovers and a single treated city

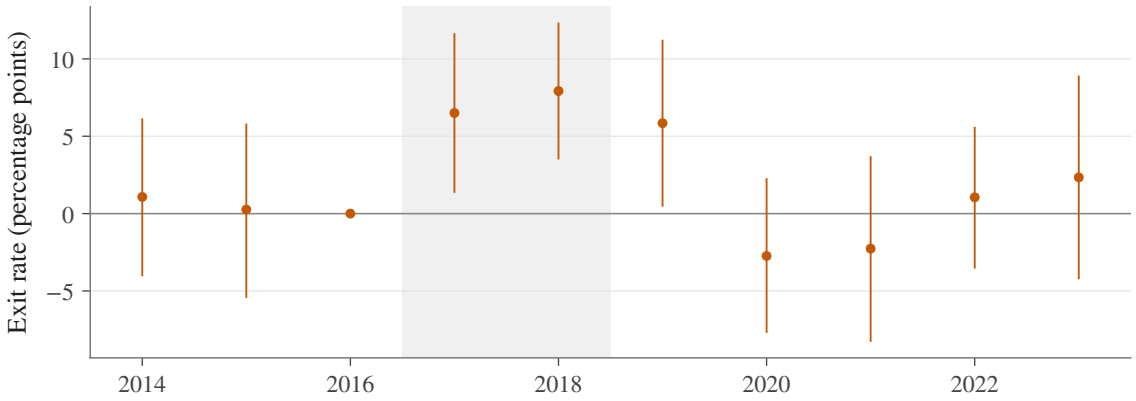
Exit rises only during the drought (Figure E.1) and entry recovers after it (Figure E.2), so firms did not expect the shortage to be permanent. Employment at continuing establishments does not rise relative to its counterfactual (Figure E.3), so exits do not reflect takeovers. Workers employed in 2016 in exposed establishments in Cape Town lose formal jobs (Figure 6.3), so exits do not reflect establishments taking a new tax number. Finally, randomisation inference, needed because there is a single treated city, leads to the same conclusions (Appendix C.3).

E Further evidence

E.1 Exit

Figure E.1 shows estimates of equation (6.1) with the exit rate as the outcome (Appendix B.1). Excess exit is close to zero before the drought and concentrated in 2017–2019.

Figure E.1. Establishment exit

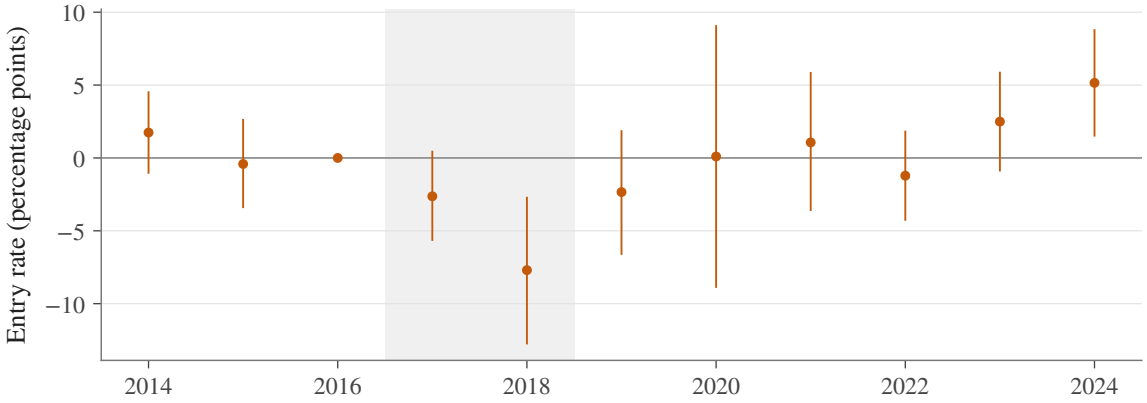


Notes: Annual exit rate of establishments in Cape Town's water-intensive sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. The exit rate is the number of exits divided by the number of establishments in the city-sector that year, among establishments with more than one full-time-equivalent worker. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

E.2 Entry

Figure E.2 shows estimates of equation (6.1) with the entry rate as the outcome, the number of new establishments relative to the cell's 2016 count. Entry falls below its counterfactual in 2018 and recovers from 2019.

Figure E.2. Entry into water-intensive sectors

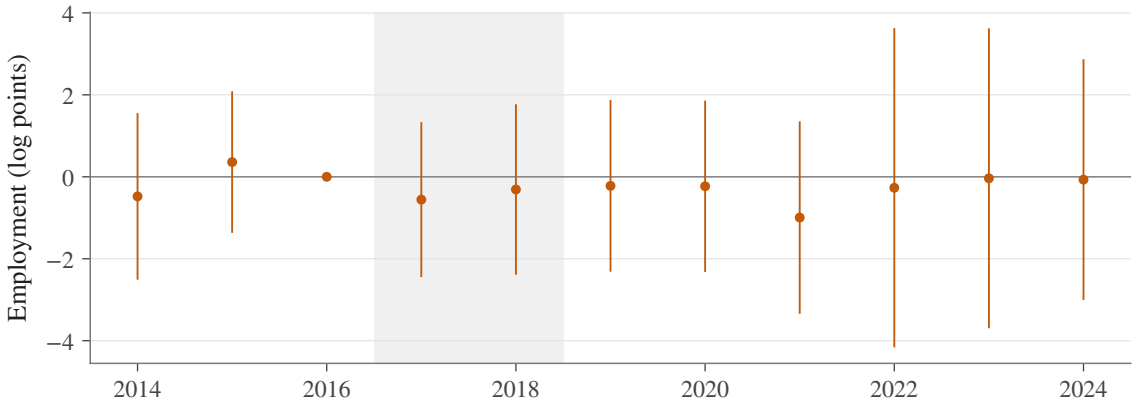


Notes: Entry rate in Cape Town's water-intensive sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. The entry rate is the number of new establishments relative to the city-sector's 2016 count. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

E.3 Continuing establishments

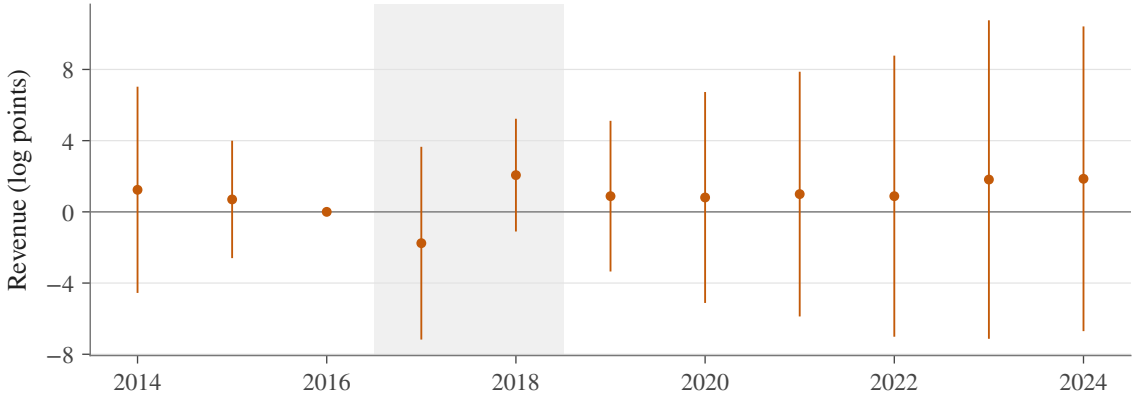
Figures E.3 and E.4 show estimates of equation (6.1) with full-time-equivalent employment and revenue at continuing establishments as outcomes (Appendix B.1). Both track their counterfactuals.

Figure E.3. Employment at continuing establishments



Notes: Full-time-equivalent employment at continuing establishments in Cape Town's water-intensive sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Continuing establishments are present in both 2016 and 2020 with at least one full-time-equivalent worker. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

Figure E.4. Revenue at continuing establishments

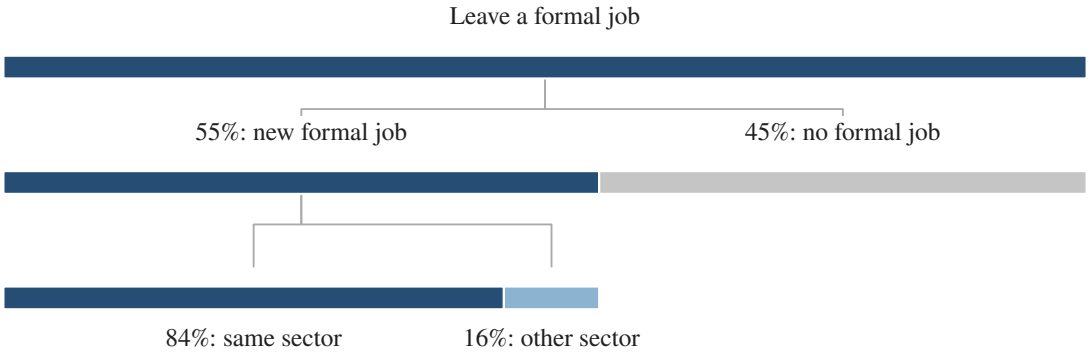


Notes: Revenue at continuing establishments in Cape Town's water-intensive sectors. Coefficients are triple-difference estimates of the change since 2016 in water-intensive relative to other sectors in Cape Town, against the same difference in the control cities. Continuing establishments are present in both 2016 and 2020 with at least one full-time-equivalent worker. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals, clustered by city-sector. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

E.4 Sector of re-employed workers

Figure E.5 shows the sector in which workers who left a Cape Town employer before the drought found their next formal job.

Figure E.5. Employment and sector after leaving an employer before the drought

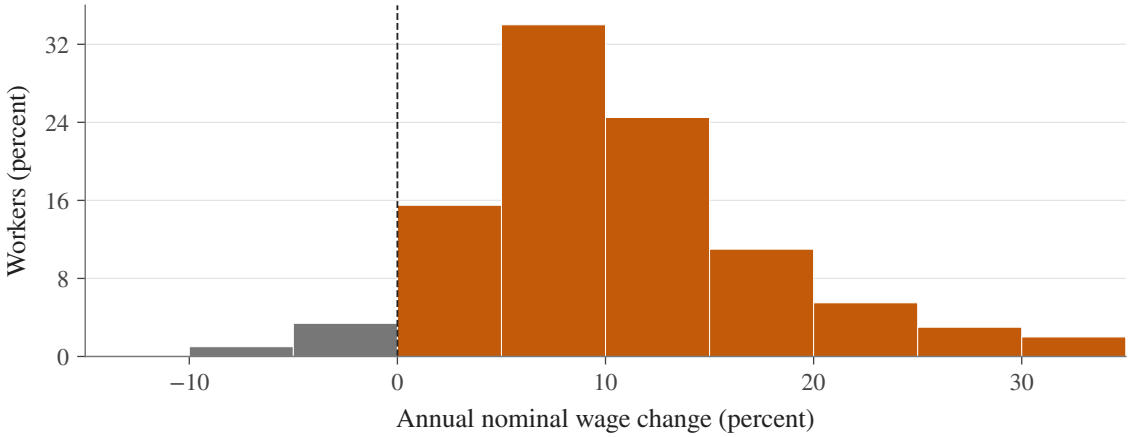


Notes: The share of workers who left a Cape Town employer before the drought with a formal job one year later, and, among those re-employed, the share in their original sector. Source: SARS and National Treasury tax records.

E.5 Wages of workers who stay

Among workers who stay with their employer in Cape Town's water-intensive industries, nominal wage cuts are rare during the drought (Figure E.6).

Figure E.6. Wage changes among workers staying with their employer



Notes: Nominal wage changes among workers who stay with their employer in Cape Town's water-intensive sectors, 2017–2019. Bins span five percentage points. Water-intensive sectors are the top quintile of sectors by water cost share. Source: SARS and National Treasury tax records.

E.6 Linked sectors and neighbouring firms

A neighbourhood n is an H3 resolution-7 hexagon (Brodsky, 2018), and each establishment is assigned to the hexagon containing most of the built-up area of its postcode. Following Ellison et al. (2010), we construct three measures of how industries were linked to water-intensive industries before the drought: purchases from and sales to them, from the national Supply and Use Tables, and the overlap in occupations with them, from the 2011 Census (Statistics South Africa, 2015). Let Z_s^k be the standardised measure of link k for industry s, d_n the share of employment in neighbourhood n in water-intensive industries in 2016, and $\text{Post}_t = \mathbf{1}\{t > 2016\}$. Table E.1 reports the results from the following regression:

$$\log E_{nst} = \sum_{k \in \{\text{buy,sell,work}\}} \rho_k Z_s^k d_n \text{Post}_t + \vartheta_{ns} + \delta_{st}^S + u_{nst}^L, \tag{E.1}$$

where E_{nst} is employment in sector s in neighbourhood n of Cape Town in year t. We estimate equation (E.1) over 2014–2024, excluding water-intensive industries, and all three links are associated with significantly lower employment.

Table E.1. Employment and links to water-intensive sectors

	Log employment
Bought from water-intensive sectors	-0.217^{***}
	(0.036)
Sold to water-intensive sectors	-0.111^{***}
	(0.041)
Shared workers with water-intensive sectors	-0.083^{**}
	(0.038)
Neighbourhood-sector fixed effects	Yes
Sector-year fixed effects	Yes
Period	2014–2024

Notes: Log employment of sectors outside the water-intensive ones in each Cape Town neighbourhood. Coefficients are on each standardised link to water-intensive sectors, interacted with the neighbourhood's 2016 share of water-intensive employment and the years after 2016, estimated jointly. Standard errors in parentheses, clustered by neighbourhood. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. Sources: tax records; 2010 Supply and Use Tables; 2011 Census.

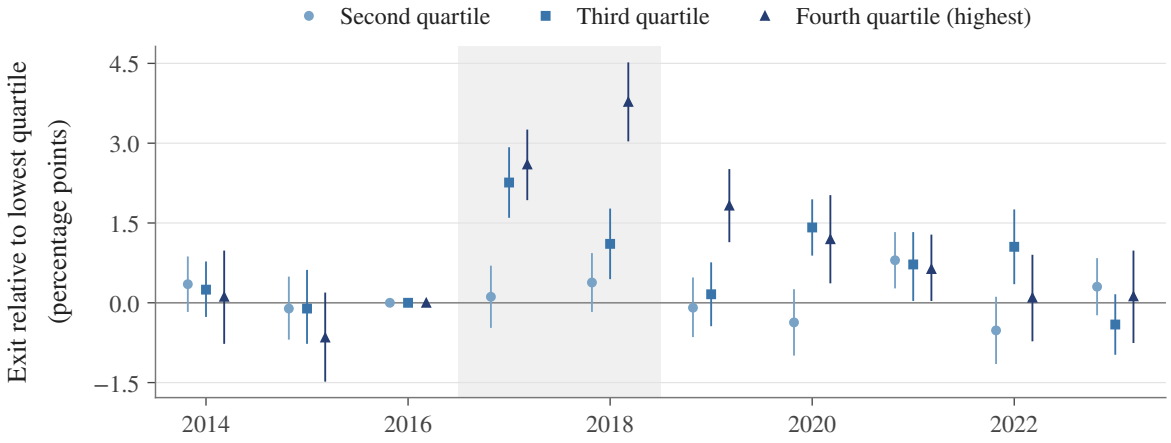
For exit, K_n is the quartile of the hexagon's exposure, the 2016 share of its employment in water-intensive industries, excluding the establishment's own employment. Using Cape Town establishment-years from 2014 to 2023, separately for water-intensive and other establishments, we estimate

$$\text{Exit}_{jnt} = \sum_{r=2}^{4} \sum_{\kappa \neq 2016} \gamma_{r\kappa}^N \mathbf{1}\{K_n = r\}\mathbf{1}\{t = \kappa\} + \delta_n^N + \delta_{s(j)t}^S + u_{jnt}^N.$$

Among water-intensive establishments, exit in the most exposed quartile was 3.8 percentage points higher than in the least exposed quartile in 2018, after flat differences before the

drought, and the gap narrows after the drought (Figure E.7).

Figure E.7. Water-intensive establishment exit by neighbourhood exposure



Notes: Annual exit rate of establishments in water-intensive sectors in Cape Town, by neighbourhood exposure. Coefficients are difference-in-differences estimates of the change since 2016 in each exposure quartile relative to the lowest quartile. Neighbourhoods are hexagons, grouped into quartiles by their 2016 share of water-intensive jobs. Water-intensive sectors are the top quintile of sectors by water cost share. 95 percent confidence intervals. The grey band marks the period of drought pricing and restrictions. Source: SARS and National Treasury tax records.

F Model decisions and equilibrium

This appendix describes the decisions and market conditions of the model in Section 7.

F.1 Household consumption

Plugging demand in equation (7.2) into the utility in equation (7.1) gives the utility from consumption, before the amenity, as a function of income Y and water price p,

$$u^c(Y,p) = \ln(Y - p\bar{q}) - \theta \ln p + C_\theta, \qquad C_\theta = (1-\theta)\ln(1-\theta) + \theta \ln \theta, \tag{F.1}$$

where $u^c_Y = 1/(Y - p\bar{q})$ and $u^c_p = -q/(Y - p\bar{q})$.

F.2 Destinations and labour supply

Let $i = (s, \ell)$ denote the state of a household and i' its destination, with switching cost $\tau_{ii'} = \tau_S \mathbf{1}\{s(i') \neq s(i)\} + \tau_L \text{dist}_{\ell(i)\ell(i')}$. If tastes over destinations are independent Gumbel, equation (7.3) gives the destination probabilities

$$\mu_{ii',t} = \frac{\exp\{\nu[\beta V_{i',t+1} - \tau_{ii'}]\}}{\sum_{i''} \exp\{\nu[\beta V_{i'',t+1} - \tau_{ii''}]\}}. \tag{F.2}$$

If $n_{i,t}$ households are in state i, the population next year is

$$n_{i',t+1} = \sum_i n_{i,t}\mu_{ii',t}, \qquad \sum_{i'} n_{i',t+1} = \bar{n}. \tag{F.3}$$

Within the year households supply labour inelastically, so labour supply in each market is $\widetilde{L}_{s\ell,t} = n_{s\ell,t}$.

F.3 Production and operating decisions

Outside demand for each sector's output has elasticity $\sigma > 1$, inverse demand $P_s(y)$ and a fixed scale, so the exit of one firm does not raise demand for the others. A firm that operates solves

$$\pi_{j,t} = \max_{Q,L,H,y} \{P_s(y)y - p_t^F Q - w_{s\ell,t}L - \rho_{\ell,t}H - f\}$$

subject to equation (7.4).

Let $K^B_{s\ell,t} = (w/(1-\gamma_f))^{1-\gamma_f}(\rho/\gamma_f)^{\gamma_f}$ be the unit cost of the bundle of labour and floorspace. The unit cost of output K_j and the cost share of water $s^W_{s\ell,t}$ are

$$K_j = \frac{[\gamma_s^W (p_t^F)^{1-\varepsilon} + (1-\gamma_s^W)(K^B_{s\ell,t})^{1-\varepsilon}]^{1/(1-\varepsilon)}}{A_{\ell,t}\varphi_j}, \tag{F.4}$$

$$s^W_{s\ell,t} = \frac{\gamma_s^W (p_t^F)^{1-\varepsilon}}{\gamma_s^W (p_t^F)^{1-\varepsilon} + (1-\gamma_s^W)(K^B_{s\ell,t})^{1-\varepsilon}}. \tag{F.5}$$

Given variable costs $X_j = K_j y_j$, payments to factors are

$$p^F Q_j = s^W_{s\ell,t} X_j, \qquad wL_j = (1-\gamma_f)(1-s^W_{s\ell,t})X_j, \qquad \rho H_j = \gamma_f(1-s^W_{s\ell,t})X_j. \tag{F.6}$$

The ratio of the wage bill to the water bill gives equation (7.6). Write $K^X_{s\ell,t}$ for the numerator of equation (F.4). The price is $\sigma K_j/(\sigma-1)$, profit before fixed costs is $v_j = X_j/(\sigma-1)$ and operating profit is $v_j - f$. Absorbing the markup into the scale of outside demand D_s, we have $v_{j,t} = \mathsf{D}_s(A_{\ell,t}\varphi_j)^{\sigma-1}(K^X_{s\ell,t})^{1-\sigma}$.

Holding wages, rent and productivity fixed, the response of water use at given output and in total is

$$\left.\frac{\partial \ln Q_{j,t}}{\partial \ln p_t^F}\right|_{y_{j,t}} = -\varepsilon(1-s^W_{s\ell,t}), \tag{F.7}$$

$$\frac{\partial \ln Q_{j,t}}{\partial \ln p_t^F} = -\varepsilon(1-s^W_{s\ell,t}) - \sigma s^W_{s\ell,t}. \tag{F.8}$$

F.4 Finance, exit and entry

Debt $B_{j,t}$ is due at the beginning of the year. Owners do not put in new equity and receive a nonnegative dividend $D_{j,t}$. A promise to repay $B_{j,t+1}$ next year, paid only if the firm survives, raises $\beta(1-d)B_{j,t+1}$ today. Lenders advance at most a fraction λ of next year's value before debt, $\Pi_{j,t+1}$,

$$D_{j,t} = \pi_{j,t} - B_{j,t} + \beta(1-d)B_{j,t+1} \geq 0, \qquad 0 \leq B_{j,t+1} \leq \lambda \Pi_{j,t+1}. \tag{F.9}$$

Owners choose the feasible plan that maximises the present discounted value of dividends. Given inherited debt B, the value of ownership is

$$V^{O}_{j,t}(B) = \max_{\text{plans carrying } B} [\pi_{j,t} + \beta(1-d)\Pi_{j,t+1}] - B, \tag{F.10}$$

or zero if no plan can carry B. Under fair lending, debt adds no value to a plan.

Given a plan, the most debt the firm can carry, $\bar{B}_{j,t}$, satisfies $\bar{B}_{j,t} = \pi_{j,t} + \beta(1-d)\min\{\bar{B}_{j,t+1}, \lambda\Pi_{j,t+1}\}$. A firm with inherited debt $B_{j,t}$ cannot operate if

$$\pi_{j,t} - B_{j,t} + \beta(1-d)\min\{\bar{B}_{j,t+1}, \lambda\Pi_{j,t+1}\} < 0.$$

If the firm has no inherited debt and no other losses to finance, this is the limited-credit condition in equation (7.8). Among the feasible plans, the owner operates the firm only if equation (F.10) is nonnegative.

Let $M^{E}_{s\ell,t}$ be the number of entrants in sector s and location ℓ. Each entrant pays f^{E} and draws a productivity from the full Pareto distribution G, and starts producing next year with no debt. Free entry implies

$$f^{E} \geq \beta(1-d)\mathbb{E}_{\varphi}\Pi^{E}_{s\ell,t+1}, \qquad M^{E}_{s\ell,t} \geq 0, \qquad M^{E}_{s\ell,t}[f^{E} - \beta(1-d)\mathbb{E}_{\varphi}\Pi^{E}_{s\ell,t+1}] = 0.$$

Entry is strictly positive only if the expected value of entering equals f^{E}. In words, the marginal entrant creates no value. Entrants whose draws do not cover their costs value the firm at zero.

Let $\mathcal{F}_{s\ell,t}$ be the measure of firms after the year's exogenous deaths and before the operating decision, and $\mathcal{A}_{s\ell,t}$ the set of those that operate. For any set $\mathcal{Z}$ of productivity–debt pairs,

$$\begin{aligned}\mathcal{F}_{s\ell,t+1}(\mathcal{Z}) = (1-d)\Big[&\int_{\mathcal{A}_{s\ell,t}} \mathbf{1}\{(\varphi, B_{t+1}(\varphi,B)) \in \mathcal{Z}\}\, \mathcal{F}_{s\ell,t}(\mathrm{d}\varphi, \mathrm{d}B) \\ &+ M^{E}_{s\ell,t} \int \mathbf{1}\{(\varphi,0) \in \mathcal{Z}\}\, \mathrm{d}G(\varphi)\Big].\end{aligned} \tag{F.11}$$

F.5 Labour and floorspace

Labour demand in each sector and location is $L^d_{s\ell,t} = \int_{\mathcal{A}_{s\ell,t}} L_{j,t}\,\mathrm{d}\mathcal{F}_{s\ell,t}$, and wages and employment satisfy equation (7.7). In the benchmark economy the wage floor is replaced by home production income, so

$$w_{s\ell,t} \geq b, \qquad L^d_{s\ell,t} \leq \widetilde{L}_{s\ell,t}, \qquad (w_{s\ell,t} - b)(\widetilde{L}_{s\ell,t} - L^d_{s\ell,t}) = 0.$$

All workers are employed if the wage is above b, and at a wage of b workers are indifferent between working and not.

Commercial rent clears the fixed supply of commercial floorspace, and paid employment determines local productivity,

$$\sum_s \int_{\mathcal{A}_{s\ell,t}} H_{j,t}\,\mathrm{d}\mathcal{F}_{s\ell,t} = \bar{H}_\ell, \qquad L_{\ell,t} = \sum_s L^d_{s\ell,t}, \qquad A_{\ell,t} = \bar{A}_\ell L^\alpha_{\ell,t}. \tag{F.12}$$

F.6 Water, timing and equilibrium

Aggregate household demand is the sum of each household's demand at its realised income,

$$Q^H_t = \sum_{s\neq 0,\ell} n_{s\ell,t}[e_{s\ell,t} q_t(w_{s\ell,t}) + (1 - e_{s\ell,t}) q_t(b)] + \sum_\ell n_{0\ell,t} q_t(b), \tag{F.13}$$

where $n_{0\ell,t}$ is the number of households in home production in each location. Using household income $Y^H_t = \sum_{s,\ell} w_{s\ell,t} L^d_{s\ell,t} + b(\bar{n} - \sum_{s,\ell} L^d_{s\ell,t})$, this becomes

$$Q^H_t = \bar{n}(1-\theta)\bar{q} + \theta Y^H_t / p^H_t, \qquad p^H_t = \frac{\theta Y^H_t}{Q^H_t - \bar{n}(1-\theta)\bar{q}}. \tag{F.14}$$

Firm demand is $Q^F_t = \sum_{s,\ell} \int_{\mathcal{A}_{s\ell,t}} Q_{j,t}\,\mathrm{d}\mathcal{F}_{s\ell,t}$. In shortage years the city sets the two prices so that $Q^H_t + Q^F_t = \bar{Q}_t$. In other years prices are at their normal levels.

The economy starts in a stationary state, in which amenities reproduce the household distribution, entry equals deaths and firms have no debt. When the policy is announced, everyone learns the whole path of the resource constraint and of prices, after destinations and entry for the first shortage year have been chosen. Each year has three stages. First, a fraction d of firms dies, firms pay the debt that is due and decide whether to operate, operating firms choose inputs and debt, and markets clear. Second, households consume out of realised income. Third, households choose next year's destination and new entrants pay the entry cost. After the announcement there is no aggregate uncertainty.

Given the distribution of firms, the resource constraint and continuation values, a within-year equilibrium consists of wages and employment, commercial rents, local productivity,

the set of operating firms and water prices such that (i) firms solve the operating and financing problems above, (ii) labour, floorspace and household water satisfy equations (7.7), (F.12), (F.13) and (F.14), and (iii) water use meets the resource constraint in shortage years.

An equilibrium is a sequence of within-year equilibria, household values and destination probabilities, financing plans, entry and firm distributions such that (i) households satisfy equations (7.2), (7.3), (F.2) and (F.3), (ii) firms satisfy free entry, (iii) the distribution of firms evolves by equation (F.11), and (iv) continuation values are consistent with the resulting choices.

Lemma F.1 (Prices and quantities)**.** *Take as given the distribution of firms, labour supply and continuation values, and suppose firm water demand is strictly decreasing and household use is feasible above basic needs. If firms' output is bought outside the city and other consumption goods are imported, each feasible allocation of water is implemented by a unique pair of household and firm water prices.*

Given the water allocated to firms, their demand curve pins down the firm price. This price does not depend on the household price, because labour supply is inherited and firms' output is bought outside the city. Given the firm price, equilibrium determines household incomes, and equation (F.14) pins down the household price.

Lemma F.2 (Uniqueness of the within-year equilibrium)**.** *Take as given the state at the beginning of year t, continuation values and the allocation of water, with $\widetilde{L}_{s\ell,t} > 0$ and $\bar{H}_\ell > 0$ for all sectors s and locations ℓ, and let firm water demand be strictly decreasing as in Lemma F.1. Suppose that (i) within each sector and location, in each year, among firms that entered in the same year, the largest loss that a firm can finance in the current year, $c_{j,t} = \beta(1-d)\min\{\bar{B}_{j,t+1}, \lambda\Pi_{j,t+1}\} - B_{j,t}$, is a nondecreasing function of firm productivity, φ_j; (ii) the water share of variable costs in each sector and location, $s^W_{s\ell,t}$, is below $(\sigma-1)/(\sigma-\varepsilon)$ in any within-year equilibrium (evaluated at the wage floor and the equilibrium rent); and (iii) $k > \sigma - 1$, $\varepsilon < 1$, and $\alpha k < 1$. Then there is at most one within-year equilibrium with positive paid employment in every location.*

Proof. To prove the result, we show (i) the within-year equilibrium, and so firm water use in each location and sector, is uniquely determined for a given price of water; (ii) there is at most one water price consistent with the water allocation in years in which water is scarce; and (iii) in other years the price of water is the normal price. We then show that there is a unique value of Y_t^H, and hence of p_t^H by equation (F.14).

Consider a given year and fix the state at the beginning of the year, continuation values, and the price of water, p_t^F (we suppress the time subscript in this part of the proof). Household labour supply and firm financial constraints are therefore given. Denote the

wage floor in sector s and location ℓ by $\underline{w}_{s\ell}$ ($w_{s\ell,t-1}$ in the model and b in the benchmark economy).

Demand for employment conditional on the price of water. First consider a location ℓ and denote its rent by ρ. Since firms sell outside the city, labour supply is inherited and c_j is given, locations interact only through the price of water, so we can characterise firm behaviour in each location taking the price of water as given. Let $K^X_{s\ell}$ denote the cost of inputs net of productivity, the numerator of equation (F.4), and define

$$m_s = \mathsf{D}_s A_\ell^{\sigma-1} (K^X_{s\ell})^{1-\sigma},$$

so that the variable profit of a firm of productivity φ_j in sector s and location ℓ is $v_j = m_s \varphi_j^{\sigma-1}$.

We show that employment demand is increasing in A_ℓ and decreasing in the wage and rent. Define $\varphi^*(m_s)$ to be the cutoff productivity in a cohort above which firms operate when the value shifter is m_s. Firms operate if and only if $v_j - f + c_j \geq 0$, and so if c_j is nondecreasing in productivity within a cohort, there is a cutoff level of productivity (unique up to a measure zero set) above which firms operate.

We next show that if $m' > m$,

$$\varphi^*(m') \geq \left(\frac{m}{m'}\right)^{\frac{1}{\sigma-1}} \varphi^*(m).$$

To see this, note that if $\varphi < \left(\frac{m}{m'}\right)^{\frac{1}{\sigma-1}} \varphi^*(m)$, then letting $\tilde{\varphi} = \left(\frac{m'}{m}\right)^{\frac{1}{\sigma-1}} \varphi$, $m'\varphi^{\sigma-1} + c(\varphi) \leq m\tilde{\varphi}^{\sigma-1} + c(\tilde{\varphi}) < f$, where the first inequality uses that $c(\varphi)$ is nondecreasing and the second that $\tilde{\varphi} < \varphi^*(m)$.

Firms of the same cohort and productivity share their history, so they have the same c_j. New entrants draw productivities from G, existing firms die with a probability independent of φ, and past exit within a cohort is by cutoff, so the productivity distribution of the firms remaining in each cohort has a density proportional to φ^{-k-1} above some productivity $\underline{\varphi}$. Firm j's employment is decreasing in ρ and $w_{s\ell}$, and so aggregating over firms, $L^d_{s\ell}$, employment demand in sector s and location ℓ, is decreasing in ρ and $w_{s\ell}$. We next show that $L^d_{s\ell}$ is increasing in A_ℓ.

By equation (F.6),

$$L^d_{s\ell} = (1-\gamma_f)(1-s^W_{s\ell}) \frac{(\sigma-1) m_s Z_{s\ell}(m_s)}{w_{s\ell}},$$

where $Z_{s\ell}(m)$ is the sum of $\varphi_j^{\sigma-1}$ over the firms that operate when the value shifter is m. Holding the incumbent firms fixed, $Z_{s\ell}(m_s)$ is increasing in m_s and hence in A_ℓ. Given that the productivity distribution of the firms remaining in each cohort has a

density proportional to φ^{-k-1}, the contribution of each cohort to $Z_{s\ell}$ is proportional to $\max\{\varphi^*, \underline{\varphi}\}^{\sigma-1-k}$, where φ^* is the cohort's cutoff productivity for operation. Given that $k > \sigma - 1$ and $\varphi^*(m') \geq \left(\frac{m}{m'}\right)^{\frac{1}{\sigma-1}} \varphi^*(m)$ if $m' > m$,

$$Z_{s\ell}(m') \leq \left(\frac{m'}{m}\right)^{\frac{k-\sigma+1}{\sigma-1}} Z_{s\ell}(m).$$

It follows that holding the wage and rent fixed, $L^d_{s\ell}$ increases at most in proportion to A^k_ℓ when A_ℓ increases.

To see that $L^d_{s\ell}$ is decreasing in $w_{s\ell}$ and ρ, note that within a given set of operating firms,

$$\frac{\partial \ln L_j}{\partial \ln w_{s\ell}} = -1 + (1 - \gamma_f)\Delta_s,$$
$$\frac{\partial \ln L_j}{\partial \ln \rho} = \gamma_f \Delta_s,$$

where $\Delta_s = (1-\varepsilon)s^W_{s\ell} - (\sigma - 1)(1 - s^W_{s\ell}) < 0$ given the maintained assumption on $s^W_{s\ell}$. When $\varepsilon < 1$, $s^W_{s\ell}$ is decreasing in $K^B_{s\ell}$, the unit cost of the bundle of labour and floorspace in sector s and location ℓ, and hence the result continues to hold at higher wages and rents. Higher $w_{s\ell}$ or ρ also lower m_s and shrink the set of operating firms. So $L^d_{s\ell}$ is strictly decreasing in $w_{s\ell}$, nonincreasing in ρ and increasing in A_ℓ, and by equation (7.7) paid employment is $L_{s\ell} = \min\{\widetilde{L}_{s\ell}, L^d_{s\ell}(\underline{w}_{s\ell}, \rho, A_\ell)\}$, while the wage is the floor or the wage at which $L^d_{s\ell} = \widetilde{L}_{s\ell}$.

Take two equilibria at p^F with $A^2_\ell \geq A^1_\ell$ and suppose $\rho^2 < \rho^1$. Then $L^d_{s\ell}$ is weakly higher at every wage in the second, so $w^2_{s\ell} \geq w^1_{s\ell}$ and $L^2_{s\ell} \geq L^1_{s\ell}$ in every sector. Since $\rho H_j = \gamma_f w_{s\ell} L_j/(1-\gamma_f)$ for every firm, floorspace demand $\sum_s \gamma_f w_{s\ell} L_{s\ell}/[(1-\gamma_f)\rho]$ would be strictly higher in the second, but both equal $\bar{H}_\ell$. Hence $\rho^2 \geq \rho^1$, and if $A^2_\ell = A^1_\ell$ the argument runs both ways, so rents, wages, employment and operating firms coincide. If $A^2_\ell > A^1_\ell$, then $L^2_{s\ell} \leq \min\{\widetilde{L}_{s\ell}, L^d_{s\ell}(\underline{w}_{s\ell}, \rho^1, A^2_\ell)\} \leq (A^2_\ell/A^1_\ell)^k L^1_{s\ell}$ in every sector, and by equation (F.12) $\ln(A^2_\ell/A^1_\ell) = \alpha \ln(L^2_\ell/L^1_\ell) \leq \alpha k \ln(A^2_\ell/A^1_\ell)$, which contradicts $\alpha k < 1$. So at each p^F the within-year equilibrium is unique and firm water use is a function of p^F. As this function is strictly decreasing, at most one p^F_t delivers the allocation in a shortage year, and in other years p^F_t is at its normal level. Household income Y^H_t is then unique, and equation (F.14) gives p^H_t. □

Condition (i) holds for firms without debt, as in the stationary state, since $\Pi_{j,t+1}$ and $\bar{B}_{j,t+1}$ then rise with φ_j. At the estimates $\alpha k = 0.09$. The bound in (ii) is 0.69, while the largest sectoral water share is 0.056 at normal prices and 0.17 at the peak price holding the cost of the labour and floorspace bundle fixed, or 0.28 if the wage also falls to home production income, $b = 0.4w$.

We compute the equilibrium year by year over a long horizon, with a stationary continuation that fixes the final year's employment, wages, rents, productivity, entry and normal water prices. In the benchmark economy wages are flexible and $\lambda = 1$. By Lemma F.2 the within-year equilibrium is unique, and numerically this holds for the entire path given its initial state and our parameter values.

G Welfare and the pricing rule

G.1 The experiment and welfare accounts

Let $\mathcal{T}^S$ be the set of shortage years and x the household share of the saving. For each x a single ratio of the household to the firm price applies throughout the shortage, and each year's total use meets the resource constraint (Section 9). A prime denotes a derivative along this curve of allocations, and $h_t = Q_t^{F\prime} = -Q_t^{H\prime}$ for $t \in \mathcal{T}^S$.

The dated experiment moves one unit of water from households to firms in shortage year m, holding fixed the state inherited at m. Write ∂_m for this derivative, with $\partial_m Q_m^F = -\partial_m Q_m^H = 1$ and all other shortage-year allocations fixed. The associated welfare is W_m, discounted to the announcement date. Welfare along the announced path is $W = W_0$.

Household consumption is valued in Rand at the normal household price $\bar{p}^H$. The income that gives the same utility from consumption as (Y, p) is

$$\mathfrak{m}(Y,p) = \bar{p}^H \bar{q} + (Y - p\bar{q})(p/\bar{p}^H)^{-\theta}, \qquad \xi_t = (p_t^H/\bar{p}^H)^{-\theta}.$$

Using equation (F.1), $\mathfrak{m}_Y = \xi$ and $\mathfrak{m}_p = -\xi q$. In state i, expected Rand consumption is $\overline{\mathfrak{m}}_{i,t} = e_{i,t}\mathfrak{m}(w_{i,t}, p_t^H) + (1 - e_{i,t})\mathfrak{m}(b, p_t^H)$, with $e = 0$ in home production, and $\bar{u}_{i,t}^c$ is the corresponding expected utility from consumption.

The household account is

$$\mathcal{W}^H = \mathcal{C}^H + \frac{\mathcal{V} - \mathcal{U}}{\bar{\varkappa}}, \qquad \mathcal{C}^H = \sum_t \beta^t \sum_i n_{i,t}\overline{\mathfrak{m}}_{i,t},$$
$$\mathcal{V} = \sum_i n_{i,0} V_{i,0}, \qquad \mathcal{U} = \sum_t \beta^t \sum_i n_{i,t}\bar{u}_{i,t}^c,$$

where $\bar{\varkappa}$ is the population-weighted average marginal utility of income without a shortage. The second term converts changes in amenities, tastes and switching costs into Rand. Welfare is

$$W = \mathcal{W}^H + \mathcal{O} + \mathcal{R} + \mathcal{G}, \tag{G.1}$$

where $\mathcal{O}$ is the flow of dividends net of entry costs and fairly priced lending, $\mathcal{R}$ is commercial rent and $\mathcal{G}$ is the water account. All terms are simply added, and we ignore the surplus of

buyers outside the city. The water account is

$$\mathcal{G} = \sum_{t=0}^{\infty} \beta^t (p_t^H Q_t^H + p_t^F Q_t^F) - \mathcal{C}^{\text{supply}}, \tag{G.2}$$

where $\mathcal{C}^{\text{supply}}$, the discounted cost of supplying water, does not depend on the allocation. The dated accounts are the same sums starting at m, holding the state at m fixed,

$$\mathcal{C}_m^H = \sum_{t=m}^{\infty} \beta^t \sum_i n_{i,t} \overline{\mathfrak{m}}_{i,t}, \qquad \mathcal{U}_m = \sum_{t=m}^{\infty} \beta^t \sum_i n_{i,t} \bar{u}_{i,t}^c,$$
$$\mathcal{V}_m = \beta^m \sum_i n_{i,m} V_{i,m}, \qquad \mathcal{W}_m^H = \mathcal{C}_m^H + (\mathcal{V}_m - \mathcal{U}_m)/\bar{\varkappa},$$
$$W_m = \mathcal{W}_m^H + \mathcal{O}_m + \mathcal{R}_m + \mathcal{G}_m.$$

G.2 Hiring and household income

Let $L_{i,t} = e_{i,t}\widetilde{L}_{i,t}$ be employment in formal state i. The change in hiring among workers already in the market is

$$J_{i,t|m} = \widetilde{L}_{i,t} \partial_m e_{i,t} = \partial_m L_{i,t} - e_{i,t} \partial_m \widetilde{L}_{i,t}.$$

When wages are flexible, either $J = 0$ or $w_{i,t} = b$. Hired and unhired workers face the same amenities and choice set, so one more hire is worth

$$\mathfrak{m}(w_{i,t}, p_t^H) - \mathfrak{m}(b, p_t^H) = \xi_t (w_{i,t} - b). \tag{G.3}$$

Differentiating Rand consumption gives

$$\begin{aligned} \partial_m \mathcal{C}_m^H = \sum_{t \geq m} \beta^t \Big[& \sum_i J_{i,t|m} \xi_t (w_{i,t} - b) + \xi_t \sum_i L_{i,t} \partial_m w_{i,t} \\ & - \xi_t Q_t^H \partial_m p_t^H + \sum_i \overline{\mathfrak{m}}_{i,t} \partial_m n_{i,t} \Big]. \end{aligned} \tag{G.4}$$

Differentiating equation (7.3), the envelope condition for destinations removes the effect of changed choice probabilities,

$$\partial_m V_{i,t} = \partial_m \bar{u}_{i,t}^c + \beta \sum_{i'} \mu_{ii',t} \partial_m V_{i',t+1}.$$

Iterating and using equation (F.3),

$$\partial_m \mathcal{V}_m = \sum_{t \geq m} \beta^t \sum_i n_{i,t} \partial_m \bar{u}_{i,t}^c, \qquad \frac{\partial_m \mathcal{V}_m - \partial_m \mathcal{U}_m}{\bar{\varkappa}} = -\sum_{t \geq m} \beta^t \sum_i \frac{\bar{u}_{i,t}^c}{\bar{\varkappa}} \partial_m n_{i,t}.$$

Combining with equation (G.4) and evaluating at date m,

$$\begin{aligned}\beta^{-m}\partial_m \mathcal{W}_m^H &= \sum_{t\geq m}\beta^{t-m}\Big[\sum_i J_{i,t|m}\xi_t(w_{i,t}-b)+\xi_t\sum_i L_{i,t}\partial_m w_{i,t}-\xi_t Q_t^H\partial_m p_t^H\Big]+\zeta_m^{\text{moves}},\\ \zeta_m^{\text{moves}} &= \sum_{t\geq m}\beta^{t-m}\sum_i\Big[\overline{\mathfrak{m}}_{i,t}-\bar{u}_{i,t}^c/\bar{\varkappa}\Big]\partial_m n_{i,t}.\end{aligned} \tag{G.5}$$

G.3 Financing boundaries and marginal entry

At the limited-credit boundary of a firm without debt, $\pi_{j,t}+\lambda\beta(1-d)\Pi_{j,t+1}=0$, so the owner loses

$$V_{j,t}^{\text{cl}}=\pi_{j,t}+\beta(1-d)\Pi_{j,t+1}=(1-\lambda)\beta(1-d)\Pi_{j,t+1}. \tag{G.6}$$

With inherited debt, V^{cl} is the value of continuing net of that debt, under the convention of Appendix F.4. With full credit it is zero at the exit boundary.

For a density of firms $\bar{N}_i g_i(\varphi)$ and continuation value $\Pi_i(\varphi)$ above a cutoff $\varphi_{c,i}$,

$$\begin{aligned}\partial_m\Big[\bar{N}_i\int_{\varphi_{c,i}}^{\infty}\Pi_i(\varphi)g_i(\varphi)\,\mathrm{d}\varphi\Big] &= \bar{N}_i\int_{\varphi_{c,i}}^{\infty}\partial_m\Pi_i(\varphi)g_i(\varphi)\,\mathrm{d}\varphi\\ &\quad-\bar{N}_i g_i(\varphi_{c,i})\partial_m\varphi_{c,i}\,V_i^{\text{cl}}.\end{aligned}$$

If there are several feasible plans ι ordered by productivity, with $z_{i,\iota}$ the cutoff between plans $\iota-1$ and ι and plan 0 denoting exit, the boundary terms are

$$\bar{N}_i\sum_{\iota}g_i(z_{i,\iota})\partial_m z_{i,\iota}[\Pi_{i,\iota-1}(z_{i,\iota})-\Pi_{i,\iota}(z_{i,\iota})].$$

At a voluntary boundary the values on both sides are equal and the boundary term is zero. A change in financing plan is counted once, in the year of the loss, at V^{cl} in equation (G.6), net of inherited debt.

There is no gain from fairly priced lending. The dividend constraint telescopes to

$$\sum_{t'\geq t}[\beta(1-d)]^{t'-t}D_{j,t'}=\sum_{t'\geq t}[\beta(1-d)]^{t'-t}\pi_{j,t'}-B_{j,t}.$$

There is no gain from marginal entry. Using $\mathcal{E}_{i,t}=\beta(1-d)\mathbb{E}_\varphi\Pi_{i,t+1}^E$,

$$\partial_m[M_{i,t}^E(\mathcal{E}_{i,t}-f^E)]=M_{i,t}^E\partial_m\mathcal{E}_{i,t}+(\mathcal{E}_{i,t}-f^E)\partial_m M_{i,t}^E.$$

The second term is zero by free entry, and the first is already part of the operating and financing envelopes of the entering firms.

G.4 Profits, rents and water receipts

Changes in the inputs of continuing firms have no first-order effect on profits,

$$\frac{\partial \pi_j}{\partial p^F} = -Q_j, \qquad \frac{\partial \pi_j}{\partial w} = -L_j, \qquad \frac{\partial \pi_j}{\partial \rho} = -H_j.$$

Let $v_{i,t} = \int_{\mathcal{A}_{i,t}} v_{j,t} \, \mathrm{d}\mathcal{F}_{i,t}$ be total variable profit in state i. Then

$$\frac{\partial \pi_{i,t}}{\partial \ln A_{\ell(i),t}} = (\sigma - 1) v_{i,t}, \qquad \partial_m \ln A_{\ell,t} = \alpha \partial_m \ln L_{\ell,t},$$

and their product is the agglomeration externality term.

Adding the gains of owners, landlords and the water account to equation (G.5) cancels firms' payments for water and rent. Wage income leaves $(\xi_t - 1) \sum_i L_{i,t} \partial_m w_{i,t}$ and household water bills leave $(1 - \xi_t) Q_t^H \partial_m p_t^H$. The bill term is the same Rand conversion applied to the household water bill and is part of the first component of r_m. In shortage years the direct quantity terms satisfy

$$p_t^F \partial_m Q_t^F + p_t^H \partial_m Q_t^H = (p_t^F - p_t^H) \partial_m Q_t^F,$$

and are nonzero only at m. The remainder term is

$$\begin{aligned} \xi_m^p &= \sum_{t=m}^{\infty} \beta^{t-m} \left[(\xi_t - 1) \sum_i L_{i,t} \partial_m w_{i,t} + (1 - \xi_t) Q_t^H \partial_m p_t^H \right], \\ \zeta_m^{\text{water}} &= \sum_{\substack{t \geq m \\ t \text{ after shortage}}} \beta^{t-m} [\bar{p}^F \partial_m Q_t^F + \bar{p}^H \partial_m Q_t^H], \\ \zeta_m &= \zeta_m^{\text{moves}} + \zeta_m^{\text{water}}, \qquad r_m = \xi_m^p + \zeta_m. \end{aligned}$$

Beyond the horizon we compute, the sums use the stationary continuation of Appendix F.6. This continuation is the end-of-horizon part of r_m in Section 7.6.

G.5 The proposition and the pricing rule

Adding up the accounts gives

$$\begin{aligned}\beta^{-m}\partial_m W_m &= p_m^F - p_m^H \\ &\quad + \sum_{t=m}^{\infty} \beta^{t-m} \sum_i J_{i,t|m}\xi_t(w_{i,t} - b) \\ &\quad + \sum_{t=m}^{\infty} \beta^{t-m} \sum_i N^{\mathrm{cl}\prime}_{i,t|m} V^{\mathrm{cl}}_{i,t} \\ &\quad + \sum_{t=m}^{\infty} \beta^{t-m} \sum_i \alpha\partial_m \ln L_{\ell(i),t} \frac{\partial \pi_{i,t}}{\partial \ln A_{\ell(i),t}} + \xi^p_m + \zeta_m \\ &= p_m^F - p_m^H + \omega_m^F,\end{aligned} \tag{G.7}$$

which proves Proposition 7.1. Setting it to zero gives equation (7.12).

Welfare along the announced path has the same form. Let $J_{i,t}(x) = \widetilde{L}_{i,t} e'_{i,t}(x)$ and let $N^{\mathrm{cl}\prime}_{i,t}(x)$ count changes in financing plans once, at the date of the loss. Then

$$\begin{aligned}W'(x) = &\sum_{t\in\mathcal{T}^S} \beta^t h_t (p_t^F - p_t^H) \\ &+ \sum_{t=0}^{\infty} \beta^t \sum_i \left[J_{i,t}\xi_t(w_{i,t} - b) + N^{\mathrm{cl}\prime}_{i,t} V^{\mathrm{cl}}_{i,t} + \alpha(\ln L_{\ell(i),t})' \frac{\partial \pi_{i,t}}{\partial \ln A_{\ell(i),t}} \right] + \xi^p(x) + \zeta(x),\end{aligned} \tag{G.8}$$

where every prime is a response to the whole announced path. With $\mathcal{B}(x) = \sum_{t\in\mathcal{T}^S} \beta^t h_t$, the response-weighted prices are

$$\widetilde{p}^H(x) = \frac{\sum_{t\in\mathcal{T}^S} \beta^t h_t p_t^H}{\mathcal{B}(x)}, \qquad \widetilde{p}^F(x) = \frac{\sum_{t\in\mathcal{T}^S} \beta^t h_t p_t^F}{\mathcal{B}(x)},$$

and the response-weighted wedge $\widetilde{\omega}^F(x)$ is the non-price part of equation (G.8) divided by $\mathcal{B}(x)$. Setting $W'(x)$ to zero equates $\widetilde{p}^H$ with $\widetilde{p}^F + \widetilde{\omega}^F$. These are the prices and the wedge we report in Section 9.

Corollary 7.2 sets the terms to zero one at a time. Flexible wages imply $J = 0$, or $w - b = 0$ if the wage equals home production income. Full credit implies $V^{\mathrm{cl}} = 0$, and $\alpha = 0$ removes the agglomeration externality. The remainder term is zero if the Rand conversion leaves no residual and later water use does not change. Equation (G.7) then leaves $p_m^F - p_m^H$. Under Lemma F.1, as water shifts to firms p^F falls and p^H rises, so $p^F - p^H$ crosses zero only once.

With a single firm price, the wedge that matters is an average of the wedges, weighted by

where the marginal unit of water goes,

$$\omega_m^F = \sum_{s,\ell} \psi_{s\ell,m} \omega_{s\ell,m}^F, \qquad \psi_{s\ell,m} = \frac{\partial Q_{s\ell,m}^F}{\partial Q_m^F}, \qquad \sum_{s,\ell} \psi_{s\ell,m} = 1,$$

where $\omega_{s\ell,m}^F$ is the wedge on water that goes to sector s in location ℓ. This is the correction that can be implemented with a common price (Diamond, 1973).

G.6 The involuntary unemployment term

Let ω_m^{jobs} denote the first term of equation (7.10). Using equation (F.6), we can write it as

$$\frac{\omega_m^{\text{jobs}}}{p_m^F} = \sum_{t=m}^{\infty} \beta^{t-m} \sum_i \xi_t \left(1 - \frac{b}{w_{i,t}}\right) \frac{(1-\gamma_f)(1-s_{i,t}^W)}{s_{i,t}^W} \frac{p_t^F Q_{i,t}^F}{p_m^F Q_m^F} \frac{J_{i,t|m} Q_m^F}{L_{i,t}}. \tag{G.9}$$

The term $1 - b/w_{i,t}$ is the fraction of the wage lost by rationed workers, the cost-share ratio is equation (7.6), and the last term is the proportional change in jobs from a proportional change in firm water use. The firm's water spending in year t relative to year m and ξ_t weight each market and year.

G.7 Finite changes and their sources

To compute finite changes in welfare, we integrate the marginal welfare effect along the path of the allocation,

$$W(x_1) - W(x_0) = \int_{x_0}^{x_1} W'(x)\,\mathrm{d}x. \tag{G.10}$$

Table I.1 decomposes these finite changes, both the cost of the shortage relative to no shortage and the gain from moving to the crossing.

We define $\Delta z = z_1 - z_0$, $\langle z \rangle = (z_0 + z_1)/2$, and $\mathsf{LM}(z) = (z_1 - z_0)/(\ln z_1 - \ln z_0)$, the logarithmic mean. In the household part of the water-prices effect, Δ_p is the effect of finite price changes holding Rand income Y fixed,

$$\Delta_p \ln(\mathfrak{m} - \bar{p}^H \bar{q}) = \Delta_p[\ln(Y - p^H \bar{q}) - \theta \ln p^H].$$

In each formal state, we divide workers into $n_{i,t} e_{i,t}$ workers employed at $w_{i,t}$ and $n_{i,t}(1 - e_{i,t})$ workers who earn b. Workers in the home state also earn b. We denote this household effect, the first line of equation (G.11), by $\mathsf{P}_{\text{water}}^H$.

Let $K_{i,t}^X$ denote the CES cost of inputs, net of productivity. A finite change in this cost has an exact decomposition using the Sato–Vartia weight (Sato, 1976; Vartia, 1976),

$$\widetilde{s^W}_{i,t} = \frac{\mathsf{LM}(s_{i,t}^W)}{\mathsf{LM}(s_{i,t}^W) + \mathsf{LM}(1 - s_{i,t}^W)},$$

so that

$$\Delta \ln K^X_{i,t} = \widetilde{s^W}_{i,t} \Delta \ln p^F_t + (1 - \widetilde{s^W}_{i,t})[(1-\gamma_f)\Delta \ln w_{i,t} + \gamma_f \Delta \ln \rho_{\ell(i),t}].$$

Water prices enter households' utility through consumption, firms' operating profits through their input costs, and the city's water receipts,

$$\begin{aligned} \mathsf{P}_{\text{water}} = & \sum_{t \in \mathcal{T}^S, i} \beta^t \langle n_{i,t} \rangle \mathsf{LM}(\mathfrak{m}_{i,t} - \bar{p}^H \bar{q}) \Delta_p \ln(\mathfrak{m}_{i,t} - \bar{p}^H \bar{q}) \\ & - (\sigma - 1) \sum_{t \in \mathcal{T}^S, i} \beta^t \mathsf{LM}(v_{i,t}) \widetilde{s^W}_{i,t} \Delta \ln p^F_t \\ & + \sum_{t \in \mathcal{T}^S} \beta^t \Delta (p^H_t Q^H_t + p^F_t Q^F_t). \end{aligned} \tag{G.11}$$

Involuntary unemployment enters through

$$\mathsf{J}_{\text{jobs}} = \sum_{t,i} \beta^t \langle \widetilde{L}_{i,t} \rangle \langle \xi_t (w_{i,t} - b) \rangle \Delta e_{i,t}. \tag{G.12}$$

Let $N^{\text{op}}_{i,t}$ denote the number of operating firms in state i at time t, $Z_{i,t}$ their total stock of productivity, and $f^{E,\text{total}}_t$ total entry costs at time t. The welfare effect of changes in operating firms and entrants, reported as inefficient exit, is

$$\begin{aligned} \mathsf{C}_{\text{firms}} &= \sum_{t,i} \beta^t [\mathsf{LM}(v_{i,t}) \Delta \ln Z_{i,t} - f \Delta N^{\text{op}}_{i,t}] - \sum_t \beta^t \Delta f^{E,\text{total}}_t, \\ Z_{i,t} &= \int_{\mathcal{A}_{i,t}} \varphi^{\sigma-1} \, \mathrm{d}\mathcal{F}_{i,t}. \end{aligned} \tag{G.13}$$

The welfare effect of the agglomeration externality is

$$\mathsf{A}_{\text{productivity}} = (\sigma - 1)\alpha \sum_{t,i} \beta^t \mathsf{LM}(v_{i,t}) \Delta \ln L_{\ell(i),t}. \tag{G.14}$$

The effect of water sold after the shortage is

$$\mathsf{G}_{\text{later}} = \sum_{t \text{ after shortage}} \beta^t (\bar{p}^H \Delta Q^H_t + \bar{p}^F \Delta Q^F_t). \tag{G.15}$$

The effect of workers' moves between states is

$$\mathsf{M}_{\text{moves}} = -\frac{1}{\nu \bar{\varkappa}} \sum_t \beta^t \sum_i n_{i,0} \Delta \ln \mu_{ii,t} + \Delta \mathcal{S}. \tag{G.16}$$

The six effects sum to the change in welfare in Table I.1, where we combine later water use and moves as Other. Initial populations and amenities are the same in the two allocations,

so the stay-value identity gives

$$\Delta\mathcal{V} = \sum_{t,i} \beta^t n_{i,0} \Delta \bar{u}^c_{i,t} - \frac{1}{\nu} \sum_{t,i} \beta^t n_{i,0} \Delta \ln \mu_{ii,t}.$$

Let $\mathsf{F}_{w,\rho}$ be the effect of finite changes in wages and rents on firms, including landlords,

$$\begin{aligned}\mathsf{F}_{w,\rho} = & -(\sigma-1) \sum_{t,i} \beta^t \mathsf{LM}(v_{i,t})(1-\widetilde{s^W}_{i,t})[(1-\gamma_f)\Delta \ln w_{i,t} + \gamma_f \Delta \ln \rho_{\ell(i),t}] \\ & + \sum_{t,\ell} \beta^t \bar{H}_\ell \Delta \rho_{\ell,t}.\end{aligned}$$

Then the assignment term in equation (G.16) is

$$\Delta\mathcal{S} = \Delta\mathcal{C}^H - \mathsf{P}^H_{\text{water}} - \mathsf{J}_{\text{jobs}} + \frac{\sum_{t,i} \beta^t n_{i,0} \Delta \bar{u}^c_{i,t} - \Delta\mathcal{U}}{\bar{\varkappa}} + \mathsf{F}_{w,\rho}. \tag{G.17}$$

It combines the effect of who is in which state with the conversion of wage income into Rand.

H Parameter estimation

Date $t = 0$ in the model is the year before the drought. The sets $\mathcal{T}^{\text{exit}}$ and $\mathcal{T}^A$ are the model dates at which we match the exit and productivity moments.

H.1 Household demand and basic water

To estimate households' price response above the first 6,000 litres a month, we run

$$\ln Q^{\text{domestic}}_{\text{month}} = \eta_H \ln p^H_{\text{month}} + \delta^{\text{calendar}}_{\text{month}} + u^{\text{bill}}_{\text{month}}, \tag{H.1}$$

where $Q^{\text{domestic}}_{\text{month}}$ is citywide monthly water use billed to households, p^H_{month} is the price households face, and $\delta^{\text{calendar}}_{\text{month}}$ are calendar-month effects that soak up seasonality. We estimate $\widehat{\eta}_H = -0.97$, with a standard error of 0.08.

We calibrate demand per resident before the drought, using household billed water use and population from the Community Survey. We set $\bar{q} = 50$ litres a person a day and choose θ to match a 3 percent water spending share at pre-drought prices, where income is the wage bill plus the home production income of those outside formal work,

$$\frac{\bar{p}^H Q^H_0}{Y^H_0} = 0.03, \qquad Y^H_0 = \sum_{s,\ell} w_{s\ell,0} L^d_{s\ell,0} + b\Big(\bar{n} - \sum_{s,\ell} L^d_{s\ell,0}\Big).$$

Since we assume that basic water is consumed first, $\theta = p^H(q-\bar{q})/(Y - p^H\bar{q})$ for each resid-

ent, the share of income above basic needs spent on water above basic needs. Aggregation across households is as in equation (F.13).

H.2 Sector water weights

The CES weight on water γ_s^W is calibrated so that equation (F.5), evaluated at normal prices, matches the cost share of water in total inputs for each sector in the national Supply and Use Tables,

$$\frac{\sum_\ell \int_{\mathcal{A}_{s\ell}} \bar{p}^F \bar{Q}_j \, \mathrm{d}\mathcal{F}_{s\ell}}{\sum_\ell \int_{\mathcal{A}_{s\ell}} \bar{X}_j \, \mathrm{d}\mathcal{F}_{s\ell}} = \gamma_s^{\mathrm{SUT}},$$

where $\bar{X}_j$ is variable cost at normal prices. See Appendix B.3 for the sector mapping.

H.3 Water substitution

The elasticity of substitution between water and other inputs, ε, is estimated so that the implied elasticity of water demand at given output, $-\varepsilon(1 - s^W)$ from equation (F.7), matches the evidence in Figure 6.1. With the small water share set to zero,

$$\left.\frac{\Delta \ln Q}{\Delta \ln p^F}\right|_y \simeq -\varepsilon, \qquad \widehat{\varepsilon} \simeq -\frac{\ln(0.88)}{\ln(65/17)} = 0.095.$$

Water use by commercial accounts that are active throughout the sample fell 12 percent from before the price increases to the peak of the drought, while the price of water rose from R17 to R65 per kilolitre. Sales of these continuing establishments stayed close to their counterfactual, as shown in Appendix E.3. A regression of log annual water use on the log real commercial tariff over the drought years gives 0.15 (standard error 0.09), and we use this standard error for $\widehat{\varepsilon}$. Alternative estimates range from 0.07 to 0.15. Using the ratio of real peak prices gives 0.115, using the ratio of real annual-mean prices gives 0.131, and the recovery in use when the real price fell after the drought gives 0.07.

H.4 Worker destinations and amenities

Using the logit probabilities, we have

$$\ln \frac{\mu_{ii',t}}{\mu_{ii,t}} = \nu\beta(V_{i',t+1} - V_{i,t+1}) - \nu\tau_{ii'}. \tag{H.2}$$

Plugging in next year's flows for the continuation values, using $V_{i,t} = \bar{u}_{i,t} + \beta V_{i,t+1} - \nu^{-1} \ln \mu_{ii,t}$, gives

$$\ln \frac{\mu_{ii',t}}{\mu_{ii,t}} = \beta \ln \frac{\mu_{ii',t+1}}{\mu_{i'i',t+1}} + \nu\beta(\bar{u}_{i',t+1} - \bar{u}_{i,t+1}) - (1-\beta)\nu\tau_{ii'}.$$

All markets clear before the drought, so we interpret $\bar{u}$ as utility at the wage, using mean log earnings as a measure. Origin and destination effects soak up amenities, and year effects soak up other changes common to all workers, such as the water price. Setting $\beta = 0.95$ outside the estimation, we back out $\nu = 1.3$ from the coefficient, which equals $\nu\beta$.

The cost of moving is the same in both directions, while the sign of the value difference flips for workers making the opposite move, so

$$\frac{1}{2}\left[\ln \frac{\mu_{ii',t}}{\mu_{ii,t}} + \ln \frac{\mu_{i'i,t}}{\mu_{i'i',t}}\right] = -\nu\tau_{ii'}. \tag{H.3}$$

The data $\mu_{ii',t}$ are annual origin-to-destination flows of Cape Town workers in formal employment in consecutive years before the drought. Sectors are binned into 12 sector groups. The two-way log odds of moving between sector groups give $\nu\tau_S = 4.68$ (standard error 0.08), so $\tau_S = 3.6$.

To estimate τ_L, we map employer postcodes to H3 hexagons (Brodsky, 2018) and define a location move as a change in workplace hexagon. For moves within a sector, equation (H.3) becomes $-\nu\tau_L \,\mathrm{dist}_{\ell(i)\ell(i')}$. At the move-weighted average distance of 8 kilometres between hexagon centroids, the pooled two-way log odds give $\nu\tau_L\overline{\mathrm{dist}} = 1.87$. With $\nu = 1.3$ from above, $\tau_L = 1.87/(8 \times 1.3) = 0.18$ per kilometre.

We set amenities to solve $\sum_i n_{i,0}\mu_{ii'}(a) = n_{i',0}$, with one amenity normalised, where $n_{i,0}$ is the pre-drought number of workers in state i. Amenities therefore reproduce the pre-drought distribution of workers across formal employment and home production.

Lemma H.1 (Inversion of amenities and productivity)**.** *(i) Let $\nu > 0$, $\beta \in (0,1)$, the switching costs $\tau_{ii'}$ and the pre-drought utilities from consumption $\bar{u}^c_{i,0}$ be given, with $n_{i,0} > 0$ for all states i. There exist amenities a such that $\sum_i n_{i,0}\mu_{ii'}(a) = n_{i',0}$ for all i', and they are unique up to a common additive constant (and hence unique once one amenity is normalised). (ii) Let wages, rents, the price of water for firms and the outside-demand scale D_s be given, and let the incumbent firms be given, together with their financing terms. Then there is at most one value of $A_{i,t}$ such that firms' labour demand in state i is equal to the number of paid workers $L_{i,t} > 0$. If the set of firms that operate is given, it is*

$$A_{i,t}^{\sigma-1} = \frac{w_{i,t}L_{i,t}}{(1-\gamma_f)(1-s^W_{i,t})(\sigma-1)\mathsf{D}_s(K^X_{i,t})^{1-\sigma}Z_{i,t}}.$$

Proof. (i) Let $x_{i'} = \exp(\nu\beta V_{i'})$, $K_{ii'} = \exp(-\nu\tau_{ii'}) > 0$, and $r_i = \sum_{i'} K_{ii'}x_{i'}$, so that equation (F.2) reads $\mu_{ii'} = K_{ii'}x_{i'}/r_i$. With $y_i = n_{i,0}/r_i$, the matrix $\mathrm{diag}(y)K\mathrm{diag}(x)$ has row sums $n_{i,0}$, and stationarity says that its column sums are $n_{i',0}$. Conversely, if positive vectors (x, y) give $\mathrm{diag}(y)K\mathrm{diag}(x)$ row and column sums n_0, then $y_i = n_{i,0}/r_i$ and x

satisfies stationarity. Since K is strictly positive and both margins sum to $\bar{n}$, such (x, y) exist and are unique up to $(cx, y/c)$ for $c > 0$ (Sinkhorn, 1964, 1967), so stationarity determines V up to an additive constant. Given V, the stationary form of equation (7.3) gives $a_i = V_i - \bar{u}^c_{i,0} - \nu^{-1} \ln r_i$. Conversely, given a, the right side of equation (7.3) is a contraction in V with modulus β, so a determines V, and any a that reproduces n_0 comes from a V in this family. Adding c to every V_i multiplies x and r by $e^{\nu\beta c}$ and so adds $(1-\beta)c$ to every a_i. Since $\beta < 1$, fixing one amenity fixes c.

(ii) By equation (F.6), labour demand is $(1-\gamma_f)(1-s^W_{i,t})(\sigma-1)\mathsf{D}_s A^{\sigma-1}_{i,t}(K^X_{i,t})^{1-\sigma} Z_{i,t}/w_{i,t}$, where $s^W_{i,t}$ and $K^X_{i,t}$ do not depend on $A_{i,t}$ and $Z_{i,t}$ is nondecreasing in $A_{i,t}$, since a firm operates if and only if $v_{j,t} - f + c_{j,t} \geq 0$ and $v_{j,t}$ rises with $A_{i,t}$. Labour demand is therefore strictly increasing in $A_{i,t}$, and with $Z_{i,t}$ fixed solving for $A_{i,t}$ gives the display. □

H.5 Firm heterogeneity, death and entry costs

Since all firms in a sector and location face the same input prices, $L_j \propto \varphi_j^{\sigma-1}$. If productivity has a Pareto tail,

$$\ln \Pr(L_j \geq z) = c_L - \frac{k}{\sigma - 1} \ln z.$$

Following Helpman et al. (2004), we regress establishment log rank on log employment among large establishments before the drought. The absolute value of the slope is 1.48, so $k = 1.48(\sigma - 1) = 2.96$, which we round to 3.

We set the death probability $d = 0.05$ to the pre-drought exit rate among establishments with above-median employment in their sector. We choose the operating cost f to match mean employment per establishment, and the entry cost f^E from stationary free entry,

$$\mathbb{E}[L_j \mid j \text{ operates}; f] = \bar{L}^{\text{data}}, \qquad f^E = \beta(1-d)\mathbb{E}_\varphi \Pi^E_{s\ell}. \tag{H.4}$$

In the stationary economy, entry equals deaths. We calibrate location productivity $\bar{A}_\ell$, the outside-demand scales D_s and commercial floorspace $\bar{H}_\ell$ to match employment, wages and the number of establishments by sector and location before the drought. These parameters do not change across allocations or shortages.

H.6 The borrowing limit

Let $\widehat{\varsigma}_\kappa$ denote the excess-exit coefficient $\widehat{\beta}_\kappa$ from equation (6.1), and $\varsigma^M_\kappa(\lambda)$ its model counterpart,

$$\varsigma^M_\kappa(\lambda) = [\text{Exit}^{\text{WI}}_\kappa - \text{Exit}^{\text{other}}_\kappa]_{\text{shortage}} - [\text{Exit}^{\text{WI}}_\kappa - \text{Exit}^{\text{other}}_\kappa]_{\text{no shortage}}.$$

We choose λ so that the model's excess exit summed over the three drought years matches the data, $\sum_{\kappa\in\mathcal{T}^{\text{exit}}} \varsigma_\kappa^M(\widehat{\lambda}) = \sum_{\kappa\in\mathcal{T}^{\text{exit}}} \widehat{\varsigma}_\kappa$. In the data the coefficients are 6.5, 7.9 and 5.8 percentage points. We estimate $\widehat{\lambda} = 0.048$. At this value, a debt-free incumbent can borrow about 0.44 of a normal year's operating profit (equation (F.9)).

H.7 Productivity and local jobs

Let $K_{i,t}^X$ denote the CES cost of inputs net of productivity, $Z_{i,t}$ the stock of operating productivity in equation (G.13), and D_s the outside-demand scale. From labour demand,

$$A_{i,t}^{\sigma-1} = \frac{w_{i,t}L_{i,t}}{(1-\gamma_f)(1-s_{i,t}^W)(\sigma-1)\mathsf{D}_s(K_{i,t}^X)^{1-\sigma}Z_{i,t}}.$$

We compute $A_{i,t}$ using data on wages and employment, the commercial water price, water's cost share, rents that clear the market for commercial floorspace, and the productivity distribution of incumbents. This backs out productivity net of any direct effect of the water price. We aggregate to log productivity at the location level as the employment-weighted average of sector log productivity.

Let $\widehat{\text{res}}_{\ell,t}(\alpha) = \ln A_{\ell,t} - \alpha \ln L_{\ell,t}$, where $L_{\ell,t}$ is paid employment in location ℓ. Let S_ℓ denote the initial share of employment in water-intensive sectors in location ℓ, ϖ_ℓ pre-drought employment weights that sum to one, and $\bar{S} = \sum_\ell \varpi_\ell S_\ell$. For each year $t \in \mathcal{T}^A$, let

$$\text{cov}_t(\alpha) = \sum_\ell \varpi_\ell (S_\ell - \bar{S})[\widehat{\text{res}}_{\ell,t}(\alpha) - \widehat{\text{res}}_{\ell,0}(\alpha)].$$

We estimate

$$\widehat{\alpha} = \arg\min_\alpha \sum_{t\in\mathcal{T}^A} \text{cov}_t(\alpha)^2 = 0.03. \tag{H.5}$$

H.8 Sampling error of the estimated parameters

We carry the sampling error of our estimates of ε, λ, α and $\nu\tau_S$ into the welfare results. We move each parameter down and up by one standard error, except λ, for which we use the ends of the range in Table 8.1. We re-solve the model, including the no-shortage path, and clear water use in every allocation to meet the resource constraint. We then recompute the welfare curve. Half the difference between the two results is our measure of the effect of one standard error. We treat the sampling errors of the four moments as independent and report the square root of the sum of the squared effects (Table H.1).

The 52 percent welfare gain has a standard error of 9 points, the value ratio of 11 a standard error of 2.2, and the crossing at 96 percent a standard error of around one point. Sampling error in the elasticity of substitution accounts for most of this uncertainty.

Table H.1. Sampling uncertainty in welfare results

Parameter	Estimate	Re-solved at	Welfare results: Cost	Gain	Value ratio	Crossing
Estimated model			20.7	52	11	96
Change for one standard error						
Water substitution, ε	0.095 (0.09)	0.005, 0.185	−0.8	−9	−2.0	−1
Pledgeable share, λ	0.048 [0, 0.34]	0, 0.34	−0.5	0	0.3	0
Productivity elasticity, α	0.03 (0.01)	0.02, 0.04	0.7	1	0.8	0
Switching cost, $\nu\tau_S$	4.68 (0.08)	4.60, 4.76	0.4	0	0.4	0
Combined standard error			1.3	9	2.2	1

Notes: Estimates show the standard error in parentheses, or for λ the range in brackets; the model is re-solved at one standard error below and above each estimate, or for λ at the ends of its range. Each change is half the difference between the two solutions. The combined standard error is the square root of the sum of the squared changes. Cost is the welfare cost at the city's allocation, as a percentage of pre-drought annual income. Gain is the percent reduction in the welfare cost at the crossing. Value ratio is the social marginal value of water for firms divided by the household price at the city's allocation. Crossing is the household share of the saving at the crossing. Gain and crossing changes are in percentage points. Table 8.1 gives the matched moments. Source: model solutions.

H.9 Parameters set outside estimation

Table H.2. Welfare results under alternative external parameters

Parameter	Value	Cost at the city's allocation	Gain	Value ratio	Crossing
Estimated model		20.7	52	11	96
		Change from the estimated model			
Outside demand elasticity σ	2.5	1.3	−2	0.4	0
	3.5	−1.1	1	−0.4	0
Productivity-tail shape k	2.5	−1.5	0	−0.3	0
	2.75	−0.7	1	−0.2	0
	3.25	0.7	1	−1.3	0
	3.5	1.3	1	−1.5	0
Basic water $\bar{q}$, litres a person a day	40	0.5	1	0.0	0
	60	−0.5	−11	0.5	0
Household water spending share, percent	2	−1.0	−11	0.1	0
	4	1.0	0	−0.2	0

Notes: Each row re-solves the model after changing one parameter set outside estimation. Changes are relative to the estimated model. Cost uses pre-drought annual income. Gain and crossing changes are in percentage points. Source: model solutions.

Table H.2 reports welfare results from re-solving the model at other values of the parameters we set outside estimation. In every re-solved economy, the allocations in which households provide nearly all the saving have the lowest welfare cost.

I Further welfare comparisons

I.1 Welfare units

We report present-value welfare costs as a percentage of the city's annual income in the pre-drought year on the no-shortage path. Income is the paid wage bill plus the home production income of residents outside formal work. Welfare is measured as in equation (G.1), with the household money metric valued in Rand at the normal price of water.

I.2 Sources of welfare change

Table I.1 reports the welfare decomposition implied by equations (G.11)–(G.16). *Water prices* combines the effect of the prices households face on their consumption, firms' operating profits, and the city's receipts from water. We do not report the discounted cost of supplying water, since it is the same across allocations (equation (G.2)). *Other* combines the effect of water use after the shortage and of workers' later moves, as in Table 9.2.

Table I.1. Full decomposition of welfare cost and gain

Source	Share of cost, percent	Share of gain, percent
Water prices	31	−10
Involuntary unemployment	52	95
Inefficient exit	3	9
Agglomeration externality	5	6
Other	9	0

Notes: Shares of the welfare cost at the city's allocation, relative to no shortage, and of the gain from moving to the crossing. Water prices combines the effect of the prices households face on their consumption, firms' operating profits, and the city's receipts from water. Other combines the effect of water use after the shortage and of workers' later moves. Source: model solutions.

I.3 Equivalent variation

For each group of workers defined by initial sector and location, we compute equivalent variation as the constant annual Rand amount T_i^{EV} that, received every year on top of income along the no-shortage path, at no-shortage wages, hiring chances and prices, gives the same expected lifetime utility as the shortage path,

$$V_i^{\text{no shortage}}(T_i^{\mathrm{EV}}) = V_i^{\text{shortage}}.$$

Owners' profits, landlords' rents and the city's water receipts enter as in our main measure of welfare (Caliendo et al., 2019). With this measure, the crossing lowers the welfare cost

of the shortage by 57 percent (Section 9.4).

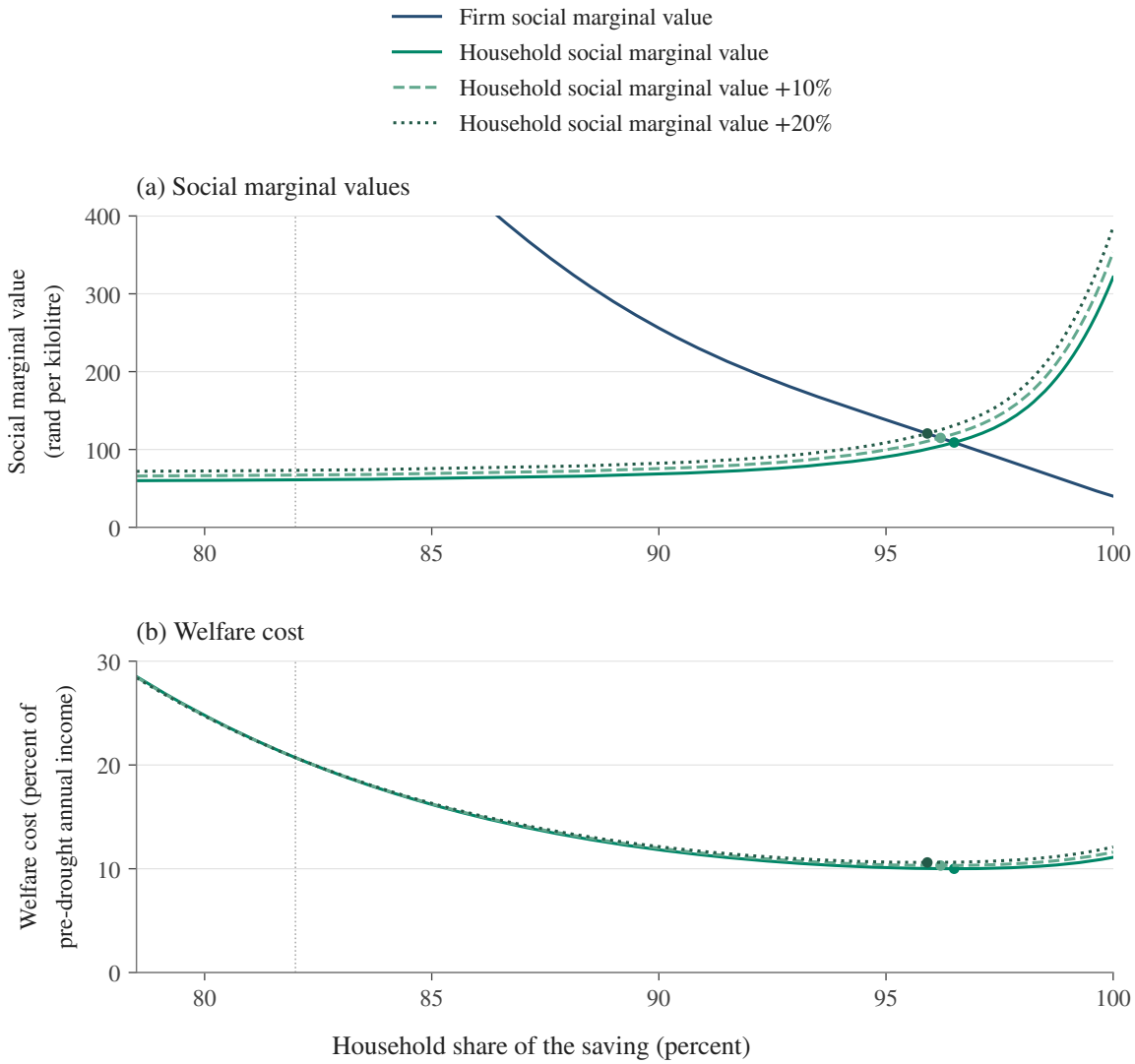
J Assumptions behind the social marginal values

We change the assumptions behind the two social marginal values, one at a time and together. In each exercise, agents make the same choices as in the baseline model at every allocation, but we revalue those choices. We integrate the new curves to compute changes in welfare (equation (G.10)) and report the results in Table J.1.

Value of household water above basic needs Our baseline measure of welfare values an additional litre of household water above basic needs at its price. Figure J.1 values it 10 and 20 percent above its price at every allocation, holding the basic-needs quantity and the firm values the same. The crossing stays at about 96 percent in both cases.

Value of firm water We scale the involuntary-unemployment, inefficient-exit and agglomeration-externality terms and the remainder r_m separately, keeping their shares at the city's allocation constant along the curve. Raising home production income b scales the involuntary-unemployment term by $(1 - b/w)/(1 - 0.4)$. Halving the involuntary-unemployment term can be interpreted as allowing for shorter spells of involuntary unemployment. Dropping the inefficient-exit term values exits as under full credit, $\lambda = 1$, holding choices fixed.

Figure J.1. Higher household social marginal values



Notes: Welfare costs are relative to no shortage, as a percentage of pre-drought annual income. The curves with higher household values are shifted to equal the main curve at the city's allocation. Firm values are held fixed. Source: model solutions.

Table J.1. Assumptions behind the social marginal values

Exercise	Wedge kept, percent	Value ratio at the city's allocation	Crossing change toward firms, percentage points	Gain, percent
Estimated model	100.0	10.9	0.0	51.7
Household social marginal value 10 percent above its price	100.0	9.9	0.3	50.2
Household social marginal value 20 percent above its price	100.0	9.1	0.6	48.8
Home production income 0.5 of the wage	87.0	9.6	0.3	48.4
Home production income 0.6 of the wage	74.0	8.4	0.7	44.4
Home production income 0.8 of the wage	48.0	5.9	2.0	33.8
Home production income equal to the wage	22.0	3.4	4.8	17.5
No inefficient-exit term	85.0	9.4	0.4	44.3
No agglomeration-externality term	95.0	10.4	0.1	51.4
No inefficient-exit or agglomeration-externality term	80.0	9.0	0.5	43.6
Involuntary-unemployment term halved (the limit of a much shorter loss)	61.0	7.1	1.2	39.6
Involuntary-unemployment term alone, home production income 0.6 of the wage	52.0	6.3	1.7	32.5

Notes: Each row changes one assumption behind the social marginal values. Wedge kept is the share of the estimated firm wedge at the city's allocation that remains. Welfare is revalued at fixed allocations. Gains compare each exercise's crossing with the city's allocation. Source: model solutions.

K Beliefs about the drought

Our benchmark assumes that agents know the duration of a drought once it begins. In this appendix we relax this assumption in two ways. First, we allow agents to be uncertain about the length of a drought. Second, we allow agents to expect the drought to recur.

K.1 An uncertain end date

We now allow the drought to end each year with some probability. In this case, water prices can only depend on whether a drought is ongoing or not. Nevertheless, Proposition 7.1 still applies, except that the wedge should now be interpreted as the *expected* wedge. This is because each step of the proof of Proposition 7.1 in Appendix G still applies in expectation. However, the components of the wedge change.

The component due to involuntary unemployment does not depend much on beliefs. With less water, firms want to hire fewer workers. As wages cannot fall, this leaves workers involuntarily unemployed whether or not agents expect the drought to continue. Beliefs only marginally affect this component through the recovery. New entrants wait for a signal that the drought is over before paying the sunk cost of entry (Dixit, 1989), so jobs lost to exiting firms take slightly longer to recover.

Beliefs are most important for the component due to inefficient exit. For a firm that makes losses during a drought but profits afterwards, the sooner agents expect the rain to return, the more valuable it is to keep the firm open. With an uncertain end date, keeping the firm open has option value, since the drought may end early. Even if it does not end, the firm can always exit later. Since lenders advance only a small share of this value, financially constrained firms may exit even though it is socially valuable to keep them open. An uncertain end date therefore makes each exit more costly, but does not change the number of exiting firms by much. Since household water saving can be reversed when the drought ends but firm exit cannot, this effect strengthens the case for households providing the saving, at least early in the drought (Arrow and Fisher, 1974; Henry, 1974).

Still, the quantitative effect is likely to be small. In the benchmark, inefficient exit amounts to 15 percent of the wedge, and the household price and the firm social marginal value are both steep around the crossing. Setting this component to zero moves the welfare-minimising allocation only 0.4 percentage points towards firms (Table J.1), so a larger component moves it by a similarly small amount towards households.

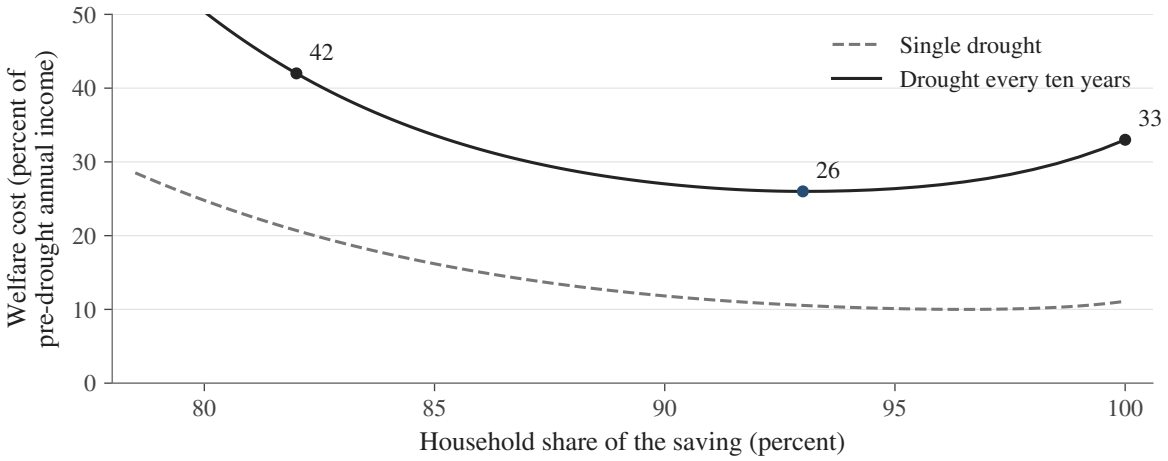
A limiting case is one where agents believe that the drought might be permanent. A firm making losses during a *permanent* drought has no option value, so the inefficient-exit component is close to zero in this case. Nevertheless, as long as wages cannot fall, the involuntary-unemployment component remains. Therefore, even in this case the welfare-

minimising policy still charges households a higher price than firms. Setting the inefficient-exit component to zero moves the welfare-minimising allocation only 0.4 percentage points towards firms, and even halving the involuntary-unemployment component moves it only 1.2 percentage points (Table J.1).

K.2 Droughts that recur

Events similar to Day Zero might recur. Here we consider the extreme case where the same drought recurs every ten years. Agents learn this when the first drought hits, and from that point on make their entry, exit and employment decisions taking future droughts into account. Figure K.1 plots the resulting welfare cost of different allocations and compares it with the case where the drought hits only once, as in Figure 9.3.

Figure K.1. The welfare cost when droughts recur



Notes: The solid line repeats the drought every ten years. The dashed line is the single drought of Figure 9.3. Costs are relative to no shortage, as a percentage of pre-drought annual income. Source: model solutions.

The shape of the welfare curve is unchanged, but the entire curve shifts upwards, as the city now suffers several droughts. At the city's allocation the welfare cost amounts to 42 percent of annual pre-drought income, instead of 20.7 percent when the city suffers a drought only once. At the welfare-minimising allocation households provide 93 percent of the saving instead of 96 percent, and the welfare cost is 26 percent instead of 10.0 percent. Had households provided all of the saving, the welfare cost would have amounted to 33 percent instead of 11.1 percent. Moving from the city's allocation to the welfare-minimising allocation therefore still reduces the welfare cost substantially, by 38 percent instead of 52 percent with a single drought. Overall, the expectation of recurring droughts shifts the welfare-minimising allocation slightly towards firms, but households should still provide almost all of the saving.